Novel Technologies and Systems for Food Preservation

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In a world where traditional business practices are reconsidered and economic activity is performed in a global context, new areas of economic developments are recognized as the key enablers of wealth and income production. This knowledge of information technologies provides infrastructures, systems, and services towards sustainable development.

The Practices, Progress, and Proficiency in Sustainability (PPPS) Book Series focuses on the local and global challenges, business opportunities, and societal needs surrounding international collaboration and sustainable development of technology. This series brings together academics, researchers, entrepreneurs, policy makers and government officers aiming to contribute to the progress and proficiency in sustainability.

MISSION

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Nattawut Chaomuang, King Mongkut’s Institute of Technology Ladkrabang, Thailand

The use of closed refrigerated display cabinets in supermarkets is in progression because of the potential energy saving compared to the open ones with an air infiltration at the front. However, the influence of the presence of doors on product temperatures (determining factor of product quality) is much less studied. For better understanding the interest of the use of closed display cabinets, this chapter presents the state of the art of field studies, the airflow and temperature profile in the closed display cabinet, the influence of the presence of doors/the frequency of door openings and the room temperature. Finally, a literature review of studies on food quality in the closed display cabinet is presented.

Chapter 2
Frost Measuring and Prediction Systems for Demand Defrost Control .............................................. 24

Martim Lima de Aguiar, Universidade da Beira Interior, Portugal
Pedro Dinis Gaspar, University of Beira Interior, Portugal
Pedro Dinho da Silva, University of Beira Interior, Portugal

It is widely known that the defrosting operation of evaporators of commercial refrigeration equipment is one of the main causes of inefficiency on these systems. Several defrosting methods are used nowadays, but the most commonly used are still time-controlled defrosting systems, usually by either electric resistive heating or reverse cycle. This happens because most demand defrost methods are still considered complex, expensive, or unreliable. Demand defrost can work by either predicting frost formation by processing measured conditions (fin surface temperature, air humidity, and air velocity), operative symptoms of frost accumulation (pressure drop and refrigerant properties), or directly measuring the frost formation using sensors (photoelectric, piezoelectric, capacitive, resistive, etc.). The data measured by the sensors can be directly used by the system but can also be processed either by simple algorithms or more complex systems that use artificial intelligence and predictive methods. This chapter approaches frost sensing and prediction for command of demand defrost systems.
Chapter 3
Processes and Technological Systems for Thawing of Fish

Vladimir Stefanovskiy, All-Russia Scientific Research Institute of Refrigerating Industry (VNIHI), Russia

This chapter describes the principles and methods of the fish thawing process, as well as the thawing systems’ structure, functioning, and development. A new method for calculating the duration of food thawing is introduced. The author shares best practices from the refrigeration industry of Russia and developed countries as well as his own experience. He hopes it may help scientists to choose research topics in the field of food freezing. The chapter is meant for students, post-graduate students, and experts working in the field of refrigeration production.

Chapter 4
Energy Efficiency in Meat Processing

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Anthony Paul Roskilly, Newcastle University, UK
Sandeep Jagtap, University of Lincoln, UK

Energy conservation plays a vital role towards sustainable development of meat processing. Energy costs for many meat plants represent the fourth highest operational cost. In meat processing, moderate levels of both electrical and thermal energy are consumed in wide range of processes and applications. However, energy efficiency improvement in the meat processing industry have been a focus to increase the sustainability of meat processing in the past decades. This chapter started with the examination of the energy use in meat processing facilities. The emerging energy-efficient technologies for meat processing were discussed in detail. Energy requirement for well-cooked meats varies with cooking method, appliances, and consumer behavior. Energy consumption reduction during meat cooking may have an influence on global energy requirement. Selection of cooking method, fuel, and cookware are beneficial for reducing the carbon footprint of the cooking unit. This chapter also presents the effects on quality characteristics of meat and meat products by different cooking methods.

Chapter 5
Solar Refrigeration for Post-Harvest Storage of Agricultural Products

Marek J. Bergander, Magnetic Development Inc., USA
Sarken D. Kapayeva, Eastern Kazakhstan Technical University, Kazakhstan

The main objective of this chapter is the demonstration of the entire development process leading to prototype fabrication and commercialization of a new, ejector-based system for refrigeration that is environmentally clean and is powered by low quality heat, either solar or waste, without any need for electricity. In many rural areas throughout the world, the availability of fresh food is limited by lack of refrigerated warehousing facilities often due to limited access to electrical power. Authors are describing a new, ejector-based refrigeration system that 1) utilizes solar or waste heat (below 100°C temperature) as a main source of energy; 2) eliminates the mechanical compressor, which is a main user of electricity and the main contributor to maintenance and reliability issues in cooling systems; and 3) operates without any ozone depletion effects and any greenhouse gas emissions, when used with natural refrigerants. Such a technique contributes to protection of the ecosystem, conservation of energy, and broad application of alternative energy sources.
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Siva Kalaiselvam, Anna University, India
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Thermal technologies for food preservation prevent the degradation of desired properties of the perishable food items for a longer duration to fulfill the needs of the consumers in the aspects of nutrition, safety, and price. Each freezing method has its distinct characteristics on quality of frozen food products. The major physical and chemical changes observed during the freezing process were freezer burns, recrystallization, protein denaturation, color, flavor, release of enzymes, etc. These will be detailed with appropriate examples. The comparative analysis of the aforementioned thermal technologies based on the quality of food products will be discussed with the recommendations for the selection of appropriate thermal technologies. It will guide the practicing engineers and researchers to understand the drawbacks of conventional thermal technologies and how they affect food qualities along with the advancements made to overcome the drawbacks.

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Seydi Yikmis, Tekirdag Namuk Kemal University, Turkey

Heat treatments are the most basic methods used to provide microbiological and enzymatic inactivation of food. However, the applied high temperature affects important parameters such as color, nutritional value, taste, and sensory characteristics of foods in the negative direction. Therefore, in recent years, producers and consumers have sought to obtain healthy food with little deviation in quality parameters, and new techniques of non-thermal emerged from this point. In this chapter, non-thermal food such asaccented electric fields, ultrasonic waves, high-pressure application, microfiltration, X-rays, ionizing radiation, high voltage electrical discharge, pulsed light, ultrasound, magnetic field heating, and information on conservation methods are given.

Chapter 8
Pinus Pinaster Bark Composition and Applications: A Review ....................................................... 174

Catarina Vieito, Polytechnic Institute of Viana do Castelo, Portugal
Preciosa Pires, Polytechnic Institute of Viana do Castelo, Portugal
Manuela Vaz Velho, Polytechnic Institute of Viana do Castelo, Portugal

The food market is demanding natural antioxidants either to be applied to food or cosmetic and nutraceutical purposes. Plants are very rich in polyphenols that have diverse biological functions, such as defending plants against microbiological attacks, becoming essential to plant life. The bark of Pinus pinaster Aiton subsp. atlantica is known to have a great amount of polyphenols with antioxidant and antimicrobial properties. P. pinaster has a large area of distribution in the northwest of Portugal, making this source a biomass feedstock of great interest for the food industry in Portugal. Therefore, embarking on the trend of circular economy, polyphenols are being extracted aiming for the exploitation of their antioxidant and antimicrobial properties as a food additive in a variety of food matrices. This chapter aims to provide a more insightful view of the chemical composition, extraction methods, and food applications of pine bark of Pinus pinaster Aiton subsp. atlantica polyphenols.
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Technologies for Monitoring the Safety of Perishable Food Products ................................................. 190

Pedro Dinis Gaspar, University of Beira Interior, Portugal
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Food safety and eradication of food waste are current concerns of society and governments due to health,
economics, and sustainable economics. There are multiple technologies for monitoring food safety at different
chain stages, among them, time-temperature integrators (TTI). Temperature is a major factor affecting
food quality and safety during its life cycle. This parameter can be monitored using TTI devices on
food packages, allowing users to know the thermal exposure. This chapter addresses food safety issues,
notably factors related to microbial growth responsible for food deterioration. Moreover, TTI monitoring
technologies are also described, focusing on features, advantages, disadvantages, applicability, and product
examples. Analysis of the current state of TTI and technological evolution, a prediction is provided for
future TTI devices designed for more assertive, traceable, safe, and quality food products.

Chapter 10
Reference on Rice Quality and Safety ............................................................................................................ 226

Griffiths Atungulu, University of Arkansas, USA
Soraya Shaffekhani, University of Arkansas, USA

Over the last decade, there have been massive investments and research to improve rice yield per hectare.
Alongside successful stories of improved rice yields are corresponding concerns stemming from pre-
and post-harvest rice quality- and safety-related issues. Such concerns in rice production, handling, and
storage systems present public health and economic problems. To consumers and producers, a serious
concern is the potential growth of toxigenic fungi on rice during storage leading to contamination of
the rice with mycotoxins. That withstanding, diminished functional, sensory, and nutritional attributes
hugely impact the investment returns. The author understands that discourse on rice storage is incomplete
without reflections on nutritional related losses. In rendering a strong chapter to meet a wider readership,
the above issues are discussed with deliberate effort to highlight technological advances making headway
in the rice industry; these are outlined in the introduction, at first, and then expounded on in subsequent
sections.

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Dixit V. Bhalani, Central Salt and Marine Chemicals Research Institute, India
Arvind Kumar Singh Chandel, Central Salt and Marine Chemicals Research Institute, India
Poonam Singh Thakur, Rashtrasant Tukadoji Maharaj Nagpur University, India

The quality and safety of all food products are the essential parameter for both ends manufactures and
end consumers. This parameter of the food products we cannot overlook or liberalize in any situation.
More than two-thirds of diseases are spread through the contaminated or spoiled food source. Looking at
the importance of quality and safety management issue, the various governments made a series of rules
and regulations for the assessment of food products. This chapter explains the role of various assessment
agencies and their rights and workflows.
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Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems .......... 294

Griffiths Atungulu, University of Arkansas, USA
Zeinab Mohammadi-Shad, University of Arkansas, USA

Mycotoxins are a group of naturally occurring toxins that are produced by different filamentous fungi genera such as Aspergillus, Penicillium, Fusarium, etc. The word mycotoxin literally is derived from Greek word “myke” meaning fungus and “toxicum” meaning toxin. These contaminants can develop on different food and feed commodities during different stages including pre-harvest, harvest, and storage. Mycotoxins are of concern because their outbreak result in animal and human diseases and economic losses. It has been estimated that global post-harvest losses are approximately at 50%. Human exposure to mycotoxins is typically through consumption of contaminated agricultural products or indirectly by consumption of animal products containing mycotoxins or their metabolites. The chapter provides the latest information on mycotoxin issues and challenges related to food and feed safety.

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Preface

The sustainability and safety of food are a major concern of consumers in recent years. There has been an increasing demand for foods as well as a change in consumption habits. To deal with this new trend, there is a greater availability and variety of food with longer shelf life. In this context, several thermal and non-thermal processes play an important role, being an indispensable tool for processing, distributing and storage of perishable foods. The improvement of the food chain sustainability requires chasing new technological and scientific advances both on processes and equipment, through their innovative designs.

The technology based on the thermodynamic vapor compression cycle is widely used as industrial, commercial and domestic refrigeration system. It is a technology with proven merits and accepted by many different sectors. It continues to be a constantly evolving technology, by the technological enhancement of the various components of the system (compressor, evaporator, expansion valves and condenser) and its accessories. These advances include the application of new materials, new coolant fluids with greater heat exchange capacity and reduced environmental impact, technological solutions and innovative designs and the precise control, regulation and command of the refrigeration system. This latter technological advance may lie in the adoption of a multiplicity of sensors for direct or indirect monitoring of numerous parameters, actuators with regulated operation, and the use of microcontrolled systems with algorithms that may use intelligent control techniques. However, depending on the specificity of the industrial process, there is a need to further develop the refrigeration system and its components, both by considering innovative solutions at the level of the system components, and of control, regulation and command that enable the food products processing with the required nutritional and organoleptic characteristics.

By other hand, the current demand for healthier products with superior organoleptic quality and that have specific health and well-being properties (such as functional foods or bioactive properties) has grown exponentially. These trends added to the need of ensuring the microbiological safety and the extension of shelf life promoted the development of new and emerging alternative technologies for food processing. The competition with emerging economies, allows delivering products to the market at increasingly competitive prices, forcing the agrifood industry to compete through innovation and creation of added value products.

The thermal processing includes a set of unit operations such as bleaching, pasteurization and sterilization, based on external heat generation and its transfer by conduction, convection and radiation mechanisms. In order to avoid compromising the microbiological safety, all these operations end up affecting quality parameters, reducing nutritional value, as well as causing changes in organoleptic properties, namely flavor, texture, color and aroma.
Preface

To overcome the limitations of traditional methods of pasteurization and sterilization, it is increasingly necessary the strict control of the applied heat treatment and of other processing/non-heat technologies in order to ensure the food safety with the highest quality. In this context, the development and implementation of emerging and innovative food processing technologies that aim, besides overcoming the limitations of food quality, to increase efficiency and production rates.

Beyond the traditional food preservation methods of thermal processing, freezing, salting and drying, novel methods of processing and packaging continue to emerge. These methods can extend the shelf life and freshness of perishable foods. They can be classified as non-thermal technologies (High hydrostatic pressure; HHP; Pulsed electric fields: PEF; High-intensity light pulses; Membrane Technology; Irradiation; Food Preservation with Ozone and Modified and Controlled Atmosphere Storage) or thermal technologies (Ohmic heating; Infrared heating: IR; Microwave heating: MW and Radio frequency heating: RF). Thus, research and development in food preservation is towards the development of novel and emerging cooling and heating technologies in order to improve the food chain sustainability, reduce carbon footprint, mitigate climate change and improve energy efficiency. The research focus on the development of innovative and/or alternative cooling/heating technologies and their novel concepts, associated with improved control and monitoring systems.

The Novel Technologies and Systems for Food Preservation identifies the main issues involving novel and emerging cooling and heating technologies, processes and systems for food preservation. It reviews the state of the art and recent advances in several application areas of these technologies. It covers specific subjects, from the technological demand of some thermal and non-thermal technologies to the carbon footprint triggered from its use. Nevertheless, it also provides a broad insight of these cooling and heating processes, focusing general aspects likewise optimization, sustainability and technology innovation in food chain. At the same time, it is aimed to be a reference text presenting true implications of the use of these novel and emerging cooling and heating technologies, processes and systems for food preservation, its devices operation and research efforts to improve processes and systems efficiency. The book is organized in such a way that highlights both specific and general topics in order to provide its use by a large audience interested in food preservation issues. Although some topics are placed at a level that does not require considerable previous expertise in the technical details of specific areas, others are somehow knowledge demanding due to the complex research discussion.

The Novel Technologies and Systems for Food Preservation intends to be a reference for all interested parties, from undergraduate students, to researchers and decision-makers. It provides an introduction to thermal and non-thermal processes and systems and their advance due to the ongoing research, being not limited to these topics but exploring a wide span of applications, their technologies, equipment, procedures, environmental impact and energy concerns. Moreover, it aims to unveil trends and opportunities for the improvement of the food sector’s efficiency and sustainability.

The Novel Technologies and Systems for Food Preservation is organized into twelve chapters. The chapters include the recent research on novel and emerging cooling and heating technologies for food preservation and survey the state of the art in this field. The contributors review advances in processes and equipment design, efficient heat and mass transfer processes, optimization of real operating systems, modelling and predictive computational tools, innovative technologies, among others. A brief description of each of the chapters follows:
Preface

Chapter 1 presents the state of the art of field studies related with the closed refrigerated display cabinets. The authors discuss the airflow and temperature profile, the influence of the presence of doors, the frequency of door openings and the room temperature on the performance of the display cabinet. Additionally, the chapter includes a literature review of studies on food quality in closed display cabinets.

Chapter 2 approaches frost sensing and prediction for command of demand defrost systems. Authors review the different methods for demand defrosting that include directly measuring, predicting or hybrid solutions. Due to the technological evolution of regulation, command and control systems, these new and innovative systems and techniques are becoming more attractive in terms of cost and usefulness.

Chapter 3 describes principles and methods of fish thawing process, as well as thawing systems' structure, functioning and development. The author presents a new method for calculating the duration of food thawing and shares best practices from refrigeration industry of Russia and developed countries.

Chapter 4 addresses the issue of the energy efficiency in meat processing. The authors examine the energy use in meat processing facilities and discuss in detail the emerging energy-efficient technologies for meat processing. The chapter also presents the effects on quality characteristics of meat and meat products by different cooking methods.

Chapter 5 presents a new ejector-based system for refrigeration that is environmentally clean and is powered by low quality heat, either solar or waste, without any need for electricity. The authors present the concept through theoretical analysis and CFD modeling, model validation by laboratory experiments and finally a bench model/prototype.

Chapter 6 presents a comparative analysis of the thermal technologies for food preservation based on the quality of food products. The authors present their recommendations for the selection of appropriate thermal technologies for food preservation.

Chapter 7 presents the use of non-thermal treatment technologies in liquid foodstuffs. The author discusses several food conservation methods as accentuated electric fields, ultrasonic waves, high-pressure application, microfiltration, X-rays, ionizing radiation, high voltage electrical discharge, pulsed light, ultrasound and magnetic field heating.

Chapter 8 examines the demanding of natural antioxidants to be applied to food instead of synthetic ones. The authors provide an overview of the Pinus pinaster characteristics, covering its chemical composition, extraction methods and its food applications.

Chapter 9 addresses the issue of technologies for monitoring the safety of perishables food products. The authors examine the current state of time-temperature Integrators devices as well as its technological evolution. Moreover, a prediction is provided for future devices designed for more assertive, traceable, safe and high-quality food products.

Chapter 10 examines the rice quality and safety. The authors argue that the discourse on rice storage is incomplete without reflections on nutritional related losses and these issues are discussed to highlight technological advances making headway in the rice industry.

Chapter 11 summarizes the food quality and safety regulation systems. The authors analyze the specific and integrated/advanced food quality and safety management system, along with the identification and analysis of the factors that can influence the employment process.

Chapter 12 provides the latest information on mycotoxin issues and challenges related to food and feed safety. The authors discuss several aspects related with these contaminants including health concerns, safety evaluation, detection methods, preventive and control strategies, among others.
Overall, Novel Technologies and Systems for Food Preservation, accounts with the contribution of 27 authors from 10 countries and presents as main output the improvement of the food chain sustainability, including food safety and availability, energy efficiency and carbon footprint.

This book can be used in didactic context by under-graduate and graduate students, and in research context by post-graduate students and researchers. Moreover, the practicing engineers can find in this book several topics that can be an added value to the selection, design and retrofit of food preservation systems, equipment, and facilities.

We hope that you enjoy the reading.

The Editors,

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Chapter 1

Closed Refrigerated Display Cabinets: Is It Worth It for Food Quality?

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King Mongkut’s Institute of Technology Ladkrabang, Thailand

ABSTRACT
The use of closed refrigerated display cabinets in supermarkets is in progression because of the potential energy saving compared to the open ones with an air infiltration at the front. However, the influence of the presence of doors on product temperatures (determining factor of product quality) is much less studied. For better understanding the interest of the use of closed display cabinets, this chapter presents the state of the art of field studies, the airflow and temperature profile in the closed display cabinet, the influence of the presence of doors/the frequency of door openings and the room temperature. Finally, a literature review of studies on food quality in the closed display cabinet is presented.

INTRODUCTION
Numerous studies on retail refrigerated display cabinets have been carried out over the past two decades, awareness of food product quality and energy efficiency is rising continuously. Open display cabinets are a refrigeration equipment typical used for food display in retail stores. In this cabinet type, there is no physical barrier between customers and products, except an air curtain which allows infiltration of warm and humid air from surroundings. This issue still poses problems in many research and development contexts even through plenty of research studies were undertaken by means of both experimental and numerical approaches. The application of closed doors is becoming an alternative solution and several studies have demonstrated that fitting cabinets with doors can provide several benefits. Since there is no clear observation on the loss of sales of products due to the use of doors, many researchers are conducting investigations on the influence of the presence of doors. Nevertheless, most of these stud-

ies focused on the energy efficiency perspective. Its impact on internal temperature variations, which directly affect food quality and safety, requires further elucidation. The objective of this book chapter is therefore to highlight the new trend for the use of closed display cabinets in supermarkets and its associated implications on food quality.

BACKGROUND

About 66-77% of heat input in an open refrigerated display cabinet come from the infiltration of warm and humid ambient air in a supermarket (Gaspar, Carrilho Gonçalves, & Pitarma, 2011; Tassou, Ge, Hadawey, & Marriott, 2011) which is one of the main causes of internal temperature heterogeneity. Temperature differences of more than 5°C can be found on cabinet shelves (Willocx, Hendrick, & Tobback, 1994) where the highest temperature is regularly located at the front of the cases (Evans, Scarcelli, & Swain, 2007; Laguerre, Hoang, Osswald, & Flick, 2012). To overcome this major drawback, installation of doors becomes an alternative and attracts more and more attention, and it will account for 75% of all display cabinets in retail stores by the end of 2020 in France (RPF, 2016). Closed refrigerated display cabinets have been increasingly used because of their potential energy savings of between 20-70% (Fricke & Becker, 2010; Lindberg, Axell, & Fahlén, 2010; Rhiemeier, Harnisch, Ters, Kauffeld, & Leisewitz, 2009; Rolfsman & Borgqvist, 2014). Such savings were mainly achieved through a reduction in the entrainment of ambient warm and moist air into the shelves-space storage, thus, less frost is deposited on cooling coils and compressor energy demand becomes less (Faramarzi, Coburn, & Sarhadian, 2002). The difference in the energy consumption from these studies depends on a number of factors, for example, the number of door openings, the door itself, the door seals/gaskets and the level of air infiltration during door openings (Evans, 2014). Among these influencing factors, the frequency, duration of door openings and air gaps between the doors are important which can result in higher energy consumption (Li, Zhu, Wang, & Zeng, 2007). The refrigeration energy consumption of closed display cabinets during stable night condition was approximately 10% lower than that of the display cabinet operated under periodically door openings (Vallée, 2015). Despite these findings, the energy consumption between these two cabinet types may not significantly different when the estimation of the mean total energy consumption is based on a unit display area because of the difference of cabinet design (Evans & Swain, 2010). Further research is required to access additional data.

Temperature performance of closed refrigerated display cabinets was investigated particularly in regard to spatial and temporal temperature variations. A decrease in the overall air temperature of at least 2°C in display cabinets was achieved when retrofitted with doors (Lindberg et al., 2010), Chaomuang, Flick, Denis, and Laguerre (2019) reported that the studied cabinet with doors provided less temperature heterogeneity ($\Delta T_{\text{max}} = 2.1 ^\circ C$) compared to the case without doors ($\Delta T_{\text{max}} = 4.9 ^\circ C$). About 124 closed display cabinets were tested by Evans and Swain (2010) and the comparative results obtained with open and closed display cabinets revealed that the temperature variation within the closed cabinets was lower than that within the open ones. About 94% of the products with the highest temperature were located at the front of the chilled display cabinet, and nearly half of them (49%) were located on the bottom shelf. Most often, the products with the lowest temperatures were located at the rear of the cabinet and about 70% were on the top shelf. Another study of Atilio de Frias, Luo, Kou, Zhou, and Wang (2015) also affirmed that the temperature heterogeneity in the closed cabinet was less
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compared to the open one because of the decrease of spatial temperature differences almost by 6°C. As the quality of chilled/frozen food products is directly affected by storage temperature, the improvement in temperature homogeneity in display cabinets would be expected to provide better food quality during storage. The same authors reported that higher visual quality and lower decay rate of minimally processed vegetables could be achieved by the installation of doors on display cabinets. Details of the research studies with a view to improve the performance of the display cabinets, through both experimental and numerical approaches are highlighted by Chaomuang, Flick, and Laguerre (2017).

MAIN FOCUS OF THE CHAPTER

The aim of this book chapter is to highlight the new trend for closed display cabinet use in supermarkets. The chapter is composed of 7 sections:

1. Field studies of product temperature in display cabinets,
2. Experimental air temperatures in a closed display cabinet,
3. Influence of the presence of doors,
4. Influence of the frequency and the duration of door openings,
5. Influence of room temperature on the temperature performance of the cabinet,
6. Modelling of heat transfer and airflow in closed display cabinets
7. Product quality in closed display cabinet

The presented information can enable design improvements to align with user requirements.

Field Studies of Product Temperature in Display Cabinets

This section presents the field studies for both open and closed display cabinets. Derens, Palagos, and Guilpart (2006) conducted a survey of temperature in French cold chain for three chilled products (yogurt, prepared meals and meat). A further study was later performed for sliced cooked ham (Derens-Bertheau, Osswald, Laguerre, & Alvarez, 2015). Regarding their survey method, temperature recorders were put in the product packages after fabrication in plants. These products were transferred in the cold chain until the consumption point, and the consumers returned temperature recorders to the laboratory for analysis by the experts. The analysis of the measured temperatures of these four chilled products showed that 30% of products during retail displays were 2°C above their recommended storage temperatures (6°C for yoghurt and 4°C for prepared meals, meat and sliced cooked ham) as shown Figure 1. Mean temperatures (standard deviation) of 4.2°C (±2.4°C), 3.1°C (±2.6°C), 3.4°C (±1.8°C) and 2.8 (±1.2°C) were observed for yoghurt, prepared meals, meat and sliced cooked ham, respectively. This obtained product temperature profile made possible the interpretation of the moment where the product stayed in display cabinets.

Willocx et al. (1994) measured the air temperature in open display cabinets with three decks over which minimally processed vegetables were displayed in Belgian supermarkets. They showed that the differences of more than 5°C were detected on the decks. The temperature also increased towards the end of the day in certain locations by 4°C and towards the end of the week by almost 7°C.
In Ireland, the Food Safety Authority of Ireland (FSAI) found that the temperatures of pre-packed sandwiches were above 5°C in 57% of cases (FSAI, 2002). In a similar study in 2003, the FSAI found that 14% of pre-cooked sliced ham was stored above 5°C (FSAI, 2003).

Studies in the USA have shown the temperature of foods in chilled food distribution channels were frequently in the range of 7.2°C to 12.8°C (Food Spectrum, 2002). Jol, Kassianenko, Wszol, and Oggel (2006) claimed that 20% of domestic and commercial refrigerators operated at a temperature of more than 10°C. Audits International (1999) found that 48% of product temperatures in retail refrigerators were above 5.0°C and 17% were above 8.3°C. Table 1 summarizes the field studies carried out in several countries.
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Table 1. Field studies conducted on display cabinets in various countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Sample</th>
<th>Temperature (°C)</th>
<th>% of samples at specified temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>Mean</td>
</tr>
<tr>
<td>Canada</td>
<td>Beef</td>
<td>-2.0</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Fresh-cut lettuce</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>Denmark</td>
<td>Chilled product</td>
<td></td>
<td>14.0</td>
</tr>
<tr>
<td>France</td>
<td>Yogurt</td>
<td>-2.1</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Processed meat</td>
<td>-1.1</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>Ham</td>
<td>0.2</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Bakery, ruck and dairy products</td>
<td></td>
<td>16.0</td>
</tr>
<tr>
<td>Finland</td>
<td>Fish</td>
<td>0.3</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>Minced meat</td>
<td>0.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Germany</td>
<td>Chilled products</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>Greece</td>
<td>Pasteurized milk</td>
<td>0</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>Smoked sliced turkey</td>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>Ireland</td>
<td>Cooked sliced ham</td>
<td>1.5</td>
<td>5.7</td>
</tr>
<tr>
<td>Slovenia</td>
<td>Meat products</td>
<td>0</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Dairy products</td>
<td>0</td>
<td>3.8</td>
</tr>
<tr>
<td>Spain</td>
<td>Meat products</td>
<td>-1.8</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Fish</td>
<td>2.9</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>Dairy products</td>
<td>1.2</td>
<td>6.4</td>
</tr>
<tr>
<td>Sweden</td>
<td>Chilled product</td>
<td>-1.0</td>
<td>4.9</td>
</tr>
<tr>
<td>UK</td>
<td>Cooked meat</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chilled products</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>Leafy green salad</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Meat, Fish and dairy products</td>
<td>-10.0</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>Meat products</td>
<td></td>
<td>20.0</td>
</tr>
</tbody>
</table>

Source: (Chaomuang et al., 2017)

Experimental Air Temperatures in a Closed Display Cabinet

Like other refrigerating equipment, the cooling system of display cabinets is composed of an evaporator, compressor, condenser and expansion valve. The operation of this system is presented in several books (ASHRAE, 2002; Evans & Foster, 2015; Meunier, Rivet, & Terrier, 2010). The airflow in closed and open display cabinets is illustrated in Figure 2. In both cases, air flows downward from the Discharge Air Grille (DAG, front top) to the Return Air Grille (RAG, front bottom). This airflow, termed as the cold air curtain, provides not only cooling capacity but also insulation from ambient air. Air also flows
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horizontally from the rear to the front through a Perforated Back Panel (PBP). The air flows through
the evaporator where it is cooled and then is circulated upward. This air circulation is provided by fans
allowing uniformity of air temperature and effective food protection. It is to be emphasized that this
airflow directions are available for vertical multi-deck display cabinets with an evaporator at the bottom;
the airflow can be different for other display cabinet types. The air velocity can be adjusted with respect
to the product characteristics to reduce the product weight loss due to water evaporation particularly in
un-wrapped food. The air velocity in the air curtain may vary from 0.1 m/s at the edge to 1.0 m/s at the
middle of air curtain (Laguerre, Hoang, Osswald, et al., 2012). For the open display cabinet (Figure 2b),
there is an additional air infiltration from outside.

An experimental investigation of air temperature and airflow in an empty and loaded closed refriger-
ated display cabinet was presented in Chaomuang et al. (2019). In this study, the measurements of air
temperature (with thermocouples) and of air velocity (with a hot-wire anemometer) were presented at
various positions in the shelves-space storage and in the air curtain. In order to gain the knowledge of
spatial and temporal temperature variations in the closed display cabinet, only the part of temperature
measurement was addressed in this chapter. Figure 3 shows the air temperature evolution at different
positions on the center plane of the display cabinet together with time-averaged temperatures and stan-
dard deviations during the quasi-steady state. It can be noticed that the min/max temperature variations
changed from one position to another with the same frequencies due to the on/off compressor regulation.

Figure 2. Airflow schematic in (a) closed and (b) open refrigerated display cabinets
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Because of negligible thermal inertia of air, there was not time lag of air temperature change at different positions. The air temperature variation curve at the bottom of the vertical rear duct (Figure 3a), near the thermostat sensor, provided information on the compressor working cycles.

Temperature fluctuations of the air in the vertical rear duct (positions a, b and c in Figure 3) had relatively greater amplitudes, compared to the air at the other positions. At these positions, an increase in the minimum temperature was observed while the maximum temperature was relatively similar at all positions. The heat loss through the cabinet walls explains a slight increase in the average temperature. The standard deviation, however, became slightly lower because of stabilization due to the thermal inertia of the wall of the rear duct. The same phenomena were observed in the upper horizontal duct from “c” to “d”: an increase in the average temperature due to heat losses and a lower standard deviation due to exchanges with duct walls and the honeycomb of the DAG.

In the area in which food products are stored (positions e, f, g, h, i and j in Figure 3), the average air temperature was below 2°C, which is the recommended temperature for perishable foods (for example meat and fish). As the temperature was slightly negative at the bottom (position “i” and “j”), it could cause freezing damage to foods stored at these positions.

The average temperatures at the front of the shelves (positions f, h and j in Figure 3) were higher than at the DAG. This is because the air curtain exchanges heat with doors, through which heat is transferred from the external ambient, as well as the infiltration of external air through the gaps. The average temperatures at the back of the shelves (positions e, g and i in Figure 3) were lower than those at the front, especially on the bottom shelf. This is because of the higher percentage of holes at the bottom of the PBP of the studied display cabinet which allows higher air flow rate from the rear duct.

Air temperature is generally displayed on a monitoring screen to ensure that food products are stored at appropriate temperature in the display cabinet (Baldera Zubeldia et al., 2016). As this displayed value corresponds to an instantaneous air temperature at a given position, it should be preferable to display the temperature at the warmest and coldest positions, which may vary due to cabinet types.

Influence of the Presence of Doors

A comparative study of cabinet performance in terms of temperature distribution was performed between an empty and loaded display cabinet with doors and without doors.

Doors on the studied display cabinet were removed to investigate the influence of the presence of doors on the temperature performance. Figure 4a and 4b shows the time-averaged air temperature (and standard deviation) of the empty cabinet. These temperatures were calculated from the measurement at the center plane. Thus, the edge effect can be considered as negligible. The temperature profile in the empty cabinet with and without doors had the same trend: the highest temperature at the front of the top shelf (position “f”) and the lowest temperature at the back of the bottom shelf (position “i”). Without doors, the average air temperatures in the storage zone increased in all positions, compared to the case with doors. The comparison of the air temperature at 4 cm from the shelf edges (positions “k” and “ℓ”) shows a large increase at the top and at the mid-height. This can be explained by the measurement positions which located at the outside of the air curtain. It is to be emphasized that the airflow underneath the DAG (position “k”) is complex because of the mixing of the cold air from the DAG with the horizontal air flow from the PBP and the warm air (from outside). The higher temperature at the RAG in the case without doors leads to higher heat loads on the evaporator.
Test product packages made of methylcellulose (dimensions of 20 cm × 10 cm × 5 cm) were placed in the cabinet with an occupied volume of about 60% of total storage volume. The averages and standard deviations of product (core and surface) and air temperatures on the center plane are depicted in Figure 4c (with doors) and Figure 4d (without doors). The highest product temperature at the front of the top shelf can be explained by interdependencies among various influencing factors. At this position, the products were mainly subjected to heat exchanges with the air curtain, heat diffusion through the glass doors, and heat generation due to (visible) light absorption in the products. It can be noticed (Figure 4c) that product surface temperature was slightly higher than that of the surrounding air and that of its core temperature.

The products located at the back of the bottom shelf had the lowest temperature because of more cooled air from the back delivers to the storage. This low temperature position was already observed in the empty case (Figure 4a).

Product temperature difference between the front and the back was also observed, of which the highest difference was on the top shelf. This results from a combination of convection between product and cold air coming from the PBP and conduction within and between the products.

The results of the cabinet without doors (Figure 4d) show that product and air temperatures at the front areas remarkably increased at all positions. This can be explained by the external warm air infiltration mixing with the air curtain. Product and air temperatures at the back of the cabinet without doors was slightly lower than that of the cabinet with doors because higher refrigeration capacity is required to compensate additional heat loads due to warn air infiltration. As observed in the case of loaded and closed display cabinet, product surface temperature was slightly higher than that of the surrounding air and that of its core temperature.
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Globally, lower (air and product) temperatures and less temperatures heterogeneity was observed in the storage of the closed display cabinet, thus, better temperature performance compared to the open one.

Influence of the Frequency and the Duration of Door Openings

Numerous works were carried out to study the influence of the presence of doors on the energy consumption, compared to the absence of doors (Atilio de Frias et al., 2015; Faramarzi et al., 2002; Fricke & Becker, 2010; Ligthart, 2007; Lindberg et al., 2010; Navigant Consulting Inc., 2009; Rhiemeier et al., 2009; Robertson, 2015; Rolfsman & Borgqvist, 2014). The comparison of energy consumption of open and closed display cabinets is shown in Figure 5. It can be seen that the percentage of energy savings varied from 23% to 73% when doors were fitted. The variations of these results can be explained by the difference of display cabinet configurations and the operating conditions used in the certain studies as summarized in Table 2.

The door opening frequency certainly affects the cabinet performance in terms of both temperature homogeneity and energy consumption. In spite of many tests of the impact of door openings, less published information is available on its influence on product temperature.

The cold loss was numerically quantified during a door opening procedure (opening, holding and closing) of close display cabinets with 1.8 m in height and 6 decks (Orlandi, Visconti, & Zampini, 2013). In this study, two three-door cabinets for chilled product were considered: one was equipped with sliding doors and the other one was equipped with hinged doors; only the central door opening was considered for the analysis. It was supposed in this study that the radiation and the thermal inertia of the cabinet solid parts were negligible. The comparative results showed that the internal temperatures were relatively the same for both door types when the doors remained closed. However, when doors were cyclically opened (10 openings/hour/door as prescribed in EN 23953:2005 for chilled cabinets and 60 openings/hour/door for 15 s duration of each opening including 1 s opening, 13 s holding and 1 s closing), the air temperature at the return air duct in the cabinet with sliding doors was lower than that in the cabinet with hinged doors. This explained the display cabinet with sliding doors to consume 17% less energy than the cabinet with hinged doors. The same authors reported that the cold loss due to door openings was responsible for 12% of total heat extraction rate, while the contribution of lights was 25% (Figure 6). Nevertheless, when higher door opening frequency were applied (60 openings per hour for each door), the contribution to heat load due to door openings became significant. It accounted for 44% of the total. This very high frequency may not realistic. Fricke and Becker (2010) carried out measurements in supermarkets and found that in real-life situations, the most frequent door opening duration was 5 seconds and the daily average door opening frequency was about 6.3 openings per hour, which means one door being opened every 9.5 minutes.

Influence of Room Temperature on the Temperature Performance of the Cabinet

As proven by many studies, ambient temperature in supermarkets has an impact on temperature distribution in open-front refrigerated display cabinets (Axell & Lindberg, 2005; Chen & Yuan, 2005; Heidinger, Nascimento, Gaspar, & Silva, 2013). To complement this knowledge the influence of ambient temperature on the temperature distribution in a closed display cabinet was carried out by Chaomuang et al. (2019) for three ambient temperatures.
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Figure 4. Average air and product temperatures and standard deviation (°C) during quasi-steady state (average of the measurements on the center plane) of the display cabinet exposed to a room temperature of 19°C (a) empty cabinet with doors and (b) empty cabinet without doors (c) loaded cabinet with doors and (b) loaded cabinet without doors Source: Chaomuang et al. (2019).
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Table 3 shows the influence of external ambient temperature (15°C, 19°C and 24°C) on the air temperature in the food storage zone (average value and standard deviation over 5 h of quasi steady state periods) of the studied closed display cabinet. The average temperature after the heat exchanger where the thermostat position was located (\(T_{th}\)) was slightly different for these three ambient temperatures. To be able to compare the results obtained under several ambient temperatures, temperature difference (\(T - T_{th}\)) is shown. Average for all positions \(T - T_{th}\) increased from 1.1°C to 2.0°C when \(T_e - T_{th}\) rose from 15.2°C to 25.4°C. A dimensionless temperature defined as \(T^* = \frac{T - T_{th}}{T_e - T_{th}}\) was also calculated. It appeared that \(T^*\) was almost independent of \(\bar{T}_e - T_{th}\)*. This is due to the linearity (between \(\bar{T}_e\) and \(T_i\)) since the force convection and conduction are predominant heat transfer modes. In the closed configuration, free convection is negligible because of the rather high velocities at the DAG and PBP. Radiation is also limited because the glass doors shield the radiation from the external walls in opposite to the open configuration. The highest value of \(T^*\) was at the position f (the front of the top shelf) where \(T_f - T_{th}\) is about 12% of \(\bar{T}_e - T_{th}\). The lowest value of \(T^*\) is at the position i (the back of the bottom shelf) where the temperature is slightly higher than at the position after the heat exchanger.

A comparison of the percentage of time “on” compared to the total time “on and off” of the compressor operation shows the significant influence of ambient temperature (Table 4). In fact, to maintain the desired supply air temperature, an increase in ambient temperature causes an increase in the frequency of compressor working cycles (shorter “off” period). This implies an increase in the energy consumption of the display cabinets installed in stores without air-conditioning systems in summer. Table 4 also shows that the percentage of time “on” compared to the total time “on and off” is not significantly different for the empty and loaded display cabinets.
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Table 2. Studies of the influence of open and closed display cabinets on the energy saving

<table>
<thead>
<tr>
<th>Reference</th>
<th>Cabinet configuration</th>
<th>Operating condition</th>
<th>Door openings (OPH/duration)</th>
<th>Night cover</th>
<th>Anti-sweat heaters</th>
</tr>
</thead>
</table>
| Atilio de Frias et al. (2015) | Two display cabinets: open and closed; both with LED lightings | • Thermostat setting at 0.6°C with a 12 h off-cycle defrost interval of 30 min (open) and a 24 h defrost interval of 30 min (closed).  
• Test room conditions of 21°C and 60–70% RH | 6 OPH/12 s | n/a | none |
| Faramarzi et al. (2002)     | Open display cabinet retrofitted with doors               | • Evaporator temperature at -5°C (23°F) with a 6 h off-cycle defrost.  
• Test room conditions of 24°C (75°F) and 55% RH. | 5 OPH/16 s | n/a | YES |
| Fricke and Becker (2010)    | Two display cabinets: open and closed                     | • Field measurement during 42-day test period in two supermarkets (20-45%RH, not mentioned store temperature) | 6.3 OPH/5 s (mean value over the test period) | n/a | YES |
| Lighart (2007)              | Review from the literature                                | • n/a                                                                               | n/a | n/a | n/a |
| Lindberg et al. (2010)      | Open display cabinet retrofitted with doors               | • Field measurement where the store conditions in front of the display cabinets were 15.9-17.3°C (38-343%RH) and 18.2-19.4°C (41%RH) for open and closed cases, respectively. | n/a | YES | n/a |
| Navigant Consulting Inc. (2009) | Review from the literature                                | • n/a                                                                               | n/a | NO | YES |
| Rhiemeier et al. (2009)     | Review from the literature                                | • n/a                                                                               | n/a | n/a | n/a |
| Robertson (2015)            | Open display cabinet retrofitted with doors               | • Test in the supermarket                                                            | n/a | YES | n/a |
| Rolfsman and Borgqvist (2014)| Open display cabinet retrofitted with doors               | • Heat exchanger inlet temperature at -8°C for open cabinet and -1°C for closed cabinet  
• Test room conditions of 22°C and 65% RH. | 10 and 30 OPH/6 s | YES | n/a |

*OPH: Number of door opening per hour per door; n/a: Data not available

Figure 6. Percentage of cold loss from the closed display cabinets due to different sources (Orlandi et al., 2013)
**Closed Refrigerated Display Cabinets**

**Table 3. Effect of ambient temperature on the internal air temperature of the closed refrigerated display cabinet**

<table>
<thead>
<tr>
<th>Average ambient temperature ± standard deviation</th>
<th>Temperature difference</th>
<th>Number of compressor “on” cycles/5h</th>
<th>Temperature difference and time-averaged dimensionless temperature at a given position</th>
<th>All positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$ (°C)</td>
<td>$T_e - T_{th}$ (°C)</td>
<td></td>
<td></td>
<td>e</td>
</tr>
<tr>
<td>15 ± 0.5</td>
<td>15.2</td>
<td>36</td>
<td>$T - T_{th}$</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$T^*$</td>
<td>0.07</td>
</tr>
<tr>
<td>19 ± 0.4</td>
<td>20.3</td>
<td>44</td>
<td>$T - T_{th}$</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$T^*$</td>
<td>0.08</td>
</tr>
<tr>
<td>24 ± 0.3</td>
<td>25.4</td>
<td>52</td>
<td>$T - T_{th}$</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$T^*$</td>
<td>0.09</td>
</tr>
<tr>
<td>$T^*$ for all ambient temperatures</td>
<td></td>
<td></td>
<td></td>
<td>0.08</td>
</tr>
</tbody>
</table>

Source: (Chaomuang et al., 2019)

**Table 4. Percentage of time “on” compared to the total time “on and off” of the compressor under different conditions**

<table>
<thead>
<tr>
<th>Ambient temperature (°C)</th>
<th>Closed display cabinet</th>
<th>Open display cabinet</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Empty</td>
<td>Loaded</td>
</tr>
<tr>
<td>18</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>19</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>24</td>
<td>31</td>
<td>31</td>
</tr>
</tbody>
</table>

Source: (Chaomuang et al., 2019)

**Modelling of Heat Transfer, Airflow and Energy Consumption of Close Display Cabinet**

In order to understand the mechanism of thermal transport phenomena occurring in a closed display cabinet experimental and numerical investigations are complementary. Several numerical studies were carried out on heat transfer and airflow in open refrigerated display cabinets (Alzuwaid, Ge, Tassou, & Sun, 2016; Gaspar, Gonçalves, & Pitarma, 2012; Ge, Tassou, & Hadawey, 2010; Hoang, Raoult, & Leducq, 2016; Laguerre, Hoang, & Flick, 2012; Moureh & Yataghene, 2016; Wu et al., 2014; Yu, Ding, & Chen, 2009; Zhijuan, Xuehong, Yanli, Qiuyang, & Wenhui, 2013).
Closed Refrigerated Display Cabinets

Because of the lack of numerical study of closed display cabinets for chilled products, the one for frozen products with an air curtain flowing along the internal side of the door is presented (D’Agaro, Cortella, & Croce, 2006). In this study, a model of the misting and demisting process in the glass doors was developed. The main objective of this study was only to gain insight into the physical mechanism of the thermo-fluid phenomena of fogging and defogging taking place during the door openings as it is a very important issue for this cabinet type. The high fogging level leads to the poor transparency of the glass, thus influencing product visibility. Defogging with a heater is then required, which comes with higher energy demand and cooling load. However, no case study has shown to manifest the influence of these phenomena on the cabinet performance in terms of both energy efficiency and temperature distribution.

Product Quality in Closed Display Cabinet

Kou, Luo, Ingram, Yan, and Jurick (2015) studied the influences of thermostat settings (at -0.5°C and -2.2°C with the same defrosting interval of 12 h and duration of 30 min) on the product temperature and the quality of packaged baby spinach products at various locations in the open display cabinet. With the -2.2°C thermostat temperature, the products located on the top shelf at the front of the display cabinet had the highest temperature (mean 6.5°C) and the temperature decreased towards the back of the cabinet. The lowest mean temperature was below zero (-0.6°C), thus, product located in this zone was subjected to freezing damage. To overcome this thermal problem, the temperature of thermostat was set at -0.5°C. However, the products in the front rows then underwent temperature abuse. This represents the situation in supermarkets and the major challenge is to control these temperature abuses so that all products are preserved at an adequate temperature without freezing problems. These results were in agreement with the results obtained by Laguerre, Hoang, Osswald, et al. (2012): warmer product temperature at the front and cooler product temperature at the rear for the same shelf.

Product temperatures in display cabinets can rise during the defrost operation (Lawrence & Evans, 2008). Temperature sensitive food products under fluctuating temperature condition can deteriorate at different rates than the ones under less fluctuating condition (Wells & Singh, 1989). The application of heat pipe and phase change materials (PCM) in the cabinet shelf was introduced to deal with this issue by Lu et al. (2010). Two cabinet prototypes, a shelf retrofitted with heat pipe and combined heat pipe with PCM, were experimentally tested in their study. Based on their results, the authors claimed that the use of heat pipe and PCM provides several advantages: the reduction of core product temperatures (3.0°C to 5.5°C lower with heat pipe alone), the improvement of temperature distribution homogeneity (small range of max-min temperatures during normal operation) and the reduction in temperature rise during defrost process (0.3°C rise with combined structure) with less energy consumption. The similar results were obtained by Alzuwaid, Ge, Tassou, Raeisi, and Gowreesunker (2015), they concluded that the use of PCM lowered cabinet temperatures and saved up to 5% of energy consumption. In spite of several studies on the influence of ambient temperature and humidity on the product quality (Paull, 1999; Ketsa & Pangkool, 1994; Sharkey & Peggie, 1984; Grierson & Wardowski, 1978; Berg & Lentz., 1977), these influences on food quality displayed in closed display cabinets and door openings are less studied and still needed to fulfil.
Closed Refrigerated Display Cabinets

FUTURE RESEARCH DIRECTIONS

Refrigerated display cabinets retrofitted with doors is an alternative to improve the cabinet performance since it is simple to implement. Many world’s leading retailers have already fitted their display cabinet with doors and some extend the policy of putting doors as a standard for their new and/or renovated stores (EIA, 2014, 2017). This transition implies a more important role of closed refrigerated display cabinets in the future, and consequently generates research opportunities associated with this cabinet type.

The use of doors on chilled display cabinets reaps potential energy savings. However, attention must be paid since door installation can modify airflow pattern and temperature distribution within the cabinets (Faramarzi et al., 2002) which may result in a negative impact on food temperatures.

Door openings can also disrupt the air curtain of the closed display cabinet and induce the entrainment of warm and humid air from outside, thereby increasing temperature variation and energy consumption. An investigation into the effect of door opening frequency and duration on the cabinet performance is necessary. Determining the air infiltration rate during the door openings at different opening frequency and duration would bring more confidence in establishing if the closed display cabinet is worthwhile.

A change in the transport phenomena can be characterized using advanced air velocity field measurement such as Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV). Additionally, Computational Fluid Dynamic (CFD) can be used to study the 3D airflow and heat transfer in display cabinets. The application of these methods on the closed refrigerated display cabinet is still rear.

As a complementary to the CFD model, a simplified heat transfer model based on a zonal approach should be developed to gain an insight into the mechanism of heat/mass transfer in a closed display cabinet. This model is rare while the ones for other refrigeration equipment were largely developed: processing plant (Lecoq, Flick, Derens, Hoang, & Laguerre, 2016), refrigerated vehicle (Hoang, Laguerre, Moureh, & Flick, 2012, cold room (Laguerre, Duret, Hoang, Guillier, & Flick, 2015) and household refrigerator (Laguerre & Flick, 2004). Such a model allows the prediction of product temperature at various positions in the equipment with a short calculation time. The closed display cabinet cabinets will be soon a new component of the series of refrigeration equipment in food cold chain. The simplified model of this cabinet type can be linked with the other models allows the knowledge of time-temperature history of food products from a production plant to a household refrigerator. Furthermore, predictive microbiological and/or quality models can also be established to evaluate the consumer risk (Duret et al., 2015).

CONCLUSION

Plenty of works on retail refrigerated display cabinets have been carried out for the last two decades particularly since there has been a greater awareness of food product quality and energy efficiency. Many researchers have tried to investigate and identify the key factors which influence the cabinet performance by the means of both experimental (field-based and laboratory-based) and numerical (in-house code and commercial code) approaches. The obtained knowledge will provide the opportunity to optimize this equipment in terms of both temperature homogeneity and energy consumption. The application of doors is an alternative solution and several studies have shown that doors can provide several advantages. Two studies (Carrington, 2012; Fricke & Becker, 2010) reported insignificant impact of the presence of doors on display cabinets on the product sale loss, thus, more studies should be carried out to confirm this observation. Most of studies tend to only focus on energy consumption.
Nomenclature

$T$: Temperature [$^\circ$C or K]

$\bar{T}$: Mean temperature [$^\circ$C or K]

$T^*$: Dimensionless temperature defined as $T^* = \frac{T - T_{th}}{\bar{T} - T_{th}}$

Subscripts

Th: thermostat

E: external ambient

Abbreviations

DAG: Discharge Air Grille

PBP: Perforated Back Panel

RAG: Return Air Grille

PCM: Phase Change Material

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REFERENCES


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**Closed Refrigerated Display Cabinets**


**ADDITIONAL READING**


Closed Refrigerated Display Cabinets


**KEY TERMS AND DEFINITIONS**

Air Curtain: An air jet used to protect products stored in a refrigerated display cabinet from infiltration of warmer and humid external ambient air. For a vertical multi-deck display cabinet, which is widely used, the jet flows from discharge air grille at the top to return air grille at the bottom.

Air Infiltration: An entrainment of external air into a system.

Chilling Damage: An injury of fresh/chilled food produce that exposes to too low temperatures.

Closed Refrigerated Display Cabinet: A refrigerated display cabinet equipped with (glass/solid) doors used to display (chilled/frozen) food products for sale in a retail store/supermarkets.

Cold Chain: A supply chain in which perishable products (food, vaccines, etc.) are preserved under temperature-controlled environment from production to consumption.

Defrosting: A process to remove frost which deposits on surfaces of heat exchanger/evaporator/cooling coil of refrigeration equipment.

Heat Extraction Rate: A rate of heat or thermal loads removed by heat exchanger/evaporator/cooling coil per unit time.

Open Refrigerated Display Cabinet: A refrigerated display cabinet with air curtain and without another physical barrier between the product and the customer.
Chapter 2

Frost Measuring and Prediction Systems for Demand Defrost Control

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ABSTRACT

It is widely known that the defrosting operation of evaporators of commercial refrigeration equipment is one of the main causes of inefficiency on these systems. Several defrosting methods are used nowadays, but the most commonly used are still time-controlled defrosting systems, usually by either electric resistive heating or reverse cycle. This happens because most demand defrost methods are still considered complex, expensive, or unreliable. Demand defrost can work by either predicting frost formation by processing measured conditions (fin surface temperature, air humidity, and air velocity), operative symptoms of frost accumulation (pressure drop and refrigerant properties), or directly measuring the frost formation using sensors (photoelectric, piezoelectric, capacitive, resistive, etc.). The data measured by the sensors can be directly used by the system but can also be processed either by simple algorithms or more complex systems that use artificial intelligence and predictive methods. This chapter approaches frost sensing and prediction for command of demand defrost systems.
Frost Measuring and Prediction Systems for Demand Defrost Control

INTRODUCTION

The issue of frost formation in air conditioning and refrigeration systems, more specifically on the fin-and-tube evaporators, has been studied for several years and yet it still is one of the main causes of inefficiency (Popovac, Seichter, & Benovsky, 2015; Guo, Chen, Wang, & Chen, 2008). As they are used in light commercial systems, these fin-and-tube evaporators have a large area-to-volume ratio. The demand for subfreezing operating temperatures causes the formation of a frost layer on the fin surface (Melo, Hermes, & Silva, Experimental study of frost accumulation on fan-supplied tube-fin evaporators, 2011) (Hermes, Piucco, Barbosa Jr., & Melo, 2009), as shown on Figure 1.

Being a porous medium comprised of ice crystals and pores filled with moist air, the frost buildup on the evaporators fin surface increases its air-side thermal resistance, decreasing the overall thermal efficiency of the system. If the frost is allowed to continue growing, the efficiency keeps decreasing due to not only the increment of the heat transfer resistance, but also to the blockage of the air passage between fins. This condition can lead to a full blockage if no defrost method is applied (Melo, Hermes, & Silva, Effect of frost morphology on the thermal-hydraulic performance of fan-supplied tube-fin evaporators, 2017). Several parameters can influence frost growth, but those with most influence are air relative humidity, velocity and supercooling degree (difference between inlet air dew point and fin surface temperature) (Hermes, Piucco, Barbosa Jr., & Melo, 2009; Melo, Hermes, & Silva, Effect of frost morphology on the thermal-hydraulic performance of fan-supplied tube-fin evaporators, 2017; Kwan-Soo, Woo-Seung, & Tae-Hee, 1997; Şahin, 1995; Lüer & Beer, 2000). Although, other parameters such as fin shape and spacing (Melo, Hermes, & Silva, Experimental study of frost accumulation on fan-supplied tube-fin evaporators, 2011), type of flow (laminar or turbulent) (Yang, Lee, & Cha, 2006), or air cleanliness (Wang W., Xiao, Guo, Lu, & Feng, 2011) may influence the frost growth. The lower system efficiency caused by the frost layer on fin surfaces results in a higher energy demand, and in extreme cases, system damage. Defrost methods are used to reduce the problem, although additional energy is usually consumed for their operation (Wang, Liang, & Zhang, Research of anti-frosting technology in refrigeration and air conditioning fields: A review, 2017). After literature review, the defrost methods were classified in two groups:

Restraint frost methods: methods for the retardation of the frost formation, by changing the characteristics of the inlet air (humidity, velocity and temperature) (Melo, Hermes, & Silva, Experimental study of frost accumulation on fan-supplied tube-fin evaporators, 2011), (Sheng, Pengpeng, Chaobin, & Guixin,

Figure 1. Visualization of the fins surface before (a) and after (b) the frost formation process (adapted from (Melo, Hermes, & Silva, Experimental study of frost accumulation on fan-supplied tube-fin evaporators, 2011))
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2017); changing the features of the cold surface (temperature, morphology, position and treatment) (Olcay, Avci, Bayrak, Dalkılıç, & Wongwises, 2017), (Liu & Kulacki, 2018), (Chu, Wu, & Zhu, 2016), (Wang F., Liang, Zhang, & Zhang, 2017), (Liu, Yu, & Yan, 2016) e (Wu, Hu, & Chu, Experimental study of frost formation on cold surfaces with various fin layouts, 2016); and changing the interaction between the air, condensed water or frost and the cold surface (electric field (Joppolo, Molinaroli, De Antonelli, & Merlo, 2012), magnetic field (Gou, Liu, Liu, Huang, & Zhang, 2009), ultrasound (Li, Chen, & Shi, Effect of ultrasound on frost formation on a cold flat surface in atmospheric air flow, 2010)), etc.

Frost removal methods: methods that act upon the formed frost to remove it and return the working conditions to normal. Therefore, ideally, are only used after the frost is formed. These defrosting operations usually result in undesirable temperature fluctuations on the refrigerated space (Gin, Farid, & Bansal, 2010). There are several defrost methods, such as compressor shutdown (Ameen, Coney, & Sheppard, 1993); electric resistive heater (Yin, Yang, Chen, & Zhang, 2012); reverse cycle (Song, Deng, Oan, & Mao, 2014), (Anand, Schliesing, O’Neal, & Peterson, 1989); hot gas bypass (Choi, Kim, Kang, & Kim, 2011); hot water (Abdel-Wahed, Hifni, & Sherif, 1983); air jet or air particle jet (Snobe, Fukiba, Sato, & Yoshimura, 2015); and ultrasonic vibration methods (Tan, Xu, Tao, Zhang, & Luo, 2016) (Li & Chen, Experimental study on instantaneously shedding frozen water droplets from cold vertical surface by ultrasonic vibration, 2014) (Barelli, Bidini, & Moraglia, 2004). Both restraint frost and frost removal methods can be classified as passive or active: passive if no additional energy is required and active if some additional power input is required to remove the accumulated frost (Amer & Wang, 2017). This classification is summarized on Figure 2.

Time controlled with on-off defrosting and electric resistive heater or reverse cycle are the most used defrost methods. Apart from these, none of the abovementioned methods has gained significant acceptance from the refrigeration industry, due to complex, expensive and unreliable sensing and prediction methods (Xiao, Wang, Guo, & Zhao, 2010; Jiang, Dong, Qu, Deng, & Yao, 2013).

This can cause a huge impact on energy consumption, as the timed defrost operations have to be timed for the worst-case scenario (warm air with high relative humidity) and thus, as these air conditions vary during the year, the amount of defrosting cycles could vary as well. Tassou et al. (Tassou, Datta, & Mar-

Figure 2. Classification of available defrost methods
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riott, 2001) studied the frost formation and defrost control parameters for open multideck refrigerated display cabinets and concluded that the ideal time between defrosts varies greatly with air temperature and humidity. In the conditions studied in (Jiang, Dong, Qu, Deng, & Yao, 2013), the ideal operation time between defrosts on this food display cabinet can range from 4 hours to around 9.5 hours during different times of the year as shown on Figure 3. A time-controlled defrosting must have in consideration the worst-case scenario on time between defrosting operations.

Demand defrost tries to solve this problem by predicting frost formation. This prediction can be done by using the measured factors that influence frost formation (such as surface temperature, and inlet air characteristics: relative humidity, temperature and velocity) (Cui, Li, Liu, & Jiang, 2011), using the measurable system changes caused by the frost accumulation on the evaporator (temperature difference between the air and evaporator surface (Buick, McMullan, Morgan, & Murray, 1978), pressure drop (Jarrett, 1972), degree of refrigerant superheat (United States of America Patente Nº 5,813,242, 1998), fan power sensing (Muller, 1975)) or both (Datta, Tassou, & Marriott, 1997). The computation methods such as artificial intelligence (Kalogirou, 2000) and other algorithms (Bagyaveereswaran, Subramanian, & Anitha, 2017), (Cao, Zhang, & Gu, 2013) were proposed.

Alternatively, demand defrost cycles can be controlled by directly measuring frost on the evaporator coils.

Demand defrost tries to solve this problem by predicting or measuring frost formation. This can be done by directly measuring frost on the evaporator coils.

Figure 4 shows a comparison between timed and a demand defrost system developed in (Ge, Ye, & Zou, 2012). The demand defrost output is shown in the first row, as defrosting operations are only started when the system detects frost on the evaporator fins. As a means of comparison, the bottom row shows the operation of a regular time-controlled defrost. Eight defrost cycles have been made on the controlled defrosting while 30 defrost cycles have been made on the time-controlled defrost during a period of 24 hours.

Figure 3. Optimum time between defrosts in relation to ambient air temperature and humidity
(adapted from (Jiang, Dong, Qu, Deng, & Yao, 2013))
Frost Measuring and Prediction Systems for Demand Defrost Control

FROST MEASUREMENT METHODS

One way to control demand defrost is by directly measuring the frost accumulation. In this scenario no prediction is necessary, as sensors positioned on the evaporator directly evaluate the state of the frost accumulation and their data is processed so that the defrost operation occurs when best suited.

Direct methods that require human intervention such as using a cathetometer telescope (Sengupta, Sherif, & Wong, 1988), micrometer (Kwan-Soo, Woo-Seung, & Tae-Hee, 1997), Vernier gauge movement (Sengupta, Sherif, & Wong, 1988), etc. and other methods such as laser displacement gauge (Kandula, 2012), (Qu, Komori, & Jiang, 2006) will not be approached as they are not practical for incorporating in refrigeration systems.

On this section, ice sensing methods that were found on the literature will be compiled, and a possible adaptation for implementation on a refrigeration system for ice detection proposed. For this a simplified evaporator scheme will be used as seen on Figure 5, in which the sensor implementation will be represented.

Figure 4. Comparison between timed defrosting and demand defrosting using the TEPS (adapted from (Ge, Ye, & Zou, 2012)) each dot represents a defrosting operation

Figure 5. Simplified evaporator scheme with (right) and without (left) frost
Frost Measuring and Prediction Systems for Demand Defrost Control

Photoelectric Sensors

Photoelectric sensors work with an emitter (for example an infrared light) positioned towards a receiver (photoelectric sensor) and separated by a small passage as shown in Figure 6.

Once driven with current, the emitter emits constant light to the receiver through the passage. The receiver converts the received light into a voltage, that varies gradually from a value representative of air (open path) to a value representative of frost blockage (closed path), allowing a frost formation measurement with sufficient accuracy for defrosting control. In (Ge, et al., 2016) and (Wang W., Xiao, Feng, Guo, & Wang, 2013), a tube encircled photoelectric sensor (TEPS) for defrosting control is studied. When compared with timed defrost, the difference is clear.

Extensive testing should be done for long periods of time to ensure reliability, durability and performance when frosting conditions are more severe, but the results seem promising.

To implement this sensor on the evaporator on a refrigeration system no Adaptations need to be done, as it has already been developed for a similar purpose (application as seen on figure 7 (a) and (b) on the left). However, the distribution of the frost formation is not uniform, and the application directly on the fins may be advantageous for certain evaporator morphologies. To approach this requirement, another application of this sensor is purposed as shown on Figure 7 (a) and (b) on the right, this application has minor interference on the air flow but should be able to detect ice on the surface of the evaporator efficiently, as frost will be formed in between the emitter and the receiver of the sensor.

Fiber-Optic Sensors

Nowadays the most advanced ice sensing methods rely on fiber-optic sensors (Ge, Ye, & Zou, 2012), (Zou, Ye, & Ge, 2013). This sensor relies on the reflective properties of ice to work. An IR LED positioned as shown in Fig. 8(a) emits IR light through the optic fiber bundle into the sensor tip represented in Fig. 8(b). When frost formation occurs, it reflects the light back into the system as shown in Fig. 8(c), going through the signal fiber bundle and finally received by the phototransistor.

Figure 6. Schematic of TEPS, the sensor installed on the refrigerant tube (left) is represented as a circuit (right) (adapted from (Ge, et al., 2016))
Because different frosting conditions generate different frost morphologies, the measured values differ not only depending on the frost thickness, but also on its morphology. Diverse morphologies have different reflective coefficients. This may be both a problem and an advantage: On the first hand it might cause measuring errors if not considered, but on the other hand, if properly implemented, will allow for not only the thickness to be measured, but also its morphology, as shown in Figure 9.
Frost Measuring and Prediction Systems for Demand Defrost Control

As for implementation on the evaporator, for frost detection, this sensor is purposed to be implemented directly on the fins, on the air intake front of the evaporator, without obstructing the air passage or obstructing as little as possible. When frost forms on the fins surface, it should also form on the sensors tip, and thus be detected, as shown on Figure 10.

Special care must be taken not to bend the optic fiber cable beyond its breaking point, as that would cause damage to the cable and prevent any readings from being taken. This is a special care that must be taken when implementing this sensor but should not be a problem after the sensor is installed.

Piezoelectric Sensors

Piezoelectric sensors work by applying a sinusoidal signal to a piezoceramic transducer, forcing it into resonance. This can be represented by the equivalent circuit shown in Figure 11.

$L_r$, $C_r$, and $R_r$ represent parameters associated with the piezoelectric transducer, and $C_0$ represents the parasitic shunt capacitance of the resonator due to packaging.

Figure 9. Results for different measurements using the sensor studied in [50]. from left to right no ice, glazed ice, rime ice and mixed ice. The horizontal axis is the ice thickness and the vertical axis is the sum of the optical intensities in the different signal fiber bundles.
(adapted from, (Zou, Ye, & Ge, 2013))

Figure 10. Purposed implementation of the fiber-optic sensor on the evaporator
The resonant frequency will tend to increase with greater net stiffness, while an increase in the resonating mass will tend to decrease the resonant frequency.

When water accumulates over the transducer it does not change the stiffness, but adds a weight, resulting in a decrease of the frequency. When frost forms, although its weight affects the frequency negatively, it is negligible when compared with the frequency increment due to the stiffness escalation, and thus frost can be detected and measured. The more frost forms on the transducer surface, the more its frequency will increase. In (Roy, Izad, DeAnna, & Mehregany, 1998) some promising measurements were achieved as shown in Figure 12.

The application of this sensor on the evaporator is suggested as shown in Figure 13. The sensor can be applied along and in between the fins (the application on the left on both (a) and (b)). The frost is formed mainly in the air intake front where the sensor is purposed to be applied. As the sensor is small, it should not significantly disturb the air flow, but for extremely small fin spacings the sensor cannot be

Figure 11. Equivalent lumped electrical network of a piezoelectric resonator (adapted from (Roy, Izad, DeAnna, & Mehregany, 1998)) The capacitance Co represents the parasitic shunt capacitance due to packaging

\[ \begin{align*}
C_0 & \quad \text{Co represents the parasitic shunt capacitance due to packaging} \\
L_r & \quad \text{representing the resonant inductance} \\
C_r & \quad \text{representing the resonant capacitance} \\
R_r & \quad \text{representing the resonant resistance}
\end{align*} \]

Figure 12. Results for the ice detection system studied by (Roy, Izad, DeAnna, & Mehregany, 1998). Comparison in mm of the determined frost thickness (vertical axis) vs the actual film thickness (horizontal axis) (adapted)
Frost Measuring and Prediction Systems for Demand Defrost Control

placed in between the fins as it might not fit or fit but without leaving space for air circulation and frost deposit on the sensor surface. Therefore, another application is purposed, not along the fins, but on the air intake front, perpendicular to the fins. It should be taken into consideration that this sensor placement will disturb the air flow more significantly.

Capacitive Sensors

The capacitance of an electrode assembly generally depends on the shape and dimensions of the electrodes, distance between them and on the permittivity of the dielectric, which is the amount of charge needed to generate one unit of electric flux in the material placed between the electrodes.

This permittivity varies not only with the material but also with its temperature and measurement frequency. The relation between the relative permittivity of water, its temperature and measurement frequency or ice, its temperature and measurement frequency is shown in Figure 14.

Knowing that the air permittivity will be low and constant in all frequencies, a sensor can be made by measuring the capacitance at different frequencies. An ice sensor was developed in (Toriano, Pasero, & Mesin, 2011) using this principle as shown in Figure 15.

Figure 13. Purposed implementation of the piezoelectric sensor on the evaporator

Figure 14. Relative permittivity of water (a) and ice (b)
(adapted from (Toriano, Pasero, & Mesin, 2011))
Frost Measuring and Prediction Systems for Demand Defrost Control

Theoretically this sensor could be used to detect water, ice, and measure its thickness although results show that the frost/water layer thickness affect very little the measured results. Perhaps, a different electrode configuration or data processing could show more promising results, as this study was developed to detect water or ice on roads, with little concern for its thickness.

As shown in Figure 16, if only used for ice detection, this sensor should be possible to implement in a similar way to the piezoelectric sensor, as the shape is almost the same. One thing that must be taken into consideration if the sensor is placed along the fin is the distance between the fin and the electrodes, as if that distance is too small it might cause interference.

Resistive Sensor

The resistance of a given sample varies with its form and material. Air, ice and water have quite different electrical resistance values, meaning that if two electrodes are positioned in the evaporator (but close enough for a voltage drop to be measured on a highly resistive material such as ice) and a voltage is applied on the terminals, a characteristic voltage drop will be measured as water forms, and this voltage drop will decrease as this water freezes, giving accurate measures of the ice formation. A device based on this is presented in (Caetano, Gaspar, & da Silva, 2018) and (Gaspar, Silva, Nunes, & Andrade, 2016), as shown in Figure 17.

Figure 16. Purposed implementation of the capacitive sensor on the evaporator
**Frost Measuring and Prediction Systems for Demand Defrost Control**

**Figure 17. Apparatus for water and ice detection using a resistive sensor (left) (Caetano, Gaspar, & da Silva, 2018) and sensor prototype CAD model (right) (Gaspar, Silva, Nunes, & Andrade, 2016)**

Figure 18 clearly shows the results for detection of water accumulation at 45 min and then the ice detection at 95 min.

Although this method currently does not allow for the measurement of the frost layer thickness, is it possible that different electrode configurations might enable this measurement.

As for the application in the evaporator, this ice detection sensor has been developed specifically for this purpose, so the application has already been tested as shown in Figure 19 (a) in the middle. The suggestion on the left was inspired on the application of the TEPS sensor on refrigeration systems, and the application on the right is a variation that has a less bulky sensor body, and consequently, less interference with the air flow. A variant in which a single electrode is used, and the fins are connected to the controller as second electrode could also be studied.

**COMPARISON OF FROST MEASUREMENT METHODS**

A sensor developed for monitoring the ice formation in refrigeration applications has cost as determining factor. Thus, any prototype to be developed must be inexpensive and have reasonable accuracy and

**Figure 18. Output voltage during operation**
(adapted from (Caetano, Gaspar, & da Silva, 2018))
Frost Measuring and Prediction Systems for Demand Defrost Control

Figure 19. Purposed implementation of the resistive sensor on the evaporator

Table 1. Comparison between frost measurement methods

<table>
<thead>
<tr>
<th>Device</th>
<th>Cost</th>
<th>Accuracy</th>
<th>Reliability</th>
<th>Complexity</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>2.2</td>
<td>★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★</td>
<td>★★</td>
</tr>
</tbody>
</table>
| 2.3    | ★★★ | ★★★      | ★★★★★       | ★★         | ★★★ ★★
| 2.4    | ★★★ | ★         | ★            | ★★★★★      | ★★★ |
| 2.5    | ★★★ | ★         | ★★★★★       | ★★★★★      | ★★★ |

reliability (Caetano, Gaspar, & da Silva, 2018). Complexity and size are also obvious factors of interest for refrigeration system manufacturers as these will drive the costs of implementing the sensors, and directly affect the final price. For ease of comparison, Table 1 was created so that the different methods can be evaluated, in which ✓✓✓, is of great usability for the proposed application, and ✓ of unproper use for the proposed application:

From the results of Table 1, method 2.1 is good for implementation and has the advantage that can be conveniently placed on the refrigerant tube, with no need for large design changes and operations. Another advantage is that it has also been already tested on refrigeration systems and preformed greatly. Method 2.2 is very accurate and has the advantage that it has been proven to distinguish between different frost morphologies, although it has the disadvantage of being slightly more complex and larger than the average method approached. The method 2.3 also has the advantage of measuring not only the presence but also the thickness of the frost layer. Although, it must be tested with frost layers over 0.5 mm and in refrigeration systems setups to evaluate if vibrations do not interfere with the measurements. The method 2.4 also seems promising but should be redesigned for implementation in refrigeration systems, perhaps allowing it to measure frost thickness. Method 2.5 has the great advantage of being very cheap and very sturdy, although further studies should be developed to attempt the measurement of frost thickness and the study of a simple implementation on a refrigeration system, perhaps by adopting a new design.
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PREDICTIVE METHODS

Artificial Intelligence

Artificial intelligence computes a large set of pre-obtained reliable data (parameters and results) to learn how to predict the desired parameters of frost formation when results are not given (Li & Zendehboudi, 2017), (Zendehboudi, Wang, & Li, 2017). These methods can be, amongst others: Multiple linear regression (MLR); Artificial neural network (ANN) and Support vector machine (SVM). These methods are described in the following sections. A methods comparison is performed later.

Multiple Linear Regression (MLR) Method

It models the relationship between two or more input variables and one output variable by fitting a linear equation to the observed data. Figure 20 shows the comparison of measured frost thickness and predicted thickness using the MLR method.

Figure 20. Comparison of measured frost thickness and predicted thickness using the MLR method (Zendehboudi, Wang, & Li, 2017)
Artificial Neural Network (ANN)

ANN are inspired by biological nervous systems, which can learn and identify the correlated patterns by training and then present new values. The general goal of the approach is to find solution algorithms to complex problems, such as prediction, pattern recognition, and classification (Tahavvor & Yaghoubiab, 2011).

Figure 21 shows the comparison of measured frost thickness and predicted thickness using the ANN method performed by Zendehboudi et al. (Zendehboudi, Wang, & Li, 2017). A Multilayer Perceptron-Artificial Neural Network (MLP-ANN) (Li & Zendehboudi, 2017) was able to predict frost density on horizontal surfaces, within −7.79% and +5.1%; frost layer thickness on parallel surfaces, within 22.95% and −18.2%; and frost density on parallel surfaces, within −5.26% and +9.99%. In addition, 99.32% of data points related to the frost thickness on horizontal surfaces are within ±20%.

Support Vector Machine (SVM)

The Support Vector Machine learning algorithm is based on statistical learning and structural risk minimization concepts. By mapping nonlinear input variables to high-dimensional feature spaces, the algorithm finds a hyper plane via nonlinear mapping (Cao, Han, Gu, & Ren, 2009). A modified version
Frost Measuring and Prediction Systems for Demand Defrost Control

of SVM, the least squares support vector machine (LSSVM) has a high generalization capability, lower computational complexity, and higher solving speed (Zendehboudi, Wang, & Li, 2017). Figure 22 shows the comparison of measured frost thickness and predicted thickness using the GA-LSSVM method.

Concluding Remarks

These models can be used to predict frost deposition in a wide range of different conditions with high accuracy. In addition, because models such as MLP-ANN can give results within 1 second, with high accuracy, the models can be used to design and enhance the thermal performance of heat pumps or heat exchangers in low ambient temperatures for refrigeration packages (Li & Zendehboudi, 2017). These models could also be incorporated in refrigeration systems to compute a prediction of the frost layer in real time using the parameters already measured by refrigeration systems, and applying a demand defrost method based on these results.

As shown on Figures 20, 21 and 22, artificial intelligence methods can give different results, depending on the method and on the implementation. Less reliable results don’t necessarily mean that these methods are unsuitable but may show better results if a different implementation is applied. For example, increasing the amount of data samples to train the models is one procedure that may improve model results.

Figure 22. Comparison of measured frost thickness and predicted thickness using the GA-LSSVM method (Zendehboudi, Wang, & Li, 2017)
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Numerical Analysis

Semi-Empirical Models

Semi-empirical models use correlations derived from experimental data to enhance numerical models. Hermes et al. (Hermes, Sommers, Gebhart, & Nascimento Jr., 2017) derived a correlation from three different surfaces, to include the surface wettability in a numerical model. Errors bounds of ±15%, and an average predictive error of 11.7% were obtained for different surfaces, which reveal how practical these models can be, as graphically shown on Figure 23.

Although these correlations can simplify the inclusion of a variable or parameter (such as in the case of [61] that includes the surface wettability in a frost prediction model), these incorporations must be carefully introduced, as frost formation is a complex phenomenon and these semi-empirical models might end up oversimplifying and/or introducing errors into the model (Armengol, Salinas, Xamán, & Ismail, 2016). Nevertheless, for complex simulations such as frost formation, correlations are usually used to account the huge number of factors that influence frost formation, and thus most of the following methods use empirical correlations in their models (Bartrons, Oliet, Gutiérrez, Naseri, & Pérez-Segarra, 2018).

Finite Volume Method

The finite volume method is a numerical method used for solving partial differential equations. This method calculates the values of the preserved variables averaged across the volume. Bartrons et al. (Bartrons, Oliet, Gutiérrez, Naseri, & Pérez-Segarra, 2018) used a finite volume method to predict the frost growth using dynamic meshes. The dynamic meshes change with every iteration to account for the frost layer. Application of the model and comparison with experimental data for validation are shown in Figure 24. The transient numerical prediction provides a trend very similar to the experimental results.

Figure 23. Time-dependent predicted frost thickness versus the experimental data for hydrophilic and hydrophobic surfaces under different operating conditions
(Hermes, Sommers, Gebhart, & Nascimento Jr., 2017)
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Other variants of the finite volume method were studied in Negrelli et al. (Negrelli, Cardoso, & Hermes, 2016) in which experimental data was represented within the ±15% thresholds. Armengol et al. (Armengol, Salinas, Xamán, & Ismail, 2016) obtained model predictions of the frost thickness as function of time agree with the experimental data within ±10% deviation for the case of intermediate plate temperature. Lee & Yang (Lee, Kim, Kim, & Lee, 2018) developed a model that predicted the experimental data of the frost properties within a maximum error of 10%.

Euler Multi-Phase Flow Method

In a two-dimensional computational domain of a finite volume method, it is impossible to express the exact shape and position of the frost surface using a one-dimensional line, because the shape and position change in real time. This problem can be solved by using the Euler multi-phase flow method (Kim, Lee, & Lee, 2017). This method allows a two-phase flow in a single computational domain. The two considered phases are usually humid-air phase (dry air and water vapor) and a frost phase (Kim, Lee, & Lee, 2017).

Ma et al. (Ma, Wu, Chu, & Zhu, 2018) developed a numerical investigation of frost formation on wavy plates using the Euler multi-phase flow method, leading to average frost thickness relative and frost weight relative differences between the simulations and experiments within ± 20%, as shown on Figure 25. It should be considered that this model works for wavy plates, as opposed to most of the reviewed models that work for flat surfaces.

Computational Fluid Dynamics and Software

Although Computational Fluid Dynamics (CFD) can use the abovementioned numerical analysis methods, a special regard should be given to CFD software, as it is nowadays a great tool for simulation.
Wu et al. [68] uses FLUENT to simulate frosting on fin-and-tube heat exchanger surfaces. This model predicts frost distributions on the heat exchanger surfaces, the temperature distributions and the air flow pressure drop. This model is based on the Euler multi-phase flow method and can be used in the development of a system for frost simulation during the design phase of heat exchangers, as shown in Figure 26. This method managed to achieve an average relative error between the predicted and measured pressure drops of -12.5%.

Wu et al. (Wu, Ma, Chu, & Hu, Phase change mass transfer model for frost growth and densification, 2016) developed and simulated a phase change mass transfer model to predict the frost layer growth and densification using FLUENT. The difference between the predicted and measured frost weights is within 3.2–3.9%, which are good predictions values when considering the average accuracy of the state of the art reviewed models.

### Comparison Between Methods

It is difficult to achieve a comparison between methods as even different implementations of the same method may yield different results. Nonetheless, a general comparison between the method category can be developed based on the main differences between artificial intelligence and numerical methods, with the aim of implementing these methods in the prediction of frost formation in evaporators. This objective can be considered as a means of designing the systems for a better passive defrost, and as a means of implementing demand defrost systems, using the frost prediction to start defrosting operations, rather than time based. The comparison between frost formation prediction methods is shown in Table 2 where the methods are compared for the purposed usage, rated from ✓ to ✓✓✓ where ✓ is not very suitable for the purposed usage and ✓✓✓ is very suitable.
**Frost Measuring and Prediction Systems for Demand Defrost Control**

Figure 26. **Humid air streamlines on the heat exchanger before and after frost accumulation**
(Wu, Hu, & Chu, Experimental study of frost formation on cold surfaces with various fin layouts, 2016)

![Humid air streamlines](image)

<table>
<thead>
<tr>
<th>Method</th>
<th>Artificial Intelligence</th>
<th>Numerical analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Computational Power</td>
<td>✓✓✓</td>
<td>✓</td>
</tr>
<tr>
<td>Accuracy</td>
<td>✓✓</td>
<td>✓✓✓</td>
</tr>
<tr>
<td>Implementation for evaporator design</td>
<td>✓✓</td>
<td>✓✓✓</td>
</tr>
<tr>
<td>Implementation in demand defrost systems</td>
<td>✓✓✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Artificial intelligence methods are the most suitable methods to implement in refrigerators for demand defrost control, as these are accurate enough for demand defrost control, while being simpler to implement and require less computational power. On the other hand, numerical methods are those that can be reliable and accurate and at the same time better developed for application in a uniform software to aid the design of fin-and-tube evaporators, by allowing the frost formation prediction to dictate if the design will result in an inefficient system, or if it has reached a compromise between heat transfer efficiency and frost accumulation damages.

**CONCLUSION**

Different methods for demand defrosting have been developed so far, and although many solutions exist nowadays, defrosting operations in refrigeration systems are still mainly time controlled. Thus, they are characterized by high energy consumption and temperature fluctuations that affect the conservation state of foods.
Frost Measuring and Prediction Systems for Demand Defrost Control

Directly measuring frost on the evaporator may be one of the solutions to minimize the impact of this problem. Cheap, compact, simple, reliable, and still accurate enough to command defrost operations sensors can be easily developed. The necessity to measure the frost thickness is not one of high precision, but one precise enough to command the defrosting operations on the ideal time. On the other hand, even though prediction models usually require more than one input to be accurate (air temperature and humidity, cold surface temperature, air velocity, …) these characteristics are already usually monitored by the refrigeration systems, and thus require no additional sensor installation, as opposed to the direct frost measurement systems that require the installation of a frost detection sensor on the system.

Future studies should be made for the development of methods that could easily be implemented on an existing system without requiring a lot of work, costs, and thus having minimal impact on the sale price of the refrigeration system, while resulting in huge energy savings in refrigeration and extended shell life of the refrigerated goods. As seen on this chapter, the method could either be either:

- **Directly Measuring**: A sensor directly applied on the evaporator. This sensor could be designed to be cheap, reliable and easy to implement, allowing for measurements to be directly made and defrost operations controlled with reliability. The sensor should be thoroughly tested as different frost morphologies and densities may induce measuring errors and cause unnecessary defrosting operations or fail to command defrosting operations when needed.

- **Predicting**: A model for frost prediction could be implemented, using as inputs the measurements already taken by the refrigeration system. Although this system does not require the implementation of new sensors, it is susceptible to model errors or parameters not taken in consideration that could cause the system to fail. To avoid this any predictive system should be thoroughly tested. Another disadvantage is that the processing power of the refrigerator should probably need to be increased.

- **Hybrid Solution**: Using a frost measuring sensor and a prediction model can have several advantages, for example to help improve the prediction model, by giving feedback on the frost measurement improving the AI algorithm accuracy when previously not accounted external conditions change. This may seem a waste of resources, but with the rise of the internet of things and industry 4.0 only one refrigerator cabinet needed the sensor to rectify all the other cabinets algorithms.

Different methods for frost prediction and simulation have been developed and are present on the literature, although most of these models are for simple applications, mostly for a cold flat plate, with a few methods starting to approach tube fin evaporators and wavy fins.

Besides, in the methods for frost formation prediction, there is not a single method that has been widely accepted as the most accurate or convenient, and thus, when taking about methods for frost formation prediction, a load of different approaches can be made, which causes the problem of not having a uniform solution.

Even though some of these methods could be applied in commercial refrigerators with relative ease, to command demand defrosting, most of the refrigerator systems still rely on the timed control method for defrosting operations. Future developments on the subject could result in a significant decrease of the energy consumption by the refrigerant systems, and less thermal loads on the refrigerated chamber.
REFERENCES


Frost Measuring and Prediction Systems for Demand Defrost Control


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Chapter 3
Processes and Technological Systems for Thawing of Fish

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ABSTRACT

This chapter describes the principles and methods of the fish thawing process, as well as the thawing systems’ structure, functioning, and development. A new method for calculating the duration of food thawing is introduced. The author shares best practices from the refrigeration industry of Russia and developed countries as well as his own experience. He hopes it may help scientists to choose research topics in the field of food freezing. The chapter is meant for students, post-graduate students, and experts working in the field of refrigeration production.

INTRODUCTION

Fish is a perishable product. It can be preserved by salting, drying, smoking, chilling, freezing, etc. Freezing is predominantly used as it helps to preserve the most of the natural properties of fish, removes seasonal fluctuations in the operation of fish processing, and expands the assortment of products.

Frozen fish accounts more than 70% of all fish products in Russia. In summer and winter, the processing volumes are maintained at the same level primarily through the use of frozen raw fish – which comes in blocks, individual units or in bulk. Before further processing, frozen raw fish is thawed.

On an industrial scale, fish freezing has been used since 1860. However, first attempts at designing fish thawing equipment were made only 68 years ago. The reason is that frozen fish had not been used as raw material for further processing before 1950. Thawing a small amount of fish was not difficult. Contrawise, bulk thawing of raw fish under the sanitary and hygienic control requires special equipment.

Methods of natural thawing of fish in the air or water proved to be inefficient. They are time-consuming, difficult to be controlled and require large production areas. The quality of thawed raw fish varies, and it is often unsuitable for further mechanical processing, for example for mechanical filleting.
Correct thawing is not paid enough attention in practice. Of course, thawing cannot restore the properties of fish that are lost during freezing and freezer storage. But only correct thawing process makes it possible to obtain a high-quality product. Thus, if interrupted at a certain stage, thawing improves product appearance (in case when fish needs a smooth cut), and reduces weight loss and increases output after cutting (when handling fish with highly hydrated muscle tissue).

Managing thawing is very important in the canned food industry. For example, if thawing is slowed down, it creates favorable conditions for the growth of microorganisms. It is necessary to make the sterilization process longer or increase the temperature of the heating vapor, which reduces the nutritional value of the ready product. Thus, uncontrolled thawing deteriorates the quality of fish and the advantages of freezing may be lost in the process.

Full automation and optimization in manufacturing processes requires the creation, selection and accumulation of specific mathematical models, principles of their development, and applying computing research methods. Using mathematical models in operations in thawing equipment allows minimizing the loss of raw material, preserving the quality of the ready product while saving energy and labor costs.

THAWING METHODS

Thawing is conversion of ice contained in frozen fish tissue into water. The process requires energy, usually heat.

The medium that transmits heat to fish is called the processing medium. Air, water and water steam are commonly used as the processing medium.

Depending on the type of energy used, there are thermal and electrical methods of thawing. When using thermal methods, the heat from the processing medium is transferred to the product surface. Thawing is gradual: the surface of fish thaws first, and then the inner layers. This method is also referred to as surface heating thawing.

Electrical thawing methods are based on the electrical properties of fish. Frozen fish is a weak conductor and a dielectric, therefore, for electrical thawing, fish is either connected to the electrical circuit as a conductor or placed in an alternating high frequency electric field and is warmed up as a dielectric. This method is also referred to as volumetric heating thawing.

Thawing in contact with heated plates or by heat (infrared) radiation is not used industrially as it causes the formation of bubbles under skin.

Thermal Thawing Methods

Thermal fish thawing includes air, liquid medium and vacuum condensed vapor thawing.

Air Thawing

Air thawing can be either still air or air blast and is used in two temperature modes: at room (15÷20°C) and lower (0÷5°C) temperature.
Processes and Technological Systems for Thawing of Fish

Cold air thawing is often called the slow thawing. It guarantees uniform temperature distribution across the depth. The product is brought to semi thawed condition with minimal drip loss, but it takes too much time (up to 30 hours). In summer when the air temperature is high, the quality of fish deteriorates, so the big fish (like tuna) must be mixed with ice. This technique is a variation of the slow thawing method.

Air blast in combination with humidification to avoid drying of the surface is used to reduce thawing time and weight losses. However, high temperatures and air humidity cause condensation on the cold fish, creating ideal conditions for the growth of microorganism on the surface of the thawed product.

Using of compressed air as processing medium halves the thawing time. It involves maintaining a temperature of 15÷20°C in a sealed steel chamber at 3·10^5 Pa and an air circulation velocity of 1÷1.5 m/s.

Liquid Medium Thawing

The processing medium is either fresh water or a salt solution. Fish is immersed in or sprayed with water. It is the most expedient way to quickly process large quantities of the product. In liquid medium, it takes 5 to 10 times less time for fish to thaw than in the air, since the heat transfer coefficient from the liquid to the fish is much higher than from a gas medium.

In contact with freshwater, mackerel and cuttlefish skin becomes straw-colored. If thawing is carried out in lightly salted water, the product maintains its natural color and luster. Skipjack meat after air and vacuum thawing preserves color better than after water thawing.

In the production of smoked and spiced salted products, fish is thawed in concentrated salt solutions. Combining thawing and salting reduces the production cycle, increases productivity, and saves water and human resources. However, as with water thawing, there is the extraction of nitrogenous substances and weight loss, so it is recommended to reduce the temperature of the liquid, speed up thawing and interrupt the process when the fish is semi-thawed.

Vacuum Thawing

This thawing method is based on using the heat released by condensation of water vapor on the cold surface of frozen fish. At vapor condensation temperature of 20°C, the pressure in the thawing chamber is kept at 2,336 Pa, i.e. vacuum.

The advantages of the vacuum method are low weight loss and no threat of bacterial contamination, preservation of product taste and short thawing time.

The above discussed heat thawing methods imply heat transfer to the surface by heat conduction, convection and radiation, while inside the fish heat is transferred only by heat conduction often limiting the speed of the process. Besides, a large part of the supplied heat is spent on heating the thawing medium, conveyors and is wasted into the environment. The electrophysical heating methods – electrical and microwave – are deprived of these deficiencies.

Electrical Thawing Methods

Thawing is conducted either by electric current or microwaves.
Electric Current Thawing

The principle behind this method is that an alternating electric current passes through the frozen fish, having certain electrical conductivity properties, causing its heating (Joule heating). Joule energy losses do not depend on the current frequency and are turns into heat generated in the product volume.

The advantage of this method is in quick thawing. However, electrical thawing means large consumption of electricity, water, local boiling of fish, electric shock hazard, and so far this method has not been yet implemented industrially.

Microwave Thawing

The principle behind microwave thawing is in using the dielectric properties of frozen fish. It is also called dielectric thawing, electronic thawing, high frequency (HF) thawing, or ultra-high frequency (UHF) thawing. Upon imposition of an alternating field on a dielectric, a displacement current caused by polarization and conduction current appear due to the presence of free electrically charged particles in the dielectric. The total current flow causes uniform heat generation.

At electric field frequencies up to 300 MHz, thawing occurs in the capacitor (with a tube generator as the source of electric oscillations), at ultra-high frequencies (over 300 MHz) it occurs in the resonant chamber or emitter (the source is a magnetron).

Technical difficulties, such as uncontrolled overheating of fish, low plant efficiency and etc., had prevented for some time the introduction of microwave thawing. In order to exclude local overheating: thawing is conducted at relatively low power; the product is set in motion to neutralize the effects of the inhomogeneity of the electric field caused by inhomogeneity of the product; power supply is interrupted or the product is periodically removed from the electric field; then the product is immersed into the water, mixed with fine ice or blasted with cool air (-15°C).

Despite the high quality of the thawed product, this method is costly. It is used to heat the frozen product instead of thawing it completely.

THAWING CHARACTERISTICS

Thawing Curves

Empirical curves showing temperature changes at various points in time are often used to describe the thawing process. Time-temperature charts are used to describe heat transfer characteristics inside the body in accordance with its shape, properties and peculiarities of heat exchange on the surface and the phase transition boundary.

The typical thawing curves are shown in Figure 1. The curves in Figure 1a show the temperature change in time at a certain depth; they are called temperature isobaths.

At the beginning of thawing, each isobath is steep, and then becomes flatter and closer to the horizontal line. Such a course of curves is associated with the transformation of ice into water. The fish warms up more slowly being defrosted, because the coefficient of thermal conductivity of water is four times less than that of ice.
Imagine several thin layers in the body thawed. With the absorption of heat, the temperature of each increases, while the ice content decreases simultaneously in each of them and in the body as a whole. As long as the microlayer temperature stays below \( t_{cr} \), the thawed layer is warming up (hidden thawing). The thawed microlayer doesn’t begin to heat up until the last ice crystals melt (cryoscopic point). After all ice crystals melt, the temperature of individual microlayer tissue raises rapidly. This is due to the increase of thermal diffusivity of fish at temperatures higher than the cryoscopic temperature.

The microlayer with temperature \( t_{cr} \) is the phase transition front in the body. It separates the frozen parts from the frozen microlayers being heated up.

Let us distinguish the typical isobath segments corresponding to certain thawing stages on the isobath (see Figure 1a).

Look at isobath \( abcd \) showing the surface temperature change (\( t_s \)), isobath \( aed \) for central points of body (\( t_c \)) and intermediate isobath \( afgd \) for points at a certain depth from the surface.

At the first stage, there is a rapid heating of the surface layer (segment \( ab \)) and a lower heating of deeper layers. The surface layer temperature is quickly approaching cryoscopic temperature \( t_{cr} \) (point \( b \)). The ice content in fish is reduced by layers, but the thawing front boundary is absent. It will appear after time \( \tau_1 \).

Segment \( bcd \) reflects the increase in temperature of the thawed surface layer. The surface temperature that is now a few degrees lower than the thawing medium temperature \( t_m \) is virtually unaffected after. The more the external heat transfer coefficient, the closer fish surface temperature \( t_s \) to temperature \( t_m \).

Segments \( af \) and \( ae \) reflect the heating process for the deep frozen layers. At the points \( f \) and \( e \), temperature is equal to the cryoscopic temperature which indicates the complete thawing of the corresponding layer. It would seem that the decreasing ice content in fish, i.e. the heat absorption source capacity, should cause the central microlayer temperature to rise faster. On the contrary, this process is slowed down to be associated both with the decreased heat conductivity of fish and the increased thickness of the thawed layer with poor heat conductivity that inhibits the introduction of heat into the body of fish.
Processes and Technological Systems for Thawing of Fish

The time of complete deicing of fish (point $e$) immediately affects the rate of thawed layer heating (heads of segments $ed$ and $gd$). In the absence of the ice phase, heating of the completely thawed body is completed quickly (segment $ed$).

If we single out a segment of the horizontal axis from the core to the surface as a plate and temperature on the vertical axis, we’ll obtain a family of curves reflecting temperature distribution in fish at certain points in time (see figure 1b) that are called isochrones.

At the boundary between thawed and frozen parts, isochrons do not go smoothly into one another. The kink of the curves is due to the absorption of the heat from thawing, and the slope of the tangent, drawn at the point $K$ to the isochron of the thawed layer, will be steeper than to the isochrone of the frozen residue. This is due to the fact that the tangent of the angle of inclination of the tangent to the isochron determines the magnitude of the temperature gradient and, therefore, proportional to the value of the specific heat flow for a given point in time. The heat transferred from the processing medium to fish is consumed for heating the thawed and frozen layers and melting the ice at the phase boundary.

Thawing curves allow to estimate the heat supply dynamics. It allows to accommodate heating devices efficiently when designing continuous operation defrosters or manage the flow of the thawing medium.

**Effect of Heat Transfer**

The quantitative characteristic of the thawing process is the thickness of the thawed layer $\xi$, which increases with time accordingly the changes in temperature fields. The location of the thawing boundary and the law of its moving from the periphery to the core $\xi = f(\tau)$ is determined by the isochrom “kink” point. The more intensive the heat supply to the body surface, the greater the boundary displacement speed $d\xi/d\tau$. External heat exchange intensity is characterized by the heat transfer coefficient $\alpha$.

The calculations show that the rate of thawing is largely influenced by the heat transfer coefficient $\alpha$. This effect decreases sharply with increasing of the depth from the surface layer (Figure 2). At a depth of 20 mm, a thousandfold increase in the heat transfer coefficient from 10 to 10,000 W/(m²K) causes only a threefold increase in the linear thawing speed, whereas at a depth of 4 mm the linear thawing speed is 15 times greater. Thus, the concept of ultra-fast thawing essentially applies only to the product surface layer.

Figure 2 demonstrates that at $\alpha \geq 200$ W/(m²K) the speed of ice crystal melting at the core layer does no longer depend on the external heat transfer intensity. The time of thawing is determined by the time of disappearance of the ice phase at the block core, so increasing $\alpha$ does not reduce the duration of the process under these conditions.

If the processing medium temperature is increased, the heat transfer intensification will only lead to overheating of the product surface layer and therefore deterioration of the quality of fish.

**EFFECT OF PROCESSING MEDIUM PARAMETERS ON THAWING TIME AND QUALITY OF FISH**

The effect of the medium temperature on the key product parameters during thawing is shown in Table 1 (Ohmori et al, 1978).

As is clear from Table 1, increasing the thawing medium temperature reduces the thawing time, but degrades fish quality. The evidence of it is swelling and loss of freshness of fish (VBN content increases).
An important requirement to fish thawing technology is stable thawing medium temperature. Even a short-time increase in the medium temperature negatively impacts product quality that cannot be reversed by subsequent temperature reduction to the optimal value. This is because slow thawing triggers enzyme activity that is not stopped by subsequent temperature reduction.

Effect of high pressure processing medium. The search for the best thawing mode led the researchers from Japan to the method of thawing in the compressed air stream (Cheftel; Le Bail, 2002).

It was found that the pressurized air thawing time is reduced twice and becomes comparable to the length of water thawing. Tuna thaws in 2 hours, merluccius – in 1.25 hours.

Figure 3 demonstrates the results of pressurized air thawing at up to 0.3 MPa at two air velocities and relative humidity of 80÷90% of blocks of fish

The quality of fish remains almost the same as the quality of fish thawed at atmospheric pressure. Weight loss is reduced to 1% (compared to 2÷5% for atmospheric air thawing).

Standard air thawing may cause fat oxidation in herring, sprat, etc., so these kinds of fish are water thawed. During pressure thawing in chamber, carbon dioxide or nitrogen can be used instead of air to inhibit oxidation and preserve better quality of thawed fish.

Thawing time for water and air at atmospheric pressure and pressurized air is shown in Table 2. The data suggest that thawing time by pressurized air and water is almost the same.
### Table 1. Basic characteristics of fish depending on the temperature of the thawing water

<table>
<thead>
<tr>
<th>Fish</th>
<th>Thawing water temperature, °C</th>
<th>Thawing time, min</th>
<th>Contained in fish tissue, %</th>
<th>pH</th>
<th>VBN, mg%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>water</td>
<td>fat</td>
<td></td>
</tr>
<tr>
<td>Flounder</td>
<td>Non-frozen</td>
<td></td>
<td>79.5</td>
<td>0.9</td>
<td>6.54</td>
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<tr>
<td></td>
<td>5</td>
<td>135</td>
<td>80.0</td>
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<td>90</td>
<td>80.1</td>
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<td></td>
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<tr>
<td></td>
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<td>80.5</td>
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<td>Sandfish</td>
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<td>74.6</td>
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<td>7.07</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>55</td>
<td>75.7</td>
<td>-</td>
<td>7.07</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>45</td>
<td>75.6</td>
<td>-</td>
<td>7.10</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>35</td>
<td>75.3</td>
<td>-</td>
<td>7.18</td>
</tr>
<tr>
<td>Sardine</td>
<td>Источник: <a href="http://rus.ans4.com/22395355/kak-po-angliyski-sardina/">http://rus.ans4.com/22395355/kak-po-angliyski-sardina/</a></td>
<td>Non-frozen</td>
<td>72.7</td>
<td>4.4</td>
<td>5.95</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>70</td>
<td>73.4</td>
<td>4.6</td>
<td>5.97</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>40</td>
<td>74.1</td>
<td>4.5</td>
<td>5.97</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>30</td>
<td>75.2</td>
<td>3.3</td>
<td>5.98</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>20</td>
<td>75.9</td>
<td>3.4</td>
<td>5.98</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>17</td>
<td>76.7</td>
<td>5.1</td>
<td>6.01</td>
</tr>
</tbody>
</table>

**Note.** Block dimensions 445 X 295 X 75 mm at initial fish temperature -15 °C, water velocity 1 m/s; VBN – volatile basic nitrogen.

### Figure 3. The effect of air pressure and velocity on the thawing time at tm = 25°C for 10 kg block fish at air velocity of: 1 – 1 m/s; 2 – 2 m/s
Processes and Technological Systems for Thawing of Fish

Effect of low pressure processing medium. The effectiveness of vacuum thawing was examined for whole fish, fillet, shrimp, as well as for frozen meat, fruit and vegetables (Everington, Cooper, 1972; Stefanovskiy, 1978).

Histological analyses of the surface and deep layers of cod and horse mackerel demonstrated that the morphological structure of muscle tissue of vacuum thawed fish does not differ from water thawed fish (non-contact).

For small fish (sprat), it is important to preserve the belly intact after thawing, as the insides are vacuum removed by processing equipment. The parallel vacuum and water thawing of block of Caspian sprat revealed that the amount of torn belly for both thawing methods at temperatures 12÷22 °C is the same and does not depend on the thawing medium temperature. Thus, the vacuum parameters during thawing do not cause mechanical damage to fish muscle tissue and the amount of torn belly depends on the initial fish quality.

The effect of the number of refreezing on the time of subsequent thawing and average characteristics of fish are shown in Table 3 (Ohmori, Nakamura, Hori, 1978).

According to Table 3, each refreezing reduces thawing time by 5 min. The reason is that fish muscle tissue after refreezing loses some liquid and therefore needs less time for phase transition. Thawing drip loss not only leads to a decrease in the weight of the product, but also increases microbiological risks, reduces nutritional value and organoleptic evaluation.

Table 2. Thawing time of seafood at different thawing methods

<table>
<thead>
<tr>
<th>Thawing medium</th>
<th>Mackerel</th>
<th>Blue whiting</th>
<th>Perch</th>
<th>Squid</th>
<th>Saury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air at atmospheric pressure</td>
<td>220</td>
<td>285</td>
<td>310</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>under pressure</td>
<td>95</td>
<td>115</td>
<td>100</td>
<td>190</td>
<td>200</td>
</tr>
<tr>
<td>Water</td>
<td>90</td>
<td>100</td>
<td>100</td>
<td>185</td>
<td>280</td>
</tr>
</tbody>
</table>

Table 3. Changes in the characteristics of fish from the refreezing number

<table>
<thead>
<tr>
<th>Fish</th>
<th>Refreezing number</th>
<th>Thawing time, min</th>
<th>Contained in fish tissue, %</th>
<th>pH</th>
<th>VBN, mg%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>water</td>
<td>fat</td>
<td></td>
</tr>
<tr>
<td>Flounder</td>
<td>1</td>
<td>70</td>
<td>81.2</td>
<td>0.6</td>
<td>6.76</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>65</td>
<td>80.8</td>
<td>0.8</td>
<td>6.77</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>60</td>
<td>80.6</td>
<td>0.8</td>
<td>6.79</td>
</tr>
<tr>
<td>Sandfish</td>
<td>1</td>
<td>55</td>
<td>76.3</td>
<td>9.5</td>
<td>7.11</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>50</td>
<td>74.5</td>
<td>10.0</td>
<td>7.12</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>45</td>
<td>74.9</td>
<td>9.6</td>
<td>7.19</td>
</tr>
<tr>
<td>Sardine</td>
<td>1</td>
<td>35</td>
<td>70.4</td>
<td>7.9</td>
<td>5.86</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>30</td>
<td>65.9</td>
<td>13.0</td>
<td>6.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>25</td>
<td>69.7</td>
<td>7.6</td>
<td>6.18</td>
</tr>
</tbody>
</table>
HAWING DRIP LOSS

Drip loss is a form of moisture migration. It is known that fish usually lose weight on thawing. This drip loss may be up to 5% of the original product weight for properly frozen and cold stored whitefish, though it can be more if the thawing process is uncontrolled.

Thawing drip loss is the most reliable indicator of the reversibility of fish properties after preservation by freezing. Moisture exudation is conditioned by biochemical, colloid and chemical and physical factors. This indicator allows evaluating fish quality, its marketable characteristics and determining the yield after freezing and storage.

Previously it was thought that during thawing only ice crystal melting occurs and the resulting moisture is absorbed by meat colloids, with the histological structure restored. It was thought that the slower the thawing, the more moisture is absorbed and the better the recovery of the original fish tissue structure. Later, our knowledge has been expanded and updated.

Food thawing cannot be considered as a mere process opposite to freezing. Such definition, in fact, applies only to the transformation of ice crystals to water.

It was also assumed that mineral salts, sugars, organic acids and components of tissue solutions are characterized by chemical stability and do not undergo significant changes during freezing. However, during thawing, only a portion of them returns to the solution.

Protein Denaturation

In addition, preservation by freezing causes protein denaturation which is extremely important. The changes due to denaturation are associated with the grade of freshness of fish for freezing, as well as freezing conditions, time of freezer storage and thawing methods.

Thaw Rigor

It was found that fish that is frozen immediately after slaughter, as well as in state of rigor and relaxation produces less drip loss during fast thawing. If fish is frozen during the early rigor phase, fast thawing will cause a sharp increase in the amount of drip loss due to the lability of actomyosin complex during the onset of post rigor mortis. Therefore, it is recommended to use slow thawing if fish was frozen before rigor mortis, and fast thawing if post mortem rigidity has passed. Thaw rigor is rarely a problem in thawed whole fish.

For cod, the proportion of resulting moisture calculated as the ratio of the difference in the moisture amount after and before thawing to the total moisture amount (%) is: pre-rigor 51, during rigor mortis 34, after rigor mortis (3-day storage in ice) 20, at deeper stages of postmortem changes (storage in ice for 8 days) 30 (Podeszewski, 1969).

Physiological Condition

The most prominent changes in the physiological parameters of fish can be observed during the spawning season that happens in spring for many commercial fishes. Thawing drip loss for fish frozen after the spawning season increase up to 8%.
**Processes and Technological Systems for Thawing of Fish**

**Freezing Temperature**

Tissue moisture loss during thawing is significantly affected by freezing temperature: the lower the freezing temperature, the less thawing drip loss. The weight loss values for merling during thawing are shown in Table 4 (Borisochkina, 1984).

**Freezer Storage Time**

The impact of freezer storage time on relative weight loss in thawed fish $\Delta M/M$ is demonstrated in Figure 4 (Stefanovskyi, 1981).

Figure 4 shows that sprat weight loss is minor prior the 20th day of storage at -18 °C. As time passes, there is a dramatic decrease in water-binding capacity of fish tissues which later is relatively stabilized.

**The Time of Critical Temperature Range Transition**

The temperature range in which the intensity of biochemical reactions is maximal (called the critical temperature range) is between -5 to -1°C. Slowing of thawing in this temperature range is highly undesirable (Figure 5). Increased drip loss, accelerated breakdown of glycogen, creatine phosphate, adenosine triphosphate (ATP) at the indicated temperatures confirm the need for quick thawing.

**Table 4. Drip loss of fish frozen to different temperatures**

<table>
<thead>
<tr>
<th>Freezing temperature, °C</th>
<th>Thawing drip loss, % of fish weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>1.1</td>
</tr>
<tr>
<td>-40</td>
<td>0.9</td>
</tr>
<tr>
<td>-80…-120</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Figure 4. Changes in the weight of block anchovy sprat depending on freezer storage time and thawing method: 1 - still water immersion thawing; 2 - air-agitated (barbotage) water thawing; 3 - air-agitated (barbotage) sodium chloride solution thawing**
Processes and Technological Systems for Thawing of Fish

During slow thawing (air or in ice), the amount of moisture separated by centrifugation is 1.5 times more than during quick thawing (in water). The water-holding capacity of slowly thawed fish is two times less than that of fresh fish stored for 8 and 9 days. These data confirm that water-holding capacity changes due to thawing rather than freezing. Speeding up the process of thawing significantly reduces the amount of drip loss.

Quickly thawed fish has a juicy texture and pleasant flavor when cooked. It is recognized that water thawed fish has the best taste; while air thawed fish mixed with ice is the worst.

Individual Peculiarities

Drip loss also depends on the fish species, properties and anatomy of body muscles, as well as body shape (surface to volume ratio). It is necessary to take into consideration the size of fish cuts, and the section plane, namely the area of muscles damaged during cutting. If the section plate runs along muscle fibers, drip loss is not as significant as for transverse muscle cutting when blood vessels and capillaries are cut, with cell nuclei and protoplasm exposed.

Drip loss during thawing fish is accompanied by the loss of its soluble substances: vitamins, enzymes, mineral salts, glycogen breakdown products, free amino acids, low molecular weight peptides, and sarcoplasmic proteins. Release of tissue moisture is accompanied by deteriorating appearance and consistency of the product.

Thawed Fish Storage

When thawed fish is stored, it further loses weight. The loss values after 168 h of refrigerator storage at 3±5 °C are given in Table 5 (Gorbatov, 1969).

Table 5 shows that, under similar storage conditions, the loss in thawed fish packed in plastic film is 5 times less than for unpacked fish.
Processes and Technological Systems for Thawing of Fish

Table 5. Weight loss during storage of thawed fish

<table>
<thead>
<tr>
<th>Fish</th>
<th>Weight loss, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Saurel</td>
</tr>
<tr>
<td>Packed into a film</td>
<td>5.2 ± 7.4</td>
</tr>
<tr>
<td>No packaging</td>
<td>36.4</td>
</tr>
</tbody>
</table>

To limit drip loss during fish fillet thawing, fish is treated with phosphates and enzymatic proteolytic agents. The solution concentration is 12%. For phosphate processed fish, the yield after thawing ranges from 103.2 to 97.9% of the product weight compared to 90% in the control batches.

Effect of the Thawing Method on Subsequent Processing

A priority of the fishing industry is to optimize production processes that should cover the whole processing scheme rather than individual operations. Traditionally, the methods and efficient modes of thawing have been studies from the standpoint of the prehistory and the process of thawing itself without taking into consideration the results obtained at subsequent stages of processing.

To assess the effect of thawing on subsequent processing, one batch was vacuum thawed and immersed in water. The defrosters were loaded with 300 kg of catfish frozen in bulk (each fish weighing 2.5÷3 kg). The fish was paralleled thawed using the above methods at processing medium temperature of 20°C.

According to the effective technological instruction, after cutting, portioning and salting, the semi-finished product was sent for frying at oil temperature 150°C. The peculiarities and overall picture showing weight changes at each process stage (excluding cutting and breading) are shown in Figure 6 (Stefanovskiy, 1981).

The results show that vacuum thawing causes greater weight loss (1.2%) than water thawing (0.6%). However, the time of vacuum thawing is 40÷45% less.

Figure 6. The change in the product yield at all processing stages: a - vacuum (1) and immersion (2) thawing; b - salting; c - frying
Vacuum treatment affects the permeability of fish tissues and accelerates salting by 32÷38%. The yield of fish thawed by vapor under vacuum is approximately 2.5% times higher than after water thawing. The increase in fish weight is probably due to the formation of an extensive network of pores and a highly developed surface with many active centers during vacuum thawing.

After frying both batches thawed using different methods, no difference in weight was observed. The frying loss was 19÷20%, which runs in line with the technological standards.

By comparing the resulting weight loss during the whole cycle (thawing, salting, frying), it can be observed (see Figure 6) that vacuum thawing increases fried fish yield (2%) and decreases the overall duration of processing by almost an hour while maintaining high quality of the product. Taste tests of the experimental batch revealed that fried catfish that was thawed using vacuum was juicier than the control samples (Stefanovskiy, 1981).

The expediency of various thawing methods and modes should be determined on the basis of comparison of specific quantitative indicators of the quality of thawed and prepared fish products with respect to the parameters of the equipment used in the adopted processing scheme.

**MICROORGANISM GROWTH FOR DIFFERENT THAWING METHODS**

In the fish processing industry, the choice of the thawing method depends on the power and operational specifics of each factory. This is especially true of canned fish plants as the quality of canned products is closely related to the degree of fish contamination. The increase in contamination occurs during thawing and cutting, due to unforeseen delays in processing and violation of sanitary norms of production.

There is a direct correlation between the degree of contamination of unsterilized fish and the amount of canned products spoiled during storage: the higher the contamination, the harder the mode of sterilization for microorganism suppression. However, high sterilization temperature and increased time degrade the taste and nutritional properties of canned fish.

When the same thawing method is used, fish that has been quickly frozen compared to slowly frozen fish reveals slower microbial deterioration.

The dynamics of microorganism growth during block sardine free air thawing (thickness of 0.065 m) at temperature of 20°C is shown in Figure 7. Moreover, as evidenced by tests, the same bacteria grow at the temperature of 20 and 4°C.

As can be seen from figure 7, the duration of lag growth phase is quite substantial.

Comparing the time of thawing and lag growth phase, it can be noted that during slow thawing the massive bacterial contamination of unsterilized fish increases, and eventually degrades the overall product quality (Table 6). Quick thawing ensures satisfactory bacterial contamination status and does not impair the organoleptic characteristics of canned fish (Grepey, Han-Ching, 1979).

According to the working schedule, for example, of canned fish plants of medium capacity, we can assess the effect of different thawing methods and sterilization capabilities that correspond to the schedule of a particular plant. For example, in the case of quick thawing, the daily amount of thawed fish must be divided into several batches entering processing sequentially to eliminate the risk of spoilage due to prolonged storage of fish at ambient temperature.

When using slow thawing methods, the daily batch must be thawed all at once, as the lag growth phase is approximately equal to thawing time and most of the unsterilized fish enters the phase of massive microorganism growth.
Processes and Technological Systems for Thawing of Fish

Figure 7. The bacterial growth curve for block sardine air thawing at 20°C
I – lag growth phase; II – logarithmic phase; III – stationary phase

![Bacterial growth curve](image)

Table 6. Lag growth phase duration and thawing time for different methods of supply of heat

<table>
<thead>
<tr>
<th>Thawing medium and its temperature</th>
<th>Lag growth phase duration, h</th>
<th>Thawing time (h) at block thickness, m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>small sardine (30 pcs/kg)</td>
</tr>
<tr>
<td>Free air flow</td>
<td></td>
<td>0.065</td>
</tr>
<tr>
<td>4 °C</td>
<td>29 ± 49</td>
<td>38.5</td>
</tr>
<tr>
<td>20 °C</td>
<td>16 ± 21</td>
<td>15</td>
</tr>
<tr>
<td>Forced air flow</td>
<td>11 ± 18*</td>
<td>2.25</td>
</tr>
<tr>
<td>Water</td>
<td>7.5 ± 8.5</td>
<td>3.5</td>
</tr>
<tr>
<td>15 °C</td>
<td>7.5 ± 8.5</td>
<td>2</td>
</tr>
<tr>
<td>20 °C</td>
<td>7.5 ± 8.5</td>
<td></td>
</tr>
<tr>
<td>Condensing vapor under vacuum</td>
<td>7.5 ± 8.5</td>
<td></td>
</tr>
<tr>
<td>15 °C</td>
<td>-</td>
<td>3.5</td>
</tr>
<tr>
<td>20 °C</td>
<td>10</td>
<td>2.25</td>
</tr>
<tr>
<td>Microwaves</td>
<td>15</td>
<td>7 min</td>
</tr>
</tbody>
</table>

* after 6 month freezer storage.
Additional contamination of air thawed fish with microorganisms is associated both with their growth during thawing and contamination with microflora by air blown by the defroster, 1 m³ of which contains 1,720-2,600 microorganisms.

The bacterial contamination on the surface and at deeper layers of the microwaved product is significantly lower than during air thawing. The suppressive effect of microwaves on microorganisms appears to be associated with the inactivation of the enzymatic system and inactivation of cells. The indirect suppressive effect of microwaves on microorganisms may be due to partial electrolysis of some medium components with formation of compounds that are harmful to microorganisms. Along with the above factors, microorganisms are also affected by the thermal effect of microwaves.

The results obtained in recent years have not confirmed assumptions about non-thermal effects of microwaves as a cause of inactivation of microorganisms or biological macromolecules.

THAWING CALCULATION

The goals of thawing calculations are preparing the physical and energy (usually heat) balance, determining the consumption of heat for thawing, as well as the ratio between the average weights of fish while still frozen (M_0) to time (τ). To establish the minimum allowable time for keeping fish in the defroster, we must determine the thawing time. In some cases, to obtain a product with the desired properties, it is necessary to determine the temperature range in fish that is necessary, for example, for fish intended for cutting or subsequent salting.

Material Balance

As a result of thawing, fish weight may decrease or increase. According to the law of conservation of mass,

\[ M_0 - M_\tau = \Delta M \]  

(1)

with indices 0 and τ referring to frozen and thawed fish respectively; ΔM – weight loss (or weight gain), kg.

The balance is calculated either per unit of time, e.g. 1 hour (or a single operation in the periodical process) or per weight unit of the initial product.

Based on the material balance, we can determine the yield, which is understood as the ratio of thawed product weight to the initial weight of the frozen product in per cents.

Heat Balance

The balance is prepared on the basis of the law of conservation of energy. The amount of energy in the form of heat issued by processing medium Q₁ (J) equals to the amount of heat Qₚ (J) taken by fish, not counting energy waste to the environment. The heat balance is expressed by the equation

\[ Q_1 = Q_p \]  

(2)
**Processes and Technological Systems for Thawing of Fish**

Amount of energy \( Q_1 \) given by the processing medium is calculated by the formula:

- For air or liquid thawing

\[
Q_1 = Gc(t_i - t_e)
\]  

(3)

- For vacuum thawing

\[
Q_1 = Dr_s
\]  

(4)

- For electrical thawing

\[
Q_1 = IU\tau
\]  

(5)

- For microwave thawing

\[
Q_1 = E^2f\varepsilon'\tan\delta V\tau
\]  

(6)

with \( G \) – heating medium weight, \( kg \); \( c \) – average specific heat capacity of the heating medium in the temperature range \( t_i - t_e \), \( J/(kg\cdot K) \); \( t_i, t_e \) – initial and resulting heating medium temperature respectively, °C; \( D \) – amount of condensed vapor, \( kg \); \( r_s \) – specific heat of condensation, \( J/kg \); \( I \) – electric current, A; \( U \) – voltage, V; \( \tau \) – time, s; \( E \) – electric field intensity, \( V/m \); \( f \) – electromagnetic oscillation frequency, \( Hz \); \( \varepsilon' \) – dielectric capacity of fish; \( \tan\delta \) – tangent of dielectric loss angle; \( V \) – volume of frozen fish, \( m^3 \).

The amount of heat \( Q_p \) received by thawing fish is determined by the change in its enthalpy respectively from \( h_1 \) (\( J/kg \)) to \( h_2 \) (\( J/kg \)):

\[
Q_p = M(h_2 - h_1)
\]  

(7)

The weight of the fish during thawing varies slightly (1÷3%), thus, the heat is calculated at \( M = M_0 \) (kg). \( Q_p \) (\( J \)) is often calculated using the formula

\[
Q_p = M \left[ c_1(t_{cr} - t_1) + W\omega r_i + c_2(t_2 - t_{cr}) \right]
\]  

(8)

where

- \( c_1 \) – average specific heat capacity of frozen fish in the temperature range \( t_{cr} - t_1 \), \( J/(kg\cdot K) \); \( t_1 \) – initial temperature of frozen fish, °C; \( t_{cr} \) – cryoscopic temperature, °C; \( t_2 \) – average temperature of thawed fish, °C; \( c_2 \) – specific heat capacity of thawed fish, \( J/(kg\cdot K) \); \( W \) – water content of the fish, \( unit\ fractions \); \( \omega \) – relative quantity of moisture frozen in the product, \( unit\ fractions \); \( r_i \) – specific ice melting heat, \( J/kg \).
Processes and Technological Systems for Thawing of Fish

The calculation by formula (7) or (8) shows that the amount of heat needed for thawing at various temperature ranges varies (Table 7).

In the range from minus 5 to 0°C, the main ice mass in fish muscle tissue melts, so quick thawing at this temperature range requires peak heat rate. During slow thawing, the heat load in time is relatively evenly distributed.

Besides, at temperatures above the cryoscopic temperature the proportion of heat required to heat the product is minor. Given that thawing is complete upon reaching the cryoscopic temperature, the formula (8) is simplified for practical calculations:

\[ Q_p = M \left[ c_1 (t_{cr} - t_i) + W \omega r_i \right] = M r \]  \hspace{1cm} (9)

where \( r \) – specific fish thawing heat (Table 8), J/kg.

If the specific thawing heat is expressed as relative value \( r^* = r/r_0 \), taking \( r_0 \) – specific thawing heat as the scale at a “comparative temperature”, e.g. \( t_0 = 8°C \) (chosen arbitrarily), as evidenced by Table 8, \( r^* \) does not depend on the species, only on freezer storage temperature \( t_i \):

\[ r^* = 0.653 \left| t_i \right|^{0.2} \]  \hspace{1cm} (10)

Table 7. Amount of heat that applied to a product at its thawing up to the set temperature

<table>
<thead>
<tr>
<th>Temperature Range, °C</th>
<th>The Amount of Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kJ/kg</td>
</tr>
<tr>
<td>from minus 20 to minus 12</td>
<td>24.7</td>
</tr>
<tr>
<td>from minus 12 to minus 5</td>
<td>39.36</td>
</tr>
<tr>
<td>from minus 5 to 0</td>
<td>201.81</td>
</tr>
<tr>
<td>from 0 to 5</td>
<td>17.58</td>
</tr>
</tbody>
</table>

Table 8. Specific fish thawing heat and relative value of thawing heat

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Specific fish thawing heat, kJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sturgeon (fat content 11.4%)</td>
</tr>
<tr>
<td>-4</td>
<td>( r )</td>
</tr>
<tr>
<td>-8</td>
<td>177.24</td>
</tr>
<tr>
<td>-10</td>
<td>207.22</td>
</tr>
<tr>
<td>-15</td>
<td>215.71</td>
</tr>
<tr>
<td>-22</td>
<td>232.96</td>
</tr>
<tr>
<td>-30</td>
<td>252.48</td>
</tr>
</tbody>
</table>

|                 | \( r^* \) | \( r^* \) | \( r^* \) | \( r^* \) |
|                 | 1.12      | 1.12      | 1.12      | 1.12      |
Processes and Technological Systems for Thawing of Fish

where $t_1$ expressed in Celsius in absolute value.

The equation describing the decrease of the frozen tissue weight in fish in time, is

$$-r \, dM = k \Delta t \, F \, d\tau$$

(11)

where $k$ – heat transfer coefficient with regard to the heat transfer intensity between the heating medium and the thawing front, $W/(m^2K)$; $\Delta t$ – temperature difference of the heating medium $t_m$ and $t_{cr}$ taken as the process driving force, °C; $F$ – surface of the body of volume $V$ (in $m^3$), $m^2$; $\tau$ – time, s.

If we introduce the shape factor $\varphi = F / V^{2/3}$ and assume that complex $k\Delta t\varphi/r\rho_1^{2/3}$ is constant, the equation (11) is easily integrated:

$$\frac{dM}{M^{2/3}} = -\int_0^{\tau} \frac{k \Delta t \varphi}{r \rho_1^{2/3}} \, d\tau$$

(12)

The result is a mathematical model convenient for engineering calculations (Stefanovskiy, 2015):

$$M^{1/3}_\tau = M^{1/3}_0 - m \, \tau$$

(13)

where $M_0$ – initial weight of frozen fish, $kg$; $M_\tau$ – remainder of the frozen mass in fish by time $\tau, kg$; $m$ – thawing rate that characterizes the thawing speed, equal to $k\Delta t\varphi/(3\rho_1^{2/3})$, $kg^{1/3}/s$; $\rho_1$ – fish density, $kg/m^3$.

The equation (13) in the coordinates $M^{1/3}_\tau - \tau$ is shown as a straight line the tangent of which angle is $m$, and the section on the x-axis determines the time for complete thawing. The straight line angle is determined by the intensity of driving force of the process, as well as geometrical and thermal properties of the body. The more $k$, $\Delta t$ and the less is the size of the fish, the sharper the straight line and the shorter is the thawing time.

It must be noted that as fish is thawed, $k$, $\varphi$, $r$, included in $m$ change. However, the experiments show the constancy of complex $m$ for a specific thawing method (Figure 8). It gives a great advantage, as it eliminates the need of determining the unsteady values of $k$, $\varphi$, $r$.

Figure 8. Kinetics of block sprat thawing by still water (1) and air-agitated (2) water immersion
Parameter \( m \) for frozen fish with arbitrary initial temperature \( t_1 \) is calculated using thawing rate \( m_0 \) at \( t_0 = -8^\circ \text{C} \) selected for comparative conditions. Then, taking into account formula (10),

\[
m = m_0/r^* = m_0/(0.653 | t_1 |^{0.2})
\]  

For \( m_0 \) (kg\(^{1/3}\)/s), the following dependencies were found:

- For still water immersion thawing

\[
m_0 = 2.9 \cdot 10^{-6} t_m^{1.25}
\]  

(15)

- For vacuum thawing

\[
m_0 = 2.1 \cdot 10^{-5} t_m^{0.75}
\]  

(16)

- For water spray thawing of small fish blocks

\[
m_0 = 5.4 \cdot 10^{-6} \varphi t_m^{0.6} p^{0.2}
\]  

(17)

where \( \varphi \) – block shape coefficient; \( t_m \) – thawing medium temperature, °C; \( p \) – specific water jet pressure force, Pa.

Knowing \( m \), we can calculate thawing time \( \tau \) according to the formula

\[
\tau = \left( M_{1/3}^\tau - M_{1/3} \right) / m
\]  

(18)

Thawing of block small fish is deemed to be complete when the mechanically unstable semi-thawed remainder with weight \( M_\tau \) breaks down. Judging from the practice, prior to this point in time value \( M_{1/3}^\tau = 1\div1.3 \) kg, for whole fish thawing is completed when \( M_{1/3} = 0 \).

The kinetic method as an engineering calculation method is simple and reliable; it does not require a clear understanding of the temperature-time fields and the mechanism of internal heat transfer. However, it is based on a specific experimental material, so the kinetic dependence is only suitable in the range of the investigated thawing methods.

FISH THAWING EQUIPMENT

Defroster Classification

A defroster is a device designed for thawing frozen food products.
**Processes and Technological Systems for Thawing of Fish**

Defroster includes four subsystems: the system of energy supply; product processing system; product transportation system; management system (Stefanovskiy, 2015).

The defroster classification is shown in Figure 9.

**Air Defrosters**

Air defrosters are specially equipped rooms (chambers) or a device loaded with frozen fish which is kept there until thawed. In the cold season, the thawing medium (air) is heated by steam or electric current. Fish thawing time is more than 15 hours depending on its size and air temperature.

To increase the performance of air defrosters, air humidity, pressure flow speed may be increased. See Figure 10 for an air defroster scheme.

The frozen blocks are placed from the boot platform on the conveyor 1 manually. The air driven by the fan 2 is heated and moistened in section 3, and then sent to the frozen blocks. When heat is transferred to the blocks, some moisture from the air is condensed, which prevents dehydration of the product surface layer and increases heat transfer at low temperatures. Thawed fish at the end of the conveyor enters the discharge section 4. The recommended flow rate of humid air is 5÷6 m/s at temperature of 20÷21°C.

**Liquid Defrosters**

Spraying and immersion defrosters which use water or sodium chloride solution as the thawing medium are prevalent in the fishing industry.

An immersion defroster is an open vessel or a tub filled with water. Frozen fish is loaded into the defroster in bulk or in containers. Thawing time 2÷9 h.

An immersion defroster has low performance without liquid being mixed, operates periodically, is very time consuming to maintain and takes up a lot of space. The tub is equipped with a conveyor, impellers, pushers, etc. that allow to automate the process and make it continuous. To intensify heat transfer,
Processes and Technological Systems for Thawing of Fish

Figure 10. Air defroster scheme: 1 – system of product placement and movement; 2 – system of processing medium preparation and its interaction with the product

![Air defroster scheme](image)

the water is agitated by air or with a stirrer, a circulation pump or a nozzle. Physical impacts along with shaking, vibration, blows accelerate the destruction of fish blocks and reduce thawing time. However, mechanical impact may cause damage to the fish surface.

A spraying defroster sprays frozen fish with water. Small fish blocks are loaded into the cassettes mounted on the conveyor. This design allows organizing continuous processing, timely unloading of fish from the spraying zone and automating the process to the fullest.

To save water, a closed two or three-time water circulation system and combined (e.g. spraying and immersion) defrosters (Figure 11) with filters 1 and heater 2 are used.

Vacuum Defrosters

A vacuum defroster is a vacuum chamber 1 equipped with trucks 2 with frozen products (Figure 12).

Figure 11. Spraying and immersion defroster scheme

![Spraying and immersion defroster scheme](image)
The vacuum pump creates and maintains the pressure of 2.3 \( \div \) 2.6 kPa in the chamber. Steam is supplied to the lower part of the chamber through a layer of liquid, it then fills the vacuum chamber and condensates on the product. After thawing, the steam supply is stopped, the vacuum pump is turned down, and the valve is opened. Atmospheric air is supplied into the chamber. After vacuum breaking, the chamber cover is opened, and the trucks with thawed fish are unloaded. Waste water is drained through valve 5.

After thawing, the product chamber remains clean, odorless. During sanitary treatment, the washed chamber is sterilized by steam, and then dried. Industrial vacuum defrosters operate periodically. Thawing time depends on the type of fish and the load and is 1\(\div\)4 hours.

**Electrical Defrosters**

An electrical defroster is one or more pairs of conductive metal plates between which the frozen product (block fish) is locked. For full contact between the plate and the frozen fish, they are immersed in a water tub. Thawing occurs as a result of electric current passing through the fish at industrial frequency (50 Hz). The water is heated and serves as a thawing medium. Such defroster is also called an electric-contact, electric-thermal, convective-electro-resistive and CIF- (current of industrial frequency) defroster.

A continuous operation electrical defroster (Figure 13) consists of a tub made of insulating material where plane-parallel metal electrodes are positioned at an angle 2 and 3.

Frozen block fish is continuously supplied by belt conveyor to the processing space between the electrodes. Water is also supplied there, with the excess drained by the overflow pipe 4. The thawing time for block small fish (10 kg) is 25\(\div\)30 min.
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Microwave Defrosters

The operation principle of a microwave defroster is based on the capacity of frozen fish to absorb electromagnetic energy of high and very high frequencies (HF and UHF). A microwave defroster is often called an electronic, as well as HF- or UHF-defroster.

There are two types: with HF-heating between the condenser electrodes and with UHF-heating reflected by the walls of a closed chamber (Figure 14).

In the first case (Figure 14-a), the wavelength (approximately 10 m) is much greater than the dimensions of the frozen fish. To generate an electric field in the body 1, it is placed between the electrodes 2 which are supplied with the voltage from the generator 3. If the shape of the electrodes does not fit the shape of the body, heating efficiency decreases and may cause electrical discharge.

In the second case (Figure 14-b), on the contrary, the wavelength is small, so heating implies using a waveguide surrounded by metal sheets on all sides. Microwaves are generated in the magnetron 1 and are transferred from the antenna 2 to the waveguide 3 and the diffuser 4. Next, being reflected from the metal walls, they are randomly distributed and penetrate a body of any complex shapes. Thick fish being frozen is heated more evenly at a lower frequency. For example, the depth of penetration of microwaves into frozen fish at a temperature of -3° to -5°C at 2450 MHz is about 17 mm and is about 50 mm at 925 MHz. At 2,450 MHz, the density of the absorbed energy is higher, thus reducing thawing time by 10÷20 min.

Figure 13. Scheme of electrical defroster

![Scheme of electrical defroster](image)

Figure 14. Condenser HF-defroster (a) and UHF-defroster with mirrored emitters (b)

![Condenser HF-defroster and UHF-defroster](image)
DEFROSTERS: COMPARISON AND SELECTION

A comparison of the main technical characteristics of industrial defrosters is conducted for devices of about the same performance, as an increase of unit capacity of a defroster improves its performance. Along with this, it is necessary to consider the state of the frozen raw material, for example, semi-pressed blocks of small fish thaw 1.5÷2 times faster than pressed blocks or blocks of large fish.

Table 9 shows the technical characteristics of the six types of defrosters with capacity of 0.5÷1 t/h (Stefanovskiy, 1979).

As can be seen from Table 9, the highest thawing rate (m=3.48÷2.85) can be attributed to the microwave and electrical defrosters. However, they are energy intensive and consume less water than machines of another type. In addition, microwave defrosters have small capacity per unit of occupied space (about the same as air defrosters).

Vacuum defrosters have the second thawing rate (m=2.4). They have good performance per unit of occupied space and consumption of electricity and steam.

The energy use of defrosters is determined by coefficient ξ that represents the ratio of the energy theoretically required to melt the ice in fish to the total energy that was actually expended:

\[ \xi = \frac{r}{\sum_i Q_i} \]  

(19)

where:

\[ r \] – specific thawing heat for 1 t of fish taken as constant and equaling 2·10^8 J/t;

Table 9. The technical characteristics of defrosters

<table>
<thead>
<tr>
<th>Defroster type</th>
<th>Thawing rate, kg°/h</th>
<th>Productivity per occupied area unit, kg/(h·m²)</th>
<th>Specific energy consumption, kW-h/t</th>
<th>Specific steam consumption, kg/t</th>
<th>Specific water consumption, m³/t</th>
<th>Energy efficiency ξ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>0.8÷2.4</td>
<td>82÷90</td>
<td>9(90.7*)</td>
<td>145</td>
<td>4.3÷5.2</td>
<td>0.60÷0.65</td>
</tr>
<tr>
<td>Microwave</td>
<td>3.48</td>
<td>15.9÷17.2</td>
<td>120÷150</td>
<td>-</td>
<td>5.4÷5.6</td>
<td>0.39÷0.49</td>
</tr>
<tr>
<td>Electric (alternating current of industrial frequency)</td>
<td>2.85</td>
<td>51</td>
<td>140÷190</td>
<td>-</td>
<td>8.33÷15</td>
<td>0.30÷0.40</td>
</tr>
<tr>
<td>Immersion in still water in bubbling water (barbotage)</td>
<td>0.45÷0.63</td>
<td>35.8</td>
<td>11.1</td>
<td>-</td>
<td>2.9÷4.3</td>
<td>0.44÷0.51</td>
</tr>
<tr>
<td>Spraying</td>
<td>0.93÷1.38</td>
<td>43.9÷49.2</td>
<td>22.7</td>
<td>288</td>
<td>1.9÷4.6</td>
<td>0.28÷0.42</td>
</tr>
<tr>
<td>Air</td>
<td>0.82÷1.60</td>
<td>34.8÷38.2</td>
<td>6.7÷14</td>
<td>167÷285</td>
<td>0.16÷0.19</td>
<td>0.25÷0.29</td>
</tr>
</tbody>
</table>

* With electric steam generator
** With water recycling
Processes and Technological Systems for Thawing of Fish

\[ \sum Q_i \] – amount of energy expended in the form of heat, work and electricity for thawing 1 t of fish.

As can be seen from Table 9, microwave defrosters utilize energy by 39\(\div\)49%, while the figure is 60 \(\div\) 65% for vacuum defrosters.

CONCLUSION

When evaluating the performance and selecting a defroster, it is necessary to consider the purpose of the process (full or partial thawing), the scale of production, the cost of the device, the complexity of maintenance, operating costs, etc.

Batch-type defrosters are used for large fish processing, as frequent repetition of auxiliary operations (loading, filling with the thawing medium, unloading) reduces device performance. Batch-type defrosters are efficient for small processing plants, food shops with a diverse range of incoming products with frequently changed thawing mode.

Continuous operation defrosters are used fully only at a constant composition of the incoming raw fish at relatively large plants.

Air defrosters are used at plants with deficient or frequently interrupted water supply. They are, in comparison with liquid defrosters, structurally simple, do not require a large consumption of water, as well as purification of wastewater from the scales and foam. The disadvantages of air defrosters include bulkiness, drying of the surface layer and fat oxidation in fish (if using dry air as the processing medium), so air defrosters are mainly used to thaw lean fish.

Liquid defrosters are characterized by highly intensive heat transfer. Where there is no shortage of water, this advantage becomes crucial, but the quality of fish deteriorates due to swelling and leaching of water-soluble proteins. Immersion defrosters are used for thawing fish in bulk, in blocks and for packed fillet. In this case, thawing fillet without packaging is impractical, since fat and proteins are washed away from the cut surface, and there is a rapid growth of microorganisms outside.

A number of companies prefer vacuum defrosters in which intense external heat transfer is achieved without excessive heating of the fish surface. Vacuum prevents the growth of microorganisms. A vacuum defroster is universal, easy to maintain, but its batch-type principle of operation makes it difficult to organize continuous production. To ensure the continuity, the vacuum chamber must be equipped with loading and unloading bays with sluice gates and a vacuum tank for water change.

Plants which need a highly flexible process due to production conditions install microwave defrosters. In case of shortage of fresh fish, you can quickly thaw frozen fish and prevent disruption to the production line. However, to preserve the quality (prevent local boiling) of fish, the temperature must be increased up to not more than minus 2 °C. Partially thawed fish is too hard for immediate processing by cutting machines. The decision depends on the thawing method. For example, after a water immersion defroster, fish contains enough energy to completely thaw and only requires some time to equalize the temperature. After a microwave defroster, the temperature is distributed evenly across the body, and complete thawing makes it necessary to apply additional heat supplied in any way that complicates the whole cycle.

Thus, the choice of thawing method and defroster design largely depends on the kind of socio-geographic area of thawing and the product type.
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REFERENCES


Chapter 4

Energy Efficiency in Meat Processing

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ABSTRACT

Energy conservation plays a vital role towards sustainable development of meat processing. Energy costs for many meat plants represent the fourth highest operational cost. In meat processing, moderate levels of both electrical and thermal energy are consumed in wide range of processes and applications. However, energy efficiency improvement in the meat processing industry have been a focus to increase the sustainability of meat processing in the past decades. This chapter started with the examination of the energy use in meat processing facilities. The emerging energy-efficient technologies for meat processing were discussed in detail. Energy requirement for well-cooked meats varies with cooking method, appliances, and consumer behavior. Energy consumption reduction during meat cooking may have an influence on global energy requirement. Selection of cooking method, fuel, and cookware are beneficial for reducing the carbon footprint of the cooking unit. This chapter also presents the effects on quality characteristics of meat and meat products by different cooking methods.

MEAT PROCESSING: OVERVIEW

Meat and meat products are rich sources of nutrients including, fats, proteins, vitamins (vitamin B12) and minerals (zinc and iron) and forms an essential part of the diet and consumed across in many parts of the world (FAO, 2012). Ritchie and Roser (2018) highlighted that global meat production had increased 4-5 folds since 1961 and the Figure 1 depicts that movement. However, this trend of meat production and consumption is on the rise in both developing and developed nations.

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Figure 1. Total meat production in tonnes excluding offal & slaughter fats (Ritchie & Roser, 2018)

Meat production by livestock type has also changed dramatically since 1961 as shown in the Figure 2. Slaughtering of livestock is an important industry in most of the countries to produce meat and meat products. It involves stunning, bleeding, dehiding, dehaired/defeathering, evisceration, dressing and washing. Depending on the customer requirements it may also involve the deboning process (Hui, 2012). During the slaughtering process both edible (e.g. livers, gizzards) and inedible products (e.g. hides,

Figure 2. Meat production by Livestock Type (Ritchie & Roser, 2018)
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feathers) are produced. Figure 3 presents a flowchart for the basic processes involved in slaughtering and processing of beef.

- **Reception of Beef Cattle**: Beef cattle are delivered on a specially designed lorries to the slaughterhouse and kept in the holding area where cattle are washed and rested for one or two days.

- **Stunning and Bleeding**: The cattle are led to the stunning area where they are stunned using electric shock or bolt pistol to make animal unconscious without any discomfort or excitement. They are then chained by their rear legs and mounted on overhead rail. Using a sharp blade their carotid arteries and jugular vein are severed to allow all the blood present in the animal to flow out in a trough.

- **Dressing**: In this process unwanted parts such as skin, head, hair and hoofs are removed using machines in larger slaughterhouses or by hand in smaller operations. Antimicrobial interventions such as hot/ambient water wash, organic acid wash, steam vacuuming and bunging is carried out on the carcass to reduce the microbial activity. Steam vacuuming is used to remove any contamination from the carcass and bunging is to avoid contaminating the carcass with faecal material.

- **Evisceration**: Evisceration is the process to remove internal organs from the carcass. Care must be taken so that internal organs such as stomach and intestines are carefully separated without contaminating the carcass with faecal material.

- **Splitting**: In this stage the carcass is split with a saw which allows inspection of the carcass for any disease conditions which can be unfit for human consumption.

- **Trim Rail**: Carcass parts which are undesirable or parts which possesses quality issues are removed by trimming.

- **Final Wash & Chilling**: In this step the carcass undergoes final wash to remove any further contaminations. The carcass is weighed, marked, branded and sent to chillers. Sending it to the chillers inhibit the growth of harmful microbial pathogens. Appropriate temperatures are maintained in the chillers to ensure quality and safety of the carcass.

- **Cutting and Boning**: At this point the carcass is chopped or deboned as per the customer requirements and packed.

- **Packaging, Storage and Distribution**: This is the final step where product is packaged with correct specifications (expiry date, description), stored and sent for distribution.

Meat and meat products have the greatest environmental impact of all products in the food and drink area. In meat plants, energy costs represent the fourth highest cost (after raw materials, waste management and labour (AHDB, 2011). There are some significant challenges in meat processing industry prevent this sector from becoming more energy-efficient and sustainable, which includes evaluation of energy saving measures, implementation, and lack of use of alternative sources of energy (Brunner, Fluch, Kulterer, & Glatzi, 2014).
Energy Efficiency in Meat Processing

Figure 3. Flowchart for beef processing (FAO, 1996)

ENERGY-EFFICIENT TECHNOLOGIES FOR MEAT PROCESSING INDUSTRY

As described in the above section, the global meat production and consumption is on the rise and also the energy required by the meat industry. However, at the same time consumers want to have access to high quality, safe and convenient meat products with minimal processing and preserving the freshness, natural flavour and taste of the product (Hugas, Garigga, & Monfort, 2002). In order to achieve this meat industry came up with many preserving techniques which are low in energy consumption but still effective against pathogenic and spoilage micro-organisms.

The energy required by the meat processing industry can be distinguished between thermal and non-thermal processing technologies (Table 1).
Energy Efficiency in Meat Processing

Table 1. Meat processing technologies

<table>
<thead>
<tr>
<th>Non-thermal technologies</th>
<th>Thermal Technologies</th>
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<td>Pulsed electric fields</td>
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<td>Ohmic heating</td>
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<td>Ultraviolet</td>
<td>Induction heating</td>
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<td>Irradiation</td>
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<tr>
<td>Cold plasma</td>
<td></td>
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<tr>
<td>Dense Phase carbon dioxide</td>
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</tr>
<tr>
<td>Ozone</td>
<td></td>
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<tr>
<td>Chemicals</td>
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</tbody>
</table>

Novel Thermal Processing Technologies

Microwave (MW)

MW heating is used in meat processing for tempering, thawing, and cooking of meat (Yarmand & Homayouni, 2011). Tempering of frozen meat using MW energy allows easier slicing of meat and has been demonstrated that it results in higher product yield as it minimises the evaporative and drip losses as compared to other conventional meat tempering processes. Under appropriate conditions thawing took lesser time compared to convective thawing at ambient temperature. Commercialisation of MW thawing was not that successful in meat industry with respect to MW tempering. MW cooking is relatively newer method of cooking meat and has been widely accepted since it takes less time to reach endpoint temperatures for roasts when compared with conventional methods. MW cooking allows holding of vitamins such as retinol, thiamine and riboflavin compared with other higher cooking temperature (Zhang, Lyng, & Brunton, 2006).

Radiofrequency (RF)

RF technology is being deployed by meat industry because of its higher penetration depth, uniform heat distribution and low energy consumption. Its been successfully used in the industry to sterilise, pasteurise and disinfect meat products (Jojo & Mahendra, 2013). For e.g., Wang et al.(2012) used RF energy to process meat lasagna and demonstrated that there was no much temperature difference in the lasagne ingredients (meatballs, mozzarella cheese and sauce). There was adequate heat transfer reducing differential heating and product quality was unaffected. Another research conducted by Kirmaci and Singh (2012) established that RF cooking time for Chicken breast was reduced by 42.4% when compared to Water bath cooking and Laycock et al. (2003) illustrated that RF cooking of ground beef, comminuted meat and muscle was 5.83, 13.5 and 13.25 mins respectively when compared to 151, 130, 109 mins in water bath.
Energy Efficiency in Meat Processing

Ohmic Heating (OH)

OH is a thermal process generating internal heat in a meat product in a uniform way and is based on the principle that most of the food products are able to resist to the flow of electric current (Pereira & Vicente, 2010). OH technology usually requires electrodes to be in contact with foods and due to its very quick heating rates allows meat to reach its pasteurisation temperature in short time (De Halleux, Piette, Buteau, & Dostie, 2005). They further demonstrated that cooking time for Bologna hams were reduced by 90-95% when compared to the traditional method of smoking hams. And, if the process is replicated in industries, it would result in energy efficiency greater than 90% and reduction in energy consumption of 82 to 97% compared to conventional method of smoking hams.

Induction Heating (IH)

IH is the process of heating usually a metal via electromagnetic induction. It is often used in cooking processes where the meat products are placed in a container which is ferromagnetic in nature. This process often involves the danger of product damage due to burning, as high heat transfer from the hot surfaces (Varghese, Pandey, Radhakrishna, & Bawa, 2014).

Non-Thermal Processing Technologies

High Hydrostatic Pressure (HHP)

HHP application on food is a widely researched topic and this method involves exposing food to pressures between 100 to 1000 MPa. HPP causes denaturation of proteins resulting in inactivation of enzymes and microorganisms (Sun & Holley, 2010). This technology offers various benefits such as: uniform pressure application to food product creating homogeneity, minimum heat impact, similar shelf-lives to thermal pasteurisation and less energy needed to compress a solid or liquid food product to 500 MPa with regards to heating at 100°C (Pereira & Vicente, 2010). HHP is commercially deployed in various food industries including cooked meats, seafood and fish.

Pulsed Electric Fields (PEF)

PEF technology involves delivery of pulses of high voltage to the product placed between a pair of electrodes and this action results in inactivating microorganisms without any changes to nutritional, flavour, taste and quality (Faridinia, Bremer, Burritt, & Oey, 2016). PEF accelerates curing process of meat, enhances drying and reduces the activity of microorganism but still has a long way to cover to become a commercial reality in the meat processing industry (Bhat, Morton, Mason, & Bekhit, 2018).

Ultrasound (US)

US technology is an emerging technology with potential to accelerate the process of tenderisation, maturation and mass transfer, reduction in cooking energy and enhancing the shelf-life but at the same time preserving the quality and functional properties (Alarcon-Rojo, Janacua, Rodriguez, Paniwnyk, & Mason, 2015). This technology uses sound waves higher than those that can be detected by human ears.
Energy Efficiency in Meat Processing

(20kHz). The sound travels through a medium generating wave of compression and rarefaction of the particles resulting in formation of cavities and these cavities become unstable and collapse releasing high temperatures and pressures (Chemat, Huma, & Khan, 2011).

Ultraviolet (UV)

UV is a non-thermal technology and highly utilised in surface treatment of food. UV technology popularity and acceptance are increasing due to its effectiveness against pathogenic and spoilage microorganisms as well as low maintenance and environment friendliness (Koutchma, 2008). However, its not that efficient in penetrating the solid foods and can be ineffective against pathogens which are deep inside the meat (Degala, Mahapatra, Demirci, & Kannan, 2018).

Irradiation (IR)

Gamma IR technology is very effective for protecting food against contamination but its acceptability by consumers is still very low (Hugas, Garigga, & Monfort, 2002). Kanatt, Chander, and Sharma (2005) investigated effect of radiation on meat products and their shelf-life. The results from this research demonstrated that shelf-life of the products increased by more than 2 weeks without affecting the sensory qualities of the products.

Cold Plasma (CP)

The application of CP technology on bacterial spores is more effective than compared to other techniques like heat, chemicals and UV treatment while maintaining sensory attributes and freshness (Thirumdas, Sarangapani, & Annapure, 2014). CP technology is effective on range of the microorganisms and spores in shorter periods of time and is an alternative technology for surface sterilisation and act as a disinfectant (Philip, Saoudi, Crevier, Moisan, Barbeau, & Pelletier, 2002). Until now in order to decontaminate food, CP technology needed to work at room temperature and this condition was achieved only under vacuum which was expensive and not convenient. But, recent developments in CP technology allows production of plasmas through utilisation of simple and cheap equipment having both spatial and temporal stability at ambient temperature and atmospheric pressure (Kogelschatz, 2002).

Dense Phase Carbon Dioxide (DPCD)

DPCD technology is a cold pasteurisation method to inactivate microorganisms and affects enzymes under pressure below 50 MPa without having any undesired effects of heat and retaining the freshness, nutritional and sensory attributes (Damar & Balaban, 2006). It is continuous technique that utilises pressure in combination with CO₂. The CO₂ used in solvent form is widely used in many food applications as it is non-toxic, chemically inert, non-flammable, inexpensive and no residues are left behind (Ferrentino & Spilimbergo, 2011).
Energy Efficiency in Meat Processing

Ozone (O₃)

Ozone is a powerful oxidant and disinfecting agent. Ozone has been used in food industry for treating food surface, equipment, lowering biological and chemical oxygen demand (Guzel-Seydim, Greene, & Seydim, 2004). Researchers successfully used ozone as disinfectant for poultry carcasses (Sheldon & Brown, 1986; Yang & Chen, 1979). Ozone application has resulted in increase in shelf-life of the products and it leaves no residue behind since it decomposes quickly (Khadre, Yousef, & Kim, 2001).

Chemicals

The application of Chlorine based chemicals are widely used in the meat processing industry. Acidified sodium chlorite, alkyl dimethyl benzyl ammonium chloride, chlorine dioxide and sodium hypochlorite are some of the disinfectants added to water to reduce microbial contamination during poultry processing (Guastalli, Batista, Souza, Guastalli, Lopes, Almeida, et al., 2016). Electrolysed water which reduces the microbial growth and increases the shelf-life of meat products but at the same time there is concern regarding the applicability of this process due to stability of chlorine, corrosion resistance and chlorate residues (Wang, Duan, Wu, Xue, Xu, & Zhou, 2019). Lee, Oh, Chung, Choi, Myeong, Song, et al. (2018) demonstrated the applicability of chlorine dioxide gas (ClO₂) as a disinfectant on livestock carcasses and equipment. Nitrate and nitrite which are used for curing meat products inhibits growth of microorganisms but at the same time forms carcinogenic nitrosamines in human stomach (Honikel, 2008).

ENERGY FOR MEAT PROCESSING

A research conducted by Ramirez, Patel, and Blok (2006) showed that meat processing sector in four EU countries (France, Germany, The Netherlands and The United Kingdom) consumed energy between 40-60%. They further stated that except France (mostly used electricity) the other three countries used most of the fuel in the form of natural gas to drive their meat sector but there is an increasing trend towards the use of electricity. Fossil fuels are used mainly for heat processing while electricity for refrigeration purposes.

As per the survey report published by AHDB (2011), a slaughterhouse in the UK typically uses 50-80% of energy in the form of electricity while the rest 20-50% comes from thermal energy. Other than refrigeration, electricity is used for generating compressed air, ventilation purposes, lighting and powering of the machines such as saws, hoists, conveyors, packing lines, electrical stunning and rendering purposes. While thermal energy (from natural gas and oil) is used for boilers to provide heat and hot water which is then used for processes such as scalding, sterilisation of surfaces and equipment and cleaning activities. The survey further states that on average 775kWh of energy is needed to produce a tonne of beef and 685kWh of energy to produce a tonne of sheep meat. Pig abattoirs require 80% of its energy in the form of thermal energy as compared to beef and lamb abattoirs which need 30-50% of its energy in the form of thermal energy.
Energy Efficiency in Meat Processing

Energy Use of Beef Processing Plants

Table 2 illustrates the energy use of beef packing plants around the world. Ziara (2015) stated that energy use of these plants varies due to many factors such as size and location of the plants, automation of the production processes, capacity, machinery age and efficiency, insulation, weather and temperature.

In meat plant substantial energy savings can be made almost immediately with little or no capital investment, through simple housekeeping efforts. In addition to reducing a plant’s demand for energy, there are opportunities for using more environmentally benign sources of energy. Opportunities include replacing fuel oil or coal with cleaner fuels, such as natural gas, purchasing electricity produced from renewable sources, or cogeneration of electricity and heat on site. For some plants it may also be feasible to recover methane from the anaerobic digestion of high-strength effluent streams to supplement fuel supplies (Brunner, Fluch, Kulterer, & Glatzi, 2014).

IMPORTANCE OF MEAT COOKING

Meat and meat-based products are cooked before being eaten. Cooking step is critical for destroying foodborne pathogens, assuring microbial safety and achieving meat quality. Cooking method has great impact on eating quality of meat, and energy consumption is important parameter to consider while selecting the cooking method (Pathare & Roskilly, 2016). Eating quality of meat is mainly affected by applied cooking method. The quality characteristics of meat products change considerably depending on the type and intensity of the heat treatment applied. (Bejerholm & Aaslyng, 2004a). Cooking of meat results in better aroma and also, the cooked meat is more tender compared to raw meat (Oz, Kızıl, & Çelik, 2016). Traditional methods for cooking meat products involve heating the product by immersion in hot water or by steam cooking. In such cooking processes, heat is predominantly transferred by convection from the cooking media to the product surface and then by conduction from the surface to the

Table 2: Energy use of beef packing plants

<table>
<thead>
<tr>
<th>Year</th>
<th>Reported Energy Use</th>
<th>Calculated equivalent use</th>
<th>Location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>70-300 kWh/head</td>
<td>252-1080 MJ/head</td>
<td>Denmark</td>
<td>(Hansen, Christiansen, &amp; Hummelmose)ᵃ</td>
</tr>
<tr>
<td>2006</td>
<td>60 kWh/tonne product</td>
<td>196 MJ/1000 lb. product</td>
<td>Finland</td>
<td>(Ramirez, Patel, &amp; Blok, 2006)</td>
</tr>
<tr>
<td>2012</td>
<td>1723 MJ/tonne products</td>
<td>781 MJ/1000 lb. product</td>
<td>Poland</td>
<td>(Wojdalski, Dróżdz, Gróchowicz, Magryś, &amp; Ekielski, 2013)</td>
</tr>
</tbody>
</table>

ᵃHSCW = tonne of hot standard carcass weight

Sourced from (Ziara, 2015)
Energy Efficiency in Meat Processing

gеometrical center of the products. This could lead to overheating of the surfaces while waiting for the interior to reach the required temperature (Li, Sun, Han, & Yu, 2017). The choice of appropriate cooking techniques relies on the type of meat, the amount of connective tissue, size and shape of the meat. The different meat cooking methods commonly used are discussed below.

Oven Cooking

Oven cooking is widely used in commercial processing and food service operations as well as home cooking (Isleroglu, Kemerli, & Kaymak-Ertekin, 2015). Quality attributes and microbial safety of products have been affected by oven cooking or roasting (Goñi & Salvadori, 2010). An oven empowers heating of meat at raised temperatures normally up to 250°C. Rapid rate of heating due to high cooking temperature reduces the total cooking loss of meat. (Palka & Daun, 1999). The reduction in total cooking loss is important as meat promotes higher solubilisation of intramuscular collagen based connective tissue leading towards tenderisation due to high water holding capacity. Maintenance of moisture in the product during cooking helps improve juiciness (Ritchey & Hostetle, 1965). During roasting, the first period of toughening happens because of the denaturation of myofibrillar proteins. Subsequently, toughening is further escalated from the shrinkage of intramuscular collagen, followed by a final increment in toughness when the shrinkage and dehydration of the myofibrillar proteins take place (Bailey & Light, 1989).

In oven cooking, surface dehydration prevention and cooking time reduction have been done by coupling the forced air convection method with steam injection in the oven chamber (Murphy, Johnson, Duncan, Clausen, Davis, & March, 2001). Application of air/steam treatments accomplished the exact heat control of a convection oven and the efficiency of steam cooking with the ensuing reduction lessening in cooking time (Chiavaro, Rinaldi, Vittadini, & Barbanti, 2009). Steam induction into the oven chamber during cooking makes heat and mass transfer more complex as it increases the heat transfer and the surface water evaporation process is modified. Generally the oven temperatures higher than 150°C has been used for meat roasting, however lower cooking temperature could reduce energy with beneficial effect for domestic and commercial catering operations. And the induction of steam accelerated the cooking process, increases the overall heat transfer coefficient and reduces the cooking time (Vittadini, Rinaldi, Chiavaro, Barbanti, & Massini, 2005). Murphy et al. (2001) reported that the heat flux is firmly related with the relative humidity of the oven air and results in diverse meat heating profiles.

High cooking temperatures enhance colour and flavour and lessens the cooking times however diminish meat tenderness and juiciness. On the other hand, high relative humidity builds the heat transfer and meat juiciness yet lessening flavour and colour development (Rinaldi, Chiavaro, & Massini, 2010).

Frying

Frying is a cooking technique where fat or oil is utilized as the heat transfer medium, in direct contact with the food (Varela, Mosquera, Bender, & Morton, 1988). Heat is transmitted by contact between the pan and the meat. Frying is complex process due to coupled heat and mass transfer between meat and frying medium. Simultaneous heat and mass transfer of oil and air promote a number of chemical changes, such as moisture loss, oil uptake, crust formation, gelatinization of starch, aromatization, protein denaturation and colour change via maillard reactions, hydrolysis or oxidation, and oil polymerization (Mir-Bel, Oria, & Salvador, 2012).
Energy Efficiency in Meat Processing

Frying temperature is a crucial component to the extent meat flavour, cooking time and weight loss of products. The cooking time is generally short due to the high frying temperature, and the meat surface gets to be brown due to maillard reaction.

**Sous Vide Cooking**

Sous vide is defined as the method of heating raw meat packed inside a vacuum pouch in a water bath at a specified temperature (Vaudagna, Sánchez, Neira, Insani, Picallo, Gallinger, et al., 2002). In sous vide cooking, typical temperatures around 50-85°C are used, thus it requires longer heating times compared to conventional cooking methods. Sous vide cooking differs from traditional cooking methods in two fundamental ways: the raw food is vacuum-sealed in heat-stable, food-grade plastic pouches and the food is cooked using precisely controlled heating. Cooking takes place at a specific temperature is of particular interest for meat, which owe their textural properties mainly to the complex structural arrangement and water binding capacity of muscle proteins. Upon heating, these proteins denature, losing their native conformation and causing a change in the texture of the product. Most relevant to sous-vide cooking is the fact that different proteins, being responsible for different properties of the final product (tenderness, juiciness, etc.), denature at different temperatures. This allows tailoring the properties of the food by selectively denaturing some proteins while leaving others intact.

Sous vide cooking maintained the lower temperature, which minimises the temperature gradient and reduces the damage to heat sensitive proteins and supplements. It also reduces cooking loss and preserves the juiciness (Díaz, Nieto, Garrido, & Bañón, 2008; Vaudagna, et al., 2002). Low temperature in sous vide method has a positive effect on meat tenderness. And the extended cooking time builds collagen solubility (Bejerholm & Aaslyng, 2004a). In sous vide cooking the tenderisation of the connective tissue takes place through the solubilisation of the intramuscular collagen inside the moist in-pack environment (García-Segovia et al., 2007; Holcomb & Kalab, 1981). Sous vide cooking is promoted for its ability to retain nutrients, enhance flavour and texture in a manner that conventional roasting can’t deliver (Mortensen, Frøst, Skibsted, & Risbo, 2012).

**Ohmic Cooking**

Ohmic cooking process is based on passing electric currents through the food causing internal heat generation. It is a promising technique compared to conventional meat cooking as it is considerably fast (Yildiz-Turp, Sengun, Kendirci, & Icier, 2013). It involves the utilization of the electricity to a food material, bringing about volumetric heat generation (Stirling, 1987). The system depends on the entry of electrical current through a food item that has electrical resistance (Icier & Ilicali, 2005). Electrical energy is converted into the heat and the heat generation relies on the voltage gradient and electrical conductivity (Sastry & Li, 1996). And it resulted in efficient rising in internal temperature of food (Wang & Farid, 2015), wherein the electrical energy is converted into heat and caused efficient rising of the interior temperature of the food.

Ohmic cooking in meat products resulted in faster cooking, less power consumption and safer product (Özkan, Ho, & Farid, 2004). Ohmically cooking produces a firmer sample than conventional cooking (Bozkurt & Icier, 2010b). Ohmic heating resulted in cooking loss reduction and improved juiciness (Zell, Lyng, Cronin, & Morgan, 2009). Many researchers showed that ohmic heating could be used as a cooking process for producing safer meat products either alone or in combination with conventional
Energy Efficiency in Meat Processing

cooking methods (Bozkurt & İcier, 2010a, 2010b; İcier, Sengun, Yıldız Turp, & Arserim, 2014; Özkan, Ho, & Farid, 2004; Shirsat, Brunton, Lyng, McKenna, & Scannell, 2004; Zell, Lyng, Cronin, & Morgan, 2009). However, ohmic cooking is an inefficient cooking method for desirable changes in surface colour and texture in meat products (Bozkurt & İcier, 2010a, 2010b; Yıldız-Turp, Sengun, Kendirci, & İcier, 2013). Heterogeneous structure of meat samples affects the uniform heat distribution such as fat in meat product do not generate the heat at same rate as muscle (Shirsat, Lyng, Brunton, & McKenna, 2004). Such difficulties are encountered in applying ohmic treatment to meat and meat products.

In contrast, low temperature cooking can generally maintain high level of the nutritional values of the cooked products and is widely used in the food industry (Becker et al., 2016; Blahovec et al., 2015).

EFFECT OF COOKING METHODS ON QUALITY PARAMETER

Cooking of meat products is essential to achieve a palatable and safe product (İslерoglu, Kemerli, & Kaymak-Ertekin, 2015). Also, it may influence essential qualities identified with consumer’s inclinations, as flavour and tenderness (Pietrasik, Dhanda, Pegg, & Shand, 2005). Cooking methods affects the nutritive values of meat. Generally, heat is applied to meat in different approaches to enhance its hygienic quality by inactivation of pathogenic microorganisms and to enhance its flavour and taste, and increase shelf life (Bognar, 1998; Pokorny, 1999). Meat nutritional values could be modified due to physicochemical reactions during cooking. Cooking instigates water loss in the food, expanding its lipid content, while some fat is lost (García-Arias, Pontes, García-Linares, García-Fernandez, & Sanchez-Muniz, 2003). Cooking reasons structural changes, which diminish the water holding capacity of the meat. Shrinkage on cooking causes the most noteworthy water loss at 60–70 °C and it is assumed that water is removed by the pressure applied by the shrinking connective tissue on the aqueous solution in the extracellular void (Tornberg, 2005).

Water debinding and migration in meat amid cooking are identified with the denaturation and contraction of protein structures created by expanding temperature (Lepetit, 2007; Palka & Daun, 1999; Tornberg, 2005). Tenderness is one of the most important quality attributes of meat

Effect on Cooking Loss

Cooking loss is a combination of liquid and soluble matters lost from the meat during cooking (Aaslyng, Bejerholm, Erbberg, Bertram, & Andersen, 2003; Soyer, Ertaş, & Üzümçüoğlu, 2005). Cooking loss is a critical factor in meat industry as it determines the technological yield of the cooking process (Kondjoyan, Ōillic, Portanguen, & Gros, 2013). From a nutritional perspective, cooking loss brought about loss of soluble proteins, vitamins and different supplements (Yarmand, Nikmaram, Emam Djomeh, & Homayouni, 2013). Cooking loss was calculated as the percent weight difference between fresh and cooked samples with respect to the weight of fresh meat samples (Chiavarro, Rinaldi, Vittadini, & Barbanti, 2009).

The cooking loss begins to develop around 40 °C. In meat with low pH (below 5.4 for pork), cooking loss begins as low as around 30 °C. The rate of cooking loss development is greatest between 50 °C and 70 °C and, after which it falls (Bejerholm & Aaslyng, 2004a). Total cooking losses rely on the temperature and rate of heating (Hearne, Penfield, & Goertz, 1978; Palka & Daun, 1999). Table 3 presented the effect of different cooking methods on meat cooking loss.
### Table 3. Selected publications on cooking loss during meat cooking

<table>
<thead>
<tr>
<th>Produce</th>
<th>Cooking method</th>
<th>Cooking conditions</th>
<th>Cooking loss</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turkey meat</td>
<td>Forced convection (dry air, RH - 8%), and Oven cooking at 100 °C.</td>
<td>32.2%</td>
<td>(Mora, Curti, Vittadini, &amp; Barbanti, 2011)</td>
<td></td>
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<tr>
<td></td>
<td>Low steam (RH- 35%)</td>
<td>15.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High steam (RH - 88%)</td>
<td>22.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goat meat</td>
<td>Vacuum-packed plastic bags and returned to the following internal temperatures</td>
<td>50°C 5.91 ± 2.54</td>
<td>(Liu, Meng, Gao, Li, Luo, &amp; Dai, 2013)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>60°C 8.71 ± 2.95</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>70°C 15.38 ± 4.39</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>80°C 33.08 ± 4.86</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>90°C 41.25 ± 1.73</td>
<td></td>
<td></td>
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<tr>
<td>Foal meat</td>
<td>Roasting</td>
<td>200 °C 12 min 26.71 ± 3.51</td>
<td>(Domínguez, Gómez, Fonseca, &amp; Lorenzo, 2014)</td>
<td></td>
</tr>
<tr>
<td>(internal temperature of 70 °C)</td>
<td>Grilling</td>
<td>150–150 °C / 5 min 22.45 ± 5.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Microwave</td>
<td>1000 W / 1.5 min on each surface 32.49 ± 6.41</td>
<td>(Domínguez, Gómez, Fonseca, &amp; Lorenzo, 2014)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frying</td>
<td>170–180 °C / 4 min on each surface 23.73 ± 2.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beef</td>
<td>Oven cooking</td>
<td>200°C/15 min 31%</td>
<td>(James &amp; Yang, 2012)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sous vide</td>
<td>60°C/60min 19%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HPP</td>
<td>60°C/30min/150MPa 17%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beef</td>
<td>Sous vide</td>
<td>50°C/90min 8.33 ± 1.71</td>
<td>(Vaudagna, et al., 2002)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>50°C/390 min 10.82 ± 1.62</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>65°C/90min 19.41 ± 1.91</td>
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<tr>
<td>Pork loin meat</td>
<td>Water bath</td>
<td>75°C (Cooking temperature) 35.7 ± 0.1</td>
<td>(Li, Sun, Han, &amp; Yu, 2017)</td>
<td></td>
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<tr>
<td></td>
<td>Steam stove</td>
<td></td>
<td>22.4 ± 1.5</td>
<td></td>
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<tr>
<td></td>
<td>Electric steamer</td>
<td></td>
<td>20.6 ± 1.4</td>
<td></td>
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<tr>
<td></td>
<td>Traditional nonvariable frequency microwave oven</td>
<td>28.0 ± 1.1</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Inverter variable frequency microwave oven</td>
<td>21.3 ± 0.3%</td>
<td></td>
<td></td>
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<tr>
<td>Pork loin chop</td>
<td>Pan frying</td>
<td>175°C/75s 11.26 ± 2.19</td>
<td>(Chunbao Li, Hu, Tang, Dong, Teng, Xu, et al., 2012)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>175°C/150s 24.75 ± 3.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muscovy drake meat</td>
<td>Pan frying</td>
<td>180°C/ 5min per side 43.36</td>
<td>(Omojola, Hammad, Amuh-Kotoka, Wogar, Iyanda, &amp; Areemo, 2014)</td>
<td></td>
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<tr>
<td></td>
<td>Deep frying</td>
<td>180°C/ 10 min 52.37</td>
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<tr>
<td></td>
<td>Gas grilling</td>
<td>200°C/ 10 min per side 44.40</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Roasting</td>
<td>200°C/20 min 43.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mutton chops</td>
<td>Grilling (Internal temperature)</td>
<td>51°C 5.5</td>
<td>(Sen, Naveena, Mathukumar, &amp; Vaiithyaniathan, 2014)</td>
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<tr>
<td></td>
<td></td>
<td>65°C 12</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>71°C 16.5</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>79°C 31.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pork</td>
<td>Ohmic heating Water bath</td>
<td>EPTs (60–100 °C) 9.71-30.22 22.53-38.51</td>
<td>(Dai, Zhang, Wang, Liu, Li, &amp; Dai, 2014)</td>
<td></td>
</tr>
<tr>
<td>Whole turkey meat</td>
<td>Ohmic treatment</td>
<td>LTLT (72 °C/15 min) 25.2 31.3</td>
<td>(Zell, Lyon, Cronin, &amp; Morgan, 2010)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ohmic treatment</td>
<td>HTST (95 °C/8 min) 27.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conventional treatment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meatball</td>
<td>Ohmically cooked (Centre temperature)</td>
<td>75 °C 15.57 ± 1.61</td>
<td>(Sengun, Yıldız Turp, Icier, Kendirci, &amp; Kor, 2014)</td>
<td></td>
</tr>
<tr>
<td>Pork ham</td>
<td>Dry air cooking</td>
<td>120°C 22.25</td>
<td>(Cheng, Sun, &amp; Scannell, 2005)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wet air cooking</td>
<td>82°C 12.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water cooking</td>
<td>82°C 9.73</td>
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</tr>
</tbody>
</table>
**Energy Efficiency in Meat Processing**

Physical properties of meat and eating quality have been largely affected by cooking temperature and time (Christensen, Erbjer, Aaslyng, & Christensen, 2011). With increasing internal meat duck breast muscle temperature cooking loss gradually increased (Li, Wang, Dong, Xu, Gao, Zhou, et al., 2013). Many researcher reported the highest cooking loss for microwave cooking method (Domínguez, Gómez, Fonseca, & Lorenzo, 2014; El-Shimi, 1992; Janicki & Appledorf, 1974; Nikmaram, Yarmand, Emamjomeh, & Darehabi, 2011; Yarmand, Nikmaram, Emam Djomeh, & Homayouni, 2013). High electromagnetic field, high power and brief time related in microwaving came about protein denaturation, breaking down of the texture matrix, quick protein destruction brought on by heat shock to the proteins and, at long last, liberalization of a lot of water and fat (Yarmand & Homayouni, 2009). Cooking loss affected shear force values; samples with higher cooking loss percentages also presented the highest shear force values (Lorenzo, Cittadini, Munekata, & Domínguez, 2015).

**Effect on Meat Textural Properties**

Tenderness is one of the most important quality attributes of meat, which is significantly affected by different cooking methods and cooking duration. Consumer satisfaction has been influenced by meat tenderness (Silva, Torres Filho, Cazedey, Fontes, Ramos, & Ramos, 2015) and it is important to meet the meat tenderness that consumers demand. Most meat is eaten cooked, however, and the cooking process is one of the main determinants of tenderness (DeMan, 1976; Juárez, Aldai, López-Campos, Dugan, Uttaro, & Aalhus, 2012). Cooking has a major influence on the meat tenderness as the water- and fat-binding characteristics, and the texture, are closely related to the heating conditions applied (Pietrasik, Dhanda, Pegg, & Shand, 2005). Thermal changes that happen in muscle proteins amid heating and the development of another protein network directly affect product yield, texture, moistness, and general quality (Seideman & Durland, 1984). Thermal tenderness of meat after cooking specifically takes up with the net impact of this tenderisation and toughening, which relies on upon the cooking conditions (Li, et al., 2013).

Tenderness is thought to be the characteristic of eating quality which most impacts consumer acceptability (Boleman, Boleman, Miller, Taylor, Cross, Wheeler, et al., 1997; Delgado, Rubio, Iturbe, Méndez, Cassís, & Rosiles, 2005; Huffman, Miller, Hoover, Wu, Brittin, & Ramsey, 1996). The improvement of tenderness in meats is mainly caused by changes in structure of connective tissues solubilised by heat, while at the same time heat denaturation of myofibrillar proteins generally causes meat toughening (Palka & Daun, 1999). These heat-induced changes are time and temperature dependent, and the net effect of this toughening or tenderization relies on upon cooking conditions (Li, et al., 2013; Obuz, Dikeman, & Loughin, 2003).

Trained panel or physical methods used for meat tenderness determination. Warner–Bratzler shear force (WBSF) test has been widely used to estimate tenderness of raw and cooked meat as a standard mechanical measurement (Combes, Lepetit, Darche, & Lebas, 2004; Girard, Bruce, Basarab, Larsen, & Aalhus, 2012; Lorenzen, Calkins, Green, Miller, Morgan, & Wasser, 2010). The profile indicates either force applied over time or force applied versus the distance that the blade has travelled (Girard, Bruce, Basarab, Larsen, & Aalhus, 2012). However, there is a general lack of consistency or standards to choose and report a set of tenderness values even among researchers on the same type of meat.

James and Yang (2012) compared three cooking methods (conventional oven roasting, sous vide and high pressure processing) for their impact on toughness of bovine M. semitendinosus. The peak shear force of the beef expanded subsequent to cooking as the heat prompted denaturation of the myofibrillar
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and connective tissue proteins (Vaudagna, et al., 2002). Peak shear force was highest for the oven roasted beef (103N), then sous vide cooking (76N) and HPP treated beef was the lowest (54N).

Powell et al. (2000) showed that a slower cooking rate increased tenderness of dry roasted beef semitendinosus. Slower heating rate permits more opportunity for collagen solubilisation, consequently contributing more to meat tenderization than in meat cooked at higher heating rates. However, sous vide cooking shear force mean values decreased at higher temperature as the temperature increased (Vaudagna, et al., 2002).

Slower cooking methods shows the higher meat tenderness. Tenderness of meat should correlate with other quality parameter like colour and cooking loss. Future research should include the energy requirement for different cooking methods for consumer’s preference for meat.

Effect on Meat Colour

Meat colour is one of the critical parameter characterizing the meat quality and influencing consumer’s preference. It is thought to be an indicator of meat freshness and level of meat doneness (Mancini & Hunt, 2005). The HunterLab $L^*$, $a^*$, $b^*$ and the modified CIE system called CIELAB colour scales were opponent-type systems commonly used for colour measurement (Karamucki, Gardzielewska, Rybarczyk, Jakubowska, & Natalczyk-Szymkowska, 2011; Pathare, Opara, & Al-Said, 2013). The parameter $a^*$ takes positive values for reddish colours and negative values for the greenish ones, whereas $b^*$ takes positive values for yellowish colours and negative values for the bluish ones. $L^*$ is an approximate measurement of luminosity (Pathare, Opara, & Al-Said, 2013). Each colour parameter has a certain association with quality attributes, for example, the substance of fundamental compound parts in the meat, pH, and water holding capacity.

It is known that the myoglobin protein is the essential heme pigment accountable for meat colour. Colour estimation in cooked meat can give reliable information about eating quality characteristics (García-Segovia, Andrés-Bello, & Martínez-Monzó, 2007). Many consumers consider the colour of cooked meat as a reliable indicator of safety and doneness. Dull- brown interiors are viewed as a sign of a well-done item, though pink appearance is identified with uncooked meats (King & Whyte, 2006).

Colour opacity rises when the internal meat temperature is between 45 °C and 67 °C due to the denaturing of the meat proteins myosin and actin, which do not add to the red colour, overrides the red colour of myoglobin (Martens, Stabursvik, & Martens, 1982). Tornberg (2005) reported the increase in meat colour opacity at about 35 °C due to the denaturing of myosin. At 40 °C, most of the original myosin molecules have changed to monomers with merged myosin heads. Above 50 °C, myosin molecules are completely coagulated and the meat appears opaque (Tornberg, 2005). Heated samples has more colour brightness than raw samples. In roasted samples because of dark surface, brightness was reduced but more bright colours were found inside of the samples. Generally, the samples subsequent to heating because of pigment oxidization (heme group) become colourless (Nikmaram, Yarmand, Emamjomeh, & Darehabi, 2011). Ground beef colour appearance during cooking has been affected by interconverting system of three types of myoglobin and the debasement of them through oxygenation, oxidation and reduction reactions (Liu & Chen, 2001).

Ohmically cooking produces more homogenous colour inside of the ground beef while the crust layer in the surface of the ground beef could not have been achieved (Bozkurt & Icier, 2010b). There was an increment in hue angle values of cooked samples contrasting with raw sample. In Sous vide cooking, the hunter laboratory parameter $a^*$ was strongly influenced by temperature, diminishing as the treat-
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ment temperature increased (Vaudagna, et al., 2002). In microwaved cooking, major and critical colour changes happen in short time (Nikmaram, Yarmand, Emamjomeh, & Darehabi, 2011).

Liu et al. (2013) reported that with increasing cooking temperature, meat had a tendency to be lighter because of an expanded reflection of light, emerging from light scattering by denatured protein. The redness decreased significantly when cooking temperature increased from 50°C to 80°C and remained at a very low value above 80°C. As myoglobin, the most heat stable sarcoplasmic proteins was totally denatured when meat was cooked to temperature above 80°C. Cooking temperature had influence on meat colour. It is important for consumers to select operating conditions for preferred colour meat.

Colour measurement in cooked meat can provide reliable information about eating quality attributes (García-Segovia et al., 2007). The myoglobin protein is the primary heme pigment responsible for meat colour, with different species contributing to colour changes during the cooking of meat (deoxymyoglobin, oxymyoglobin, sulfmyoglobin, metmyoglobin, etc.). The spectral features in the visible region allow us to explain these changes. During cooking, three forms of myoglobin interconvert and are degraded through oxygenation and oxidation and reduction reactions, ultimately influencing the appearance of meat colour (Liu & Chen, 2001). Visible reflectance spectral intensity variations likely indicate a dynamic conversion and decomposition for a number of myoglobin derivatives. Four bands around 445, 485, 560, and 635 nm are identified as DeoxyMb, MetMb, OxyMb, and sulfmyoglobin (SulfMb) spices, respectively. The colours of these spices are defined as purplish-red for DeoxyMb and cherry-red for OxyMb, while MetMb is brownish-red and finally SulfMb is green in colour (Liu et al., 2003).

Effect on Meat Shrinkage

Shrinkage during cooking often thought to be the poor meat quality indication by consumers. Degree of shrinkage is essential for the consumers as different thermal treatment causes undesirable changes in meat structure and increased shrinkage consider as low quality (Barbera & Tassone, 2006). Meat shrinkage has been determined by calculating the difference between the raw and cooked areas of meat sample. The change of linear dimensions, surface and volume due to cooking has been measured. It can investigate the relationship between meat water and shrinkage and utilized as a part of meat quality examination. Recently meat shrinkage has been measured on archiving the colour image of raw and cooked meat sample (Półtorak, Wyrwisz, Moczkowska, Marcinkowska-Lesiak, Stelmasiak, Rafalska, et al., 2015; Wyrwisz, Półtorak, Poławska, Pierzchała, Jóźwik, Zalewska, et al., 2012). However, manual shrinkage estimation is tedious and variable, as a result of its subjective nature.

According to Tornberg (2005) the shrinkage of meat can be summarized as: (1) the transverse shrinkage of the fibre begins at 35–40 °C, it happens mainly at 40–60°C and it broaden the gap between the fibres and their surrounding endomysium, (2) the shrinkage of the connective tissue begins at 60 °C, and at 60–70 °C the connective tissue network and the muscle fibres cooperatively shrink longitudinally. The application of low temperature and long treatments could minimise the shrinkage effect during thermal processing (Półtorak, et al., 2015). The level of shrinkage augmentations with the addition in temperature and causes large water loss during cooking (Tornberg, 2005)

Effect on Meat Juiciness

Meat juiciness is considered to arise out of moisture discharged by meat amid chewing, and moisture from saliva (Christensen, 1984; Howard, 1976). Moisture loss has the influence on juiciness, which
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can happen by evaporation in dry heat cookery and by exudation and diffusion in moist heat cookery (Hernández, Navarro, & Toldrá, 1999).

Cooking procedure and raw meat quality had the effect on juiciness of meat. However, to date, the only reliable and consistent measure of juiciness is accomplished using sensory methods (Winger and Hagyard 1999). As the complexity of juiciness also causes difficulties in performing objective measurements (Juárez, Aldai, López-Campos, Dugan, Uttaro, & Aalhus, 2012)

The core temperature greatly affects juiciness of meat (Aaslyng, Bejerholm, Erbring, Bertram, & Andersen, 2003). An increase of the centre temperature lessens the juiciness (Bejerholm & Aaslyng, 2004b). Low oven temperature will give a more juicy meat contrasted with meat cooked at a higher oven temperature with the same centre temperature (Bejerholm & Aaslyng, 2004b). In beef cooking, juiciness and cooking loss are negatively correlated, implying that a high cooking loss results in low juiciness (Toscas, Shaw, & Beilken, 1999). Cooking loss has a great influence on the juiciness of meat.

ENERGY REQUIREMENT FOR MEAT COOKING

Cooking is an important part of daily food preparation in commercial and residential settings. Energy requirement for cooking can be prodigious and energy varies with different cooking methods. There are very limited studies in literature focused on the energy consumption for meat cooking. Suwannakam et al. (2014) investigated the energy consumption of the combination of far-infrared and superheated steam with forced air (FIR-SS-FA) system, a combination of far-infrared and superheated steam (FIR-SS) system, and a combination of forced air and superheated steam (FA-SS) system for roasting skinless deboned chicken breast meat. FIR-SS-FA system showed the lowest specific energy consumption (2.54 kWh/kg), which has the shortest cooking time also. The specific energy consumption (SEC) was obtained from the input electrical energy and the quantity of meat samples used:

\[
SEC = \frac{Input \ electrical \ energy \ (kW \cdot h)}{Weight \ of \ sample \ (kg)}
\]

De Halleux et al. (2005) used ohmic heating to cook Bologna ham and found 211 and 252 kJ/kg energy requirement. However, for conventional smoke cooking of Bologna ham required higher energy 1200 and 8100 kJ/kg compared to ohmic heating. (Reichert and Thumel 1986; Singh 1986; Reichert, 1991).

Laycock et al. (2003) used radio frequency cooking (RF) and water bath (WB) cooking for beef cooking. RF cooking is much more energy efficient than water bath cooking of beef cooking. WB cooking showed the low efficiency as it uses large amount of water to cook small amount of meat product and the large heat losses to environment.

Jouquand et al. (2015) compared the microwave cooking with traditional cooking for beef burgundy cooking. Microwave cooking (4.67 kWh) showed lower energy consumption than traditional cooking (6.52 kWh). Cooking time has been reduced by 56% compared to traditional cooking. There are higher energy losses in traditional cooking.
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Payton and Baldwin (1985) compared microwave-convection, forced-air convention and conventional electric oven for beef steak cooking. Microwave-convection oven utilises microwaves as well as forced convection heat. Microwave-convection oven required less cooking time and total cooking energy. Generally, microwaveable food is more energy efficient during cooking stages because the energy heats only the food, not the whole oven compartment. The volume of fluid or mass of food produce affected the microwave cooking energy efficiency. Compared with the conventional cooking, microwave cooking reduces the energy consumption as well as reduces the cooking time (Chang, Xu, Li, Huang, Liu, & Zhou, 2011).

De et al. (2014) developed energy-efficient cooking techniques for goat meat cooking. Pressure cooker contains the meat (1 kg) and water (0.3 litre) has been kept on the stove till the time (ti) upto to hear the first whistle. Immediately pressure cooker removed from the stove and kept in the closed insulated box for 30 minutes for cooking to use the stored heat in the meat. This method reported the considerable fuel energy saving and on stove time (19.25 min) compared to conventional cooking (40.51 min) applied in domestic cooking. Energy efficiency of cooking goat meat with this method is calculated to be 87% compared to 41% with conventional method of using pressure cooker. However the authors did not conducted quality analysis for the cooked meat.

Similarly, Oberascher, Stamminger, and Pakula (2011) demonstrated that there is a negative linear relationship between increasing water volume and the specific energy consumption (or energy per volume of water) to heat water to 90 °C under a variety of conditions (electric kettle, pots, microwave, etc.). Since water-boiling efficiency increases with pan size and volume of fluid, encouraging consumers to cook food in larger volumes, when possible, would reduce the amount of cooking energy required per mass of cooked food (J/kg food).

Other Factor Affecting Energy Consumption

Cooking is globally essential for food safety and decreases the energy utilization amid cooking may affect worldwide energy demands. Residential cooking can require significant amounts of energy—approximately 7 MJ/ kg food product (Dutilh & Kramer, 2000). The factors affecting the energy consumption includes not only cooking process but also the production and transport efficiency of fuel sources, the appliance end use efficiency and consumer behaviour during cooking. The composition, size and shape of the cookware has the impact on energy consumption.

Energy saving behaviours that consumers can perform during cooking includes reduce the length of the period of use, match sizes, volumes and amount of heat to the food for preparation. Selection of an appliance which consumes less energy or a non-energy-consuming device or method also useful for energy saving (Wood & Newborough, 2007). Study in the UK showed that the information on energy saving practices and supplying real time energy consumption meter display could reduce the cooking energy usage up to 20% (Wood & Newborough, 2003).

Cooking is a universal and indispensable process for meat and other fresh product consumption as well as food safety. Thus, implementing policies/practices that lessen energy utilisation amid cooking will significant affect worldwide energy demands. Most of the GHG discharges are identified with home processing, especially to energy use for cooking; which represented between 50% and 70% of overall GHG emissions (Edwards-Jones, Plassmann, York, Hounsome, Jones, & Milà i Canals, 2009). Therefore, more efficient meat cooking methods would achieve reductions in energy use and reduce the carbon footprints of food production.
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Alternative energy source such as biomass, solar may reduce energy uses for meat cooking. The use of wood as cooking fuel (fuel-wood) in order to meet the cooking energy requirement, due to high cost of alternative energy source results in deforestation and adverse environmental effects. Hence, there is the need for more research to develop low cost and environmentally friendly alternatives such biogas cooker and solar cookers, utilizes renewable energy sources that would diminish the dependence on traditional fuels. It could help in conservation of conventional fuels in developing countries and electricity/gas in the developed areas.

In meat cooking, it is important to increase the use of energy from renewable sources, together with energy saving and increased energy efficiency to reduce GHG emissions. Future research should focus on redesigning and improving meat cooking processes. Cooking energy demand should be optimized by improving real time cooking data and benchmarking can identify the opportunities to reduce demand.

CONCLUDING REMARK

The meat production for years has been considered a very energy intensive sector. But, with the advent of novel emergent thermal and non-thermal technologies the meat businesses have now the potential to be energy efficient and at the same time produce safe and quality products. However, application of some of the mentioned technologies needs high infrastructure investments, control of various parameters related to the technology and its legal approvability. These reasons have inhibited its wider acceptability, but it is slowly picking pace and replacing traditional energy intensive processes and practices. In future, due to rising energy prices and environmental regulations, there is tremendous pressure on meat sector to be energy-efficient and less dependent on non-renewable energy sources. And, this can only be achieved through the adoption of novel emergent thermal and non-thermal technologies. Energy efficient technologies can play an important role in ensuring a more resilient meat processing and satisfying consumer demands and needs.

Meat cooking methods play a major role on eating quality attributes. It is important to focus more on evaluating the optimum cooking process for high quality and energy efficient meat cooking. Energy efficiency or energy required for cooking is very important area to emphasis as limited studied focused on energy consumption. It is important to focus the study, which correlate the meat quality and consumer’s preference related to meat cooking.

Renewable/sustainable energy can be used for meat cooking. As energy efficient cooking is not always the consumer’s eating preference. It is important to investigate energy efficient cooking technique to conserve most extreme energy amid cooking and to secure meat quality parameter. In addition, dialogue and education to consumers is needed to reduce energy consumption without compromising the quality meat products.

REFERENCES


Energy Efficiency in Meat Processing


Blahovec, J., Kourim, P., & Kindl, M. (2015). Low temperature carrot cooking supported by pulsed electric field-DMA and DETA thermal analysis. *Food and Bioprocess Technology, 8*(10), 2027–2035.


Energy Efficiency in Meat Processing


FAO. (2012). Meat and health - Meat consumption role of meat in the diets. FAO.


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Chapter 5
Solar Refrigeration for Post–Harvest Storage of Agricultural Products

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ABSTRACT
The main objective of this chapter is the demonstration of the entire development process leading to prototype fabrication and commercialization of a new, ejector-based system for refrigeration that is environmentally clean and is powered by low quality heat, either solar or waste, without any need for electricity. In many rural areas throughout the world, the availability of fresh food is limited by lack of refrigerated warehousing facilities often due to limited access to electrical power. Authors are describing a new, ejector-based refrigeration system that 1) utilizes solar or waste heat (below 100°C temperature) as a main source of energy; 2) eliminates the mechanical compressor, which is a main user of electricity and the main contributor to maintenance and reliability issues in cooling systems; and 3) operates without any ozone depletion effects and any greenhouse gas emissions, when used with natural refrigerants. Such a technique contributes to protection of the ecosystem, conservation of energy, and broad application of alternative energy sources.

FRAMEWORK
The main objective of this chapter is the demonstration of the entire development process leading to prototype fabrication and commercialization of a new, ejector based system for refrigeration, that is environmentally clean and is powered by low quality heat, either solar or waste, without any need for electricity. The value of the chapter is that it presents a systematic way to evaluate the feasibility of the concept through theoretical analysis and CFD modeling and then to validate the theoretical results by the laboratory experiments and finally to design and fabricate a bench model/prototype.

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In many rural areas throughout the world, the availability of fresh food is limited by lack of refrigerated warehousing facilities often due to limited access to electrical power. According to FAO, one-third of food produced in the world or 1.3 billion tons every year goes to waste, and most of it is taking place just after crop harvest, between the field and the market.

Responding to these challenges, authors are describing a new, ejector based refrigeration system that 1) utilizes solar or waste heat (below 100°C temperature) as a main source of energy, 2) eliminates the mechanical compressor, which is a main user of electricity and the main contributor to maintenance and reliability issues in cooling systems and 3) operates without any ozone depletion effects and any greenhouse gas emissions, when used with natural refrigerants. Such a technique contributes to protection of the ecosystem, conservation of energy and broad application of alternative energy sources.

Key innovation is a thermodynamic cycle with an ejector as a technology platform where energy savings comes from pressurizing liquid instead of vapor. The cooling system uses a simple pump to pressurize a liquefied refrigerant, adds solar heat to evaporate it and finally re-compresses the refrigerant using an ejector without any mechanical energy. The system is well adapted for natural and synthetic refrigerants, instead of highly destructive Freons. Besides eliminating the compressor, the fundamental difference between this ejector refrigeration cycle and the conventional one (reverse Rankine cycle) is that it requires total of three heat sources/heat sinks at different temperatures, they are: (i) at the generator level, which is the temperature of the solar-heated source and is in the range 70-100C, (ii) at the condensing level, which is a heat sink at ambient temperature of 25-35C and (iii) at the evaporator temperature, which is approximately 5-10C – temperature well suited for storage of agricultural products, especially fruits and vegetables.

The presented technology addresses the following societal challenge areas as expressed by various international organizations: 1) “Global Food Security and Hunger” – it is a new technology that can effectively boost food production, especially in rural and undeveloped areas, within the USA and around the world. By providing cheaper and easily accessible refrigerated storage, even in areas without access to electricity, this new technology is a better way to protect agricultural production from diseases and pests, and is a considerable step towards better food accessibility to vulnerable populations. 2) “Climate Change”– achieved by reduction in greenhouse gas (GHG) emissions and the ability to operate refrigeration system without any ozone depletion effects. 3) “Food Safety” – it provides better accessibility to refrigeration even under conditions that exist in most rural areas and therefore has the potential to reduce the incidence of food-borne illnesses and death through a safer food supply, and develops improved food processing methods.

A commercial development of this technology required undertaking many scientific challenges not addressed before, such as ejector system operation under variable thermal loads and under various climatic conditions, adjustment to various food products, the effect of ambient temperatures. All past research in the area of ejector refrigeration has been directed towards the simulation, design and geometry of the ejector itself while no one was concerned how the ejector actually operates within a cooling system. The authors describe their own work that had solved the initial problem of ejector design and development of the CFD modeling and methodology for such designs. Then, the modeling was taken one step further by demonstrating experimentally the general concept for heat-driven cooling technology.

The systematic research on the new thermodynamic cycle started with an ejector simulation and entire cycle simulation. First, the effect of various natural refrigerants on cycle efficiency was studied and a more advanced model of a heat-driven ejector refrigeration cycle was developed. While all previous researchers were concentrating on purely theoretical approach to cycle analysis, the authors were
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combining the theoretical analysis with actual laboratory experiments even the most advanced computer modeling is of little practical use unless it is validated by the results of laboratory and/or field tests. There are always a significant number of unknown coefficients and closing equations, which could only be determined experimentally.

It was found that one of most critical factors is the selection of the refrigerant as the system behavior is greatly influenced by its thermodynamic properties. Specifically, two refrigerants provided an optimum compromise between system performance and environmental effects: they were R600a (isobutane - a natural fluid) and R245fa, an HFC fluid. In addition, during this research a new refrigerant R1234ze was introduced that offers even better performance with similar environmental effects. Based on thermodynamic data for three various refrigerants, the authors’ proprietary methodology was then used for calculating the geometry of an ejector for 10kW heat source capacity (approx. 3.5 kW or 1 Ton of refrigeration capacity).

The following step was the CFD modeling with the purpose to analyze the operation of previously designed ejector within the whole range of operation conditions, i.e. source temperature, condensing (ambient temperature) and required cooling temperatures. CFD simulation was also capable to analyze the compression process by a shock wave. Finally, based on CFD data, the main operation characteristics for the ejector, in form of a graph showing compression ratio vs. entrainment ratio was constructed. It was concluded that the proposed ejector geometry is suitable for efficient operation in the analyzed application, i.e. post harvest storage of fruits and vegetables.

As a result of above theoretical and simulation work, the first version of the ejector for isobutane was fabricated and installed on the experimental stand. The stand was equipped with temperature and pressure transducers installed in the critical locations and other locations of interest. The system allows for adjusting refrigerant flow rates as well as for varying thermal parameters. The thermal load system was equipped with electrical heater to simulate the solar/waste heat with the maximum power up to 20kW. As one of major operation parameters, the efficiency of the system at different evaporator loads and different temperatures at the generator was measured. Initially, the temperatures of solar/waste heat source were simulated with hot water system that was especially designed to deliver a broad range of temperatures and flow rates to the test stand. Comparing the CFD modeling with experimental results, it was concluded that the developed methodology can predict with reasonable accuracy the performance of ejectors of various geometries and at different operation conditions. The major results were as follows: 1) sustained cooling operation has been achieved, 2) the system was able to lower the ambient temperature (this is a difference between evaporation temp. and condensing temp) by maximum of 20C (36F) and, 3) depending on temperature levels, the system was capable of producing from 3 to 5kW of refrigeration effect by using 12-16 kW of applied heat. Therefore, it was concluded that the amount of heat required to produce a certain cooling load is reasonable and achievable with either solar or waste heat sources. Indeed, the results showed that in order to produce 1 Ton of refrigeration (12,000 Btu/hr or 3.5 kW) at standard levels of temperatures/cooling loads, it requires 3-5 typical solar panels, which is reasonable. This efficiency is comparable to absorption system but ejector cycle can achieve that at much lower source temperatures. Absorption cycle needs high temperatures at generator level (over100C), which are not achievable with either solar or waste heat sources.

Based on positive results of this research it is anticipated that an entire line of attractive, energy saving products will be developed that significantly reduce or entirely eliminate the electric power needed for cold storage of food products. The described refrigeration technique will have especially broad application for cooling in the field immediately after harvest and before the product is shipped to market.
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or a storage warehouse. Some highly perishable products such as broccoli, ripe tomatoes, carrots, leafy vegetables, strawberries, peaches, and plums must be cooled as soon as possible after harvesting; for these items, field refrigeration is of the utmost importance.

The first application being developed presently concentrates on solar-powered cooling systems for small-to-medium sized warehousing facilities; those capable of cooling and subsequent cold storage of agricultural products that require moderate storage temperatures from 4-15°C. This includes a wide variety of fruits and vegetables, eggs, milk and dairy products, baked products.

It is expected that, when fully developed, the ejector refrigeration technology will eventually bring a number of practical commercial applications, such as solar air-conditioning (A/C) for residential and commercial buildings, automobile A/C powered by the engine exhaust, cooling data centers and computers by utilizing the heat generated by the microprocessor and mobile solar-powered cool storage for food and medicines. The potential also exists for cooling field hospitals and command centers and to provide refrigeration and A/C in Third World countries and in remote areas where electricity is unavailable.

**INTRODUCTION**

One of the crucial problems in retail market of perishable foodstuff is a lack of efficient and appropriate refrigerated storage capacity for short time storage of food products. Existing refrigeration technologies contribute to environment pollution, consume a large amount of electricity and in general are expensive and in many cases even unaffordable to a small rural, retail business. Also, ensuring the required storage conditions in terms of the stability of the product temperature and humidity may be thought as a challenge for most of the existing short time storage refrigerators. The above is the reason for large amount of losses of the perishable foodstuff under retail market conditions, especially in rural areas.

The technology for refrigerated storage presented here may be applied even in areas without access to electricity so it may provide an attractive solution to protect agricultural production from diseases and pests. It maybe considered as a step towards better food accessibility to vulnerable populations as well as to increase shelf life of many food products. It will have especially broad application for cooling in the field before the product is shipped to the market or storage warehouse (this is often referred to as “precooling”). Some highly perishable products such as broccoli, ripe tomatoes, carrots, leafy vegetables, strawberries, peaches, and plums must be cooled as soon as possible after harvesting and therefore filed refrigeration becomes an utmost importance.

The fundamental condition for good storage of most vegetables and fruits is to keep them in a steady state temperature. According to van Hoff law, lowering of vegetables temperature slows down the life activity of stored vegetables and fruits including breathing. Another important factor having impact on quality of vegetables is humidity of air. Only a few percent of vegetable and fruit mass is called dry matter and the rest is water. This is the reason why most of vegetables lose very easily moisture if they are kept in too dry air. Some of the foodstuff requires moderate storage conditions for short time storage in retail market, e.g. temperature/relative humidity +5 to +12°C/85-90% (Gross, Wang & Saltveit, 2002; Mazza, 1989). However, without access to the appropriate storage equipment e.g. cooling chambers, the quality of the food products decreases quickly (Mizera & Butrymowicz, 2011). It is important to note that fresh-cut fruit products for both retail and food service applications have increasingly appeared in the market place recently. In the coming years, it is commonly perceived that the fresh cut fruit industry
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will have unprecedented growth. Table 1 below shows the optimum conditions for short time storage of various produce.

**THE GENERAL CONCEPT OF EJECTION REFRIGERATION SYSTEM**

Authors have considered a solar-powered or waste-heat powered cooling system for small-to-medium size warehousing facilities, capable for cooling and cold storage of agricultural products that require moderate temperature range, i.e. 4÷15 °C (Bergander et al., 2016). This includes a wide variety of fruits and vegetables, eggs, milk and dairy products, baked products, etc. It is expected that a line of refrigeration units will be developed and manufactured in various sizes, i.e. from 1 to 5 tons of refrigeration. The schematic and a corresponding p-h graph for this thermodynamic cycle is shown in Figure 1. The ejection refrigeration system is applied in the solar cooling chamber. The ejection system is a fully thermal driven system therefore either solar or waste heat with temperatures well below 100°C can be utilized as energy source.

### Table 1. The requirements for short-time storage conditions for selected food products

<table>
<thead>
<tr>
<th>Food product</th>
<th>storage conditions temperature/relative humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Southern fruits</strong></td>
<td></td>
</tr>
<tr>
<td>orange</td>
<td>+8 °C / 85÷90%</td>
</tr>
<tr>
<td>green lemon</td>
<td>+10 °C / 85÷90%</td>
</tr>
<tr>
<td>yellow lemon</td>
<td>+5 °C / 85÷90%</td>
</tr>
<tr>
<td>banana</td>
<td>+12 °C / 85÷90%</td>
</tr>
<tr>
<td>melon</td>
<td>+7 °C / 85÷90%</td>
</tr>
<tr>
<td><strong>Other products</strong></td>
<td></td>
</tr>
<tr>
<td>cheese</td>
<td>+12÷15 °C / 90÷95%</td>
</tr>
<tr>
<td>tomato</td>
<td>+12÷17 °C / 80÷90%</td>
</tr>
</tbody>
</table>

**Figure 1. Schematics of the solar cooler (left) and corresponding p-h diagram of thermodynamic cycle**
Solar Refrigeration for Post-Harvest Storage of Agricultural Products

A liquid refrigerant is passed through the pump to the generator (point 8). It is then heated in the generator either by energy from solar panels or waste heat. The first stage of heating produces saturated vapor (point 1), which can be further heated to produce superheated vapor. The vapor enters the motive nozzle of the ejector and undergoes expansion from the generator pressure $p_{g}$, to the evaporation pressure $p_{e}$ (point 2). The ejector sucks vapor flowing from the evaporator (point 7), mixes it with expanded vapor (point 2) with the result being the mixed vapor in state 3. The pressure of the working fluid initially rises slightly as a result of momentum exchange, and then rises more in the diffuser up to the point 4, achieving the condensation pressure $p_{c}$. Compressed vapor enters the condenser where it condenses and may also sub-cool depending on the cooling conditions in the condenser. The working fluid leaves the condenser in the liquid state (point 5). It is then divided into two parts: one part flows to the generator through the small circulating pump. Meanwhile, the remaining part flows through the expansion valve to the evaporator, where it is throttled to the evaporation pressure, $p_{e}$, achieving the condition of wet vapor (point 6). Through boiling in the evaporator, the working fluid absorbs cooling capacity, $Q_{e}$, from the refrigerant (Bergander, 2012, 2015).

Three working fluids have been chosen for the ejector design analysis:

- R-600a, i.e. isobutene (which is the natural fluid);
- R-245fa, which is HFC fluid;
- R-1234ze, which is HFE fluid of low GWP.

In order to investigate theoretically the operation of the ejector, the model of the cycle as well as the model of the ejector operation should be formulated. On the basis of the 0-D model (lumped parameter model), the geometry of the ejector for the above operation parameters was calculated and operation of the ejector was analyzed on the basis of CFD modeling.

The properties of analyzed refrigerants were calculated using the equation of state expressed in a fundamental form of the Helmholtz energy (Lemmon & Spain, 2006; Miyambo & Watanabe, 2002). This is the most widely used approach for calculation of the thermodynamic properties with high accuracy for many fluids.

\[
\phi(\delta, \tau) = \phi^o(\delta, \tau) + \phi^r(\delta, \tau)
\]

where: $\phi = a / RT$, $a$ - free Helmholtz energy, $\phi^o$ ideal gas part, $\phi^r$ residual part of free Helmholtz energy.

The comparison of the basic properties such as specific enthalpy of vaporization, saturation pressure and density ratio leads to the following observations (REFPROP, 2007):

- All three fluids have the same shape of the saturation lines, especially as saturated vapor – this means that both fluids can be treated as “dry” fluids in terms of the operation of the ejector;
- Saturation pressures are lower for R-245fa in comparison with R-600a; and R-600a has lower saturation pressure than R1234ze(E);
- Specific vaporization enthalpy for R-245fa is significantly lower than R-600a and R1234ze(E) has the lowest specific enthalpy of vaporization.
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- Density of liquid R-245fa is significantly higher than R-600a while the vapor phase is lower up to +40 °C; in comparison to R-600a refrigerant R1234ze(E) has lower density of both phases;

REVIEW OF THE STATE-OF-THE-ART IN EJECTOR REFRIGERATION

Current research in new approaches to refrigeration and air-conditioning concentrates on decreasing and/or eliminating adverse environmental effects. by either using environmentally friendly refrigerants, including natural compounds and/or by reducing the amount of refrigerant in the system. Refrigeration systems are the source of two types of pollution: ozone-depletion from chlorofluorocarbon refrigerants and greenhouse gas emissions from the electricity they use. This presents a two-fold challenge; there is an urgent need to replace conventional refrigerants with environment-friendly working fluids as well as to operate these cooling systems with as much renewable and non-polluting energy as possible. Approximately 15% of the world’s electricity consumption is used for refrigeration and air-conditioning applications. It is also important to note that the demand for cooling systems is usually in proportion to the local solar radiation. The utilization of solar energy is a logical way to meet the increasing demand for cooling both in the USA and abroad. Most current research on new and/or different approaches to cooling has been on the absorption cycle. However, this cycle has a low efficiency and requires relatively higher temperatures, usually over 100°C to regenerate the refrigerant. These temperatures are not achievable with either the low-cost flat panel thermal solar collectors or with waste heat.

For the purpose of this study, we selected only the most representative literature listed in the “Bibliography” section. Elbel and Hrnjak (2008) reviews historical developments regarding A/C and refrigeration systems that use ejectors with special emphasis on transcritical CO₂ (R744) cycles. Fischer and Labinov (2000) concludes that to-date ejector systems have low efficiencies but they may be economical when a cheap source of heat is used. Bergander (2012) classifies ejector refrigeration cycles into three (3) categories. The only cycle powered entirely by heat is his Category 3.

The most comprehensive state-of-the-art study for solar cooling is presented by Abdulateef (2009), which lists 53 bibliography sources. He admits that, although many worldwide research groups have performed theoretical calculations, computer simulations and even some experimental work, to-date no commercial solar-powered cooling system has been designed. Hwang (1998) has proposed a solar ejector cooling system using R141b that operates on a generator temperature of 95°C, and an evaporator temperature of 8°C. Several simulation models and experimental studies are found in the literature, for example (Bergander, 2005, 2008). Cizungu, Mani and Groll (2001) studied systems with more environmentally friendly refrigerants such as R123 or R134a and ammonia. Park (2007) compares a few natural refrigerants with R22 in conventional A/C systems. However, the only researcher that mentions the possibility for using natural refrigerants in solar-driven systems is Pridasawas and Lundqvist (2009). He conducts a theoretical analysis for isobutane and concludes that it has the potential to perform well in ejector systems because its small vapor volume does not require large ejector dimensions. On the other hand, the only center in the world that undertook any experimental work on ejector behavior with isobutane is the Polish Academy of Sciences in Gdansk, Poland (Bergander et al., 2016). It was concluded that the optimum generating temperature is in 80-100°C range, which can be easily achieved using standard flat-panel solar collectors. Summarizing the state-of-the-art of ejector-based solar coolers, one can conclude as follows:
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1. Only one commercial ejector system operating on natural refrigerant R744 is reported (Denso Corp). It is, however, a conventional VCC with a mechanical compressor (Takeuchi, 2009),
2. Solar cooling with ejectors has been researched by a few other organizations and centers but only to the extent of theoretical analysis and modeling,
3. Only two sources have mentioned using natural refrigerants for solar cooling (Bergander et al., 2016; Pridasawas & Lundqvist, 2006),
4. There is a very limited knowledge worldwide of heat-driven ejector refrigeration and this is probably the main reason that such systems have not been developed commercially.

ANALYSIS OF OPERATION OF EJECTION REFRIGERATION SYSTEM

The analysis of the efficiency of the ejection refrigeration system operating with considered refrigerants is presented in this chapter. The exemplary theoretical ejection cycle in isobutane system is presented in Figure 2.

In order to better understand the calculated efficiencies of the cycle, the calculations included additionally other fluids, considered as optional for ejection systems. The following assumptions were made in the analysis:

- Superheating of the primary fluid (motive vapor): $\Delta T_g = 5K$ for isobutane, R-245fa and R-123 (i.e. the so-called “dry fluids”); and $\Delta T_g = 50K$ for ammonia, propane and R-134a (i.e. the so-called “wet fluids”);1

Figure 2. Pressure-enthalpy diagram for described system operating with isobutane (R-600a)
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- The secondary vapor is at saturated state;
- Isentropic overall efficiency of the ejector: \( \eta = 0.70 \); 
- Evaporation temperature: \( t_e = 10 ^{\circ} \text{C} \);
- Condensation temperature: \( t_c = 35 ^{\circ} \text{C} \);
- Saturation temperature in the generator: \( t_g = 130 ^{\circ} \text{C} \).

For given operating pressures: \( p_g \), \( p_c \) and \( p_e \) with above assumptions, conditions of the fluid at the motive nozzle inlet and the suction chamber were calculated. The energy balance equation for the ejector has a form (Butrymowicz et al., 2007):

\[
\dot{m}_s h_1 + \dot{m}_e h_i = (\dot{m}_g + \dot{m}_d) h_i
\]

(2)

With nozzle efficiency \( \eta_n \) the velocity at the nozzle outlet can be calculated:

\[
w_2 = \sqrt{2 \cdot (h_1 - h_2)} = \sqrt{2 \cdot \eta_n (h_1 - h_2)}.
\]

(3)

Similarly, with the assumed diffuser efficiency the velocity at the ejector outlet is described by following equation:

\[
w_4 = \sqrt{2 \cdot (h_4 - h_3)} = \sqrt{2 \cdot \frac{1}{\eta_d} (h_4 - h_3)}
\]

(4)

Using momentum balance equation:

\[
\dot{m}_s w_2 + \dot{m}_e w_i = (\dot{m}_g + \dot{m}_d) w_i
\]

(5)

the entrainment ratio can be calculated assuming that the velocity at the suction chamber \( w_j \) may be neglected:

\[
U = \frac{\dot{m}_e}{\dot{m}_s} = \frac{w_2}{w_i} - 1
\]

(6)

Defining velocity as the difference of enthalpy the entrainment ratio has the form:

\[
U = \frac{h_1 - h_3}{h_4 - h_3} - 1 = \sqrt{\eta_e \eta_d \cdot \frac{h_1 - h_2}{h_4 - h_3}} - 1
\]

(7)
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Figure 3. Compression process in the ejector 3-4 in p-h diagram

where: \( \eta_n \eta_d = \eta \). The classic approach based on the assumption that the isobars are parallel in pressure-enthalpy diagram as shown in Figure 3. More details concerning the modeling approach applied in the calculations above can be found in (Bergander, 2012, Butrymoqicz et al., 2007; Smierciew et al., 2010).

The coefficient of performance of the system is found from (Bergander et al., 2016):

\[
COP = \frac{\dot{Q}_c}{\dot{Q}_s} = \frac{\dot{m}_c}{\dot{m}_s} \cdot \frac{(h_7 - h_3)}{(h_1 - h_5)} = \eta \cdot \frac{(h_7 - h_3)}{(h_1 - h_5)}
\]  

(8)

The calculation results for selected working fluids are given in Table 2 and presented graphically in Figures 4, 5 and 6. Note that the selected fluids cover both synthetic fluids (R-245fa, R-123, and R-134a) as well as natural fluids (ammonia, isobutane, propane). Also, the selection covers both “dry fluids” (isobutane, R-123, and R-245fa) and “wet fluids” (propane, ammonia, and R-134a). Further, R-123 is HCFC fluid and its application in new systems is prohibited in US, EU, and many other countries. There are no specific legislation measures concerning usage restrictions for the rest of the considered fluids, except for the European recommendation of emission reduction of HFC fluids in EC Regulation No. 517/2014 on certain fluorinated greenhouse gases (F-Gases).

It appears that isobutane and refrigerant R-245fa offers the same cycle efficiency in the wide range of the operation parameters and they both can be considered as best options, offering the same efficiencies as well as mass entrainment ratio. Of course, due to differences in properties, the geometry of the ejector will be different for both considered fluids.
Isobutane being a natural fluid, may be preferred although it is flammable. However, due to extremely low charge of the system with fluid there is a minimum danger, as well proven in domestic refrigerators, operating with this fluid in the entire EU. In the case of refrigerant R-245fa, this is HFC fluid, which is considered as GHG (Greenhouse Gas). There is a possibility of more restrictive legislation measures to prevent emission and reduce the application of such fluid (e.g. see the European recommendation of emission reduction of HFC fluids in EC Regulation No. 517/2014 on certain fluorinated greenhouse gases (F-Gases). The above was the reason for looking for another low GWP fluid that could be suitable for application in ejection refrigeration systems. As shown above in Para. 2, refrigerant R-1234ze may be thought as an alternative synthetic fluid, comparable to isobutene in terms of the operation conditions as well as attainable capacity of the system.

**Table 2.** Selected operation parameters of ejection refrigeration cycle for various refrigerants. The operations parameters are: $t_g = 130^\circ C$; $t_c = 35^\circ C$; $t_e = 10^\circ C$; $\eta = 0.70$; $\Delta t_g = 5K$ for: isobutane, R-245fa, and R-123; $\Delta t_g = 50 K$ for: R-134a, ammonia, and propane

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$h_1$</th>
<th>$h_{js}$</th>
<th>$h_s$</th>
<th>$h_{js}=h_s$</th>
<th>$h_b$</th>
<th>$p_v$</th>
<th>$v_1'$</th>
<th>$v_2'$</th>
<th>$v_{v_1'}/v_{v_2'}$</th>
<th>$U$</th>
<th>COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isobutane</td>
<td>709.5</td>
<td>603.8</td>
<td>567.8</td>
<td>271.3</td>
<td>276.1</td>
<td>4.65</td>
<td>8.3E-2</td>
<td>44.9</td>
<td>0.54</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>R-245fa</td>
<td>494.6</td>
<td>433.0</td>
<td>411/79</td>
<td>239.1</td>
<td>240.56</td>
<td>2.12</td>
<td>8.3E-2</td>
<td>109.1</td>
<td>0.55</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>R-123</td>
<td>456.8</td>
<td>400.6</td>
<td>387.5</td>
<td>230.3</td>
<td>231.1</td>
<td>130.5</td>
<td>6.9E-4</td>
<td>1.2E-1</td>
<td>175.1</td>
<td>0.58</td>
<td>0.40</td>
</tr>
<tr>
<td>R-134a</td>
<td>498.5</td>
<td>449.9</td>
<td>404.3</td>
<td>241.7</td>
<td>243.2</td>
<td>887.0</td>
<td>8.6E-4</td>
<td>2.3E-2</td>
<td>26.9</td>
<td>0.31</td>
<td>0.20</td>
</tr>
<tr>
<td>Ammonia</td>
<td>1813.0</td>
<td>1547.4</td>
<td>1615.3</td>
<td>495.0</td>
<td>489.6</td>
<td>1351.0</td>
<td>1.7E-3</td>
<td>9.6E-2</td>
<td>56.2</td>
<td>0.37</td>
<td>0.32</td>
</tr>
<tr>
<td>Propane</td>
<td>776.3</td>
<td>681.0</td>
<td>585.7</td>
<td>278.8</td>
<td>282.7</td>
<td>1217.9</td>
<td>2.1E-3</td>
<td>3.8E-2</td>
<td>17.9</td>
<td>0.32</td>
<td>0.20</td>
</tr>
</tbody>
</table>

**Figure 4.** Coefficient of performance as a function of temperature of vapor generator for various working fluids. The operations parameters are given in Table 4.1; $t_g = var$
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Figure 5. Coefficient of performance as a function of evaporation temperature. The operations parameters are given in Table 4.1; \( t_e = \text{var} \)

Figure 6. Coefficient of performance for various temperature of condensation. The operations parameters are given in Table 4.1; \( t_c = \text{var} \)
CALCULATING THE GEOMETRY OF AN EJECTOR

Basic Calculations

The required operating parameters for the ejection system were given in Para. 2 above. It is possible to calculate the general parameters describing the required capacity of the ejector in terms of:

1. Mass entrainment ratio:

\[ U = \frac{\dot{m}_h}{\dot{m}_s} \]  \hspace{1cm} (9)

2. Compression ratio:

\[ \Pi = \frac{p_c - p_e}{p_g - p_e} \]  \hspace{1cm} (10)

where: \( p_c \) is condensing pressure, \( p_e \) is evaporating pressure, \( p_g \) is generator pressure. In the calculations below, the saturation temperature in the evaporator was assumed \( t_e = +5 \, ^\circ C \), so the outlet vapor temperature from the evaporator was assumed as \( t_{eo} = t_e + \Delta T_e = +8 \, ^\circ C \). The following operation conditions were selected for prediction of preliminary geometry of ejector:

- Motive heat flux \( Q_g = 10 \, kW \);
- Temperature of motive vapor at saturation condition: \( t_g = 95 \, ^\circ C \);
- Superheating of the vapor pressure \( \Delta T_g = 5 \, K \);
- Temperature of evaporation at saturation condition: \( t_e = 5 \, ^\circ C \) with \( \Delta T_e = 2 \, K \) of superheating of the vapor;
- Condensation temperature \( t_c = 40 \, ^\circ C \).

Note that the assumed motive heat flux corresponds to the required surface area of the solar collectors approx. 10 m². It was assumed that the liquid of refrigerant at the inlet to the vapor generator is equal to condensation temperature, i.e. \( t_{gli} = 40 \, ^\circ C \), for R600a:

\[ \dot{m}_{g,R600a} = \frac{\dot{Q}_g}{q_g} = \frac{\dot{Q}_g}{\Delta h_g} = \frac{10}{686-297} = 0.025 \, kg/s = 91 \, kg/h \]

\[ \Pi_{R600a} = \frac{p_c - p_e}{p_g - p_e} = \frac{0.531 - 0.186}{1.808 - 0.186} = 0.213 \]
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for R1234ze(E):

\[ \dot{m}_{g,R1234ze(E)} = \frac{\dot{Q}_g}{q_g} = \frac{\dot{Q}_g}{\Delta h_g} = \frac{10}{235 - 47} = 0.053 \text{ kg/s} = 186 \text{ kg/h} \]

\[ \Pi_{R1234ze(E)} = \frac{p_c - p_e}{p_g - p_e} = \frac{0.766 - 0.259}{2.74 - 0.259} = 0.205 \]

for R245fa:

\[ \dot{m}_{g,R245fa} = \frac{\dot{Q}_g}{q_g} = \frac{\dot{Q}_g}{\Delta h_g} = \frac{10}{477.7 - 252.8} = 0.044 \text{ kg/s} = 160 \text{ kg/h} \]

\[ \Pi_{R245fa} = \frac{p_c - p_e}{p_g - p_e} = \frac{0.25 - 0.066}{1.13 - 0.066} = 0.173 \]

where \( Q_g \) is in kW, \( h \) in kJ/kg and \( p \) is in MPa.

From Eq. (7) and Figure 3, the theoretical mass entrainment ratio for assumed operation pressure can be calculated as:

\[ U_{t,R600a} = \frac{h_c - h_{2s}}{h_x - h_{2s}} - 1 = 0.395 \]

\[ U_{t,R1234ze(E)} = \frac{h_1 - h_{2s}}{h_x - h_{2s}} - 1 = 0.40 \]

\[ U_{t,R245fa} = \frac{h_1 - h_{2s}}{h_x - h_{2s}} - 1 = 0.41 \]

where \( h_x = h(s_1,p_1) \) and \( h_j \equiv h_{2s} \). Now, with assumption of loss coefficient \( K=0.6 \), the entrainment ratio can be predicted:

\[ U_{R600a} = K \cdot \frac{h_1 - h_{2s}}{h_x - h_{2s}} - 1 = 0.6 \cdot 0.395 = 0.237 \]
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\[
U_{R1234ze(E)} = K \cdot \sqrt[\kappa]{h_1 - h_2} - 1 = 0.6 \cdot 0.40 = 0.24
\]

\[
U_{R245fa} = K \cdot \sqrt[\kappa]{h_1 - h_2} - 1 = 06 \cdot 0.41 = 0.246
\]

The entrainment ratio \(U_{R600a} = 0.237, U_{R1234ze(E)} = 0.24\) and \(U_{R245fa} = 0.246\) can be considered as acceptable and achievable for gas ejector operating with motive temperatures higher than 80°C.

**Motive Nozzle Geometry**

The critical pressure in the motive nozzle throat may be calculated from (Miyamoto & Watanabe, 2002):

\[
p_{cr} = p_g \cdot \beta
\]

where critical pressure ratio \(\beta\) is equal to:

\[
\beta = \left( \frac{2}{\kappa + 1} \right)^{\kappa - 1}
\]

Therefore the critical temperature and density at the nozzle throat may be calculated as a function of the critical parameters: \(t_{cr} = f(p_{cr}, s_{cr}), \rho_{cr} = f(p_{cr}, t_{cr})\). The critical velocity \(w_{cr}\) at the throat may be calculated from formula:

\[
w_{cr} = \sqrt{2 \cdot \left( \frac{\kappa}{\kappa - 1} \right) \cdot p_g \cdot \rho_1^{-1} \cdot \left( 1 - \beta^{-\kappa} \right)}
\]

Based on required motive vapor mass flow rate it is possible to calculate the nozzle throat diameter:

\[
d_{cr} = \sqrt[\kappa]{\frac{4 \cdot \dot{m}_g}{\pi \cdot w_{cr} \rho_{cr}}}
\]

Based on the classic assumption that the outlet pressure from the motive nozzle is equal to the evaporation pressure: \(p_2 = p_e\).
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Since the secondary vapor expands during the suction process below the evaporation pressure, there is expansion process out of the motive nozzle. The diameter of the outlet of the motive nozzle can be calculated from the formula:

\[ d_2 = \sqrt[4]{\frac{8 \dot{m}_s}{\pi w_2 \rho_2}} \]  

(15)

where \( \rho_2 \) is the density of vapor at the nozzle outlet, and \( w_2 \) the velocity at the nozzle outlet. The outlet velocity is calculated as follows:

\[ w_2 = \sqrt{2\eta_n (h_1 - h_{2s})} \]  

(16)

where \( \eta_n \) is the efficiency of the nozzle. It was assumed that \( \eta_n = 0.98 \) (Lemmon & Span, 2006). The density of vapor at the nozzle outlet is calculated from the equation of state: \( \rho_2 = f(p_2, h_2) \), and the specific enthalpy of vapor \( h_2 \) is calculated from equation:

\[ h_2 = h_1 - \eta_n (h_1 - h_{2s}) \]  

(17)

Assuming the nozzle divergence \( \delta_n = 10^\circ \) it is possible to calculate the length of divergent part of the motive nozzle:

\[ l_n = \frac{d_2 - d_{es}}{2 \cdot tg \left( \frac{\delta_n}{2} \right)} \]  

(18)

Mixing Chamber Geometry

The geometry of the mixing chamber was predicted on the basis of existing theoretical models (Smierciew et al., 2010; Sokolov & Zinger, 1989; Huang et al., 1999). For the required mass entrainment ratio it is impossible to directly predict appropriate mixing chamber geometry which makes possible achieving compression ratio \( \Pi = 0.50 \). Therefore the motive jet parameters along with geometry are known, the required cross-section area for the secondary vapor may be calculated assuming on-design operation of the ejector\(^2\). The details concerning this procedure are given in Smierciew et al. (2010). Therefore this approach makes possible to define the diameter of the mixing chamber for on-design operation of the ejector, i.e. with the maximum entrainment up to critical back-pressure. The length of the mixing chamber was estimated on the basis of the existing analyses of the optimum length (Smierciew et al., 2010; Colarossi et al., 2012; Sokolov & Zinger, 1989). In analyzed particular case this length was estimated as:

\[ L_m = 10 \cdot d_m \]  

(19)
Diffuser Geometry

There is no exact lumped parameter model for prediction of the outlet diameter of the diffuser. Therefore usually this problem is analyzed by means of CFD analysis. On the basis of own experience (Smierciew et al., 2010; Butrymowicz et al., 2008; Butrymowicz et al., 2009; Smierciew et al., 2009; Colarossi et al., 2012; Smierciew et al., 2010; Butrymowicz et al., 2011) it could be assumed that:

$$A_{df} = 9 \cdot A_m \quad (20)$$

Assuming also the diffuse divergence $\delta_d = 8^\circ$ it is possible to calculate the length of the diffuser:

$$l_n = \frac{d_f - d_m}{2 \cdot \tan \left( \frac{\delta_d}{2} \right)} \quad (21)$$

Geometries of Ejectors

Results of calculations of the ejector geometries for analyzed fluids and operating parameters are presented in Table 3. The geometry of the ejector for R1234ze(E) is almost identical as for R600a, the only difference is in nozzle diameters.

Operation Parameters of Ejectors of Predicted Geometries

The above predicted geometries of the ejectors have to be preliminary verified by means of the lumped parameter model in order to estimate whether required operation parameters may be achieved. Therefore the numerical code was developed in MathCad system to calculate the performance of the ejector on the basis of the predicted geometry, inlet parameters and efficiencies of the expansion inside the motive nozzle and outside of the motive nozzle, expansion of the secondary flow, momentum transfer in the mixing chamber, and compression in the diffuser. The shock wave was calculated on the basis of numerical solution of equations of Rayleigh and Fanno. The details of the model are given in Butrymowicz et al. (2009). Thermodynamic properties of the fluids were calculated using CoolProp code for MathCad. The results of the calculations are presented in Table 4.

On the basis of the results presented above, it was concluded that:

- The application of refrigerant R-1234ze requires similar ejector dimensions in comparison of the geometry predicted for isobutane. Therefore this refrigerant may be thought as an alternative for isobutane for safety reasons.
- The achievable condensation temperatures are higher for isobutane than for refrigerant R-245fa. This is a strong advantage of isobutane. The similar conclusion may be also drawn for the refrigerant R-1234ze.
Table 3. Essential geometry parameters of the ejectors

<table>
<thead>
<tr>
<th></th>
<th>R600a</th>
<th>Q_g = 10 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ejector 1</td>
<td></td>
</tr>
<tr>
<td>motive nozzle throat diameter</td>
<td>d_c = 2.4 mm</td>
<td></td>
</tr>
<tr>
<td>motive nozzle outlet diameter</td>
<td>d_2 = 4.2 mm</td>
<td></td>
</tr>
<tr>
<td>motive nozzle length of the divergent part</td>
<td>l_n = 10 mm</td>
<td></td>
</tr>
<tr>
<td>mixing chamber diameter</td>
<td>d_3 = 5.7 mm</td>
<td></td>
</tr>
<tr>
<td>mixing chamber length</td>
<td>l_3 = 57 mm</td>
<td></td>
</tr>
<tr>
<td>diffuser outlet diameter</td>
<td>d_d = 17.1 mm</td>
<td></td>
</tr>
<tr>
<td>diffuser length</td>
<td>l_d = 82 mm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>R1234ze(E)</th>
<th>Q_g = 10 kW</th>
</tr>
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<tbody>
<tr>
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<td>Ejector 2</td>
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<td>motive nozzle throat diameter</td>
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<td></td>
</tr>
<tr>
<td>motive nozzle length of the divergent part</td>
<td>l_n = 10 mm</td>
<td></td>
</tr>
<tr>
<td>mixing chamber diameter</td>
<td>d_3 = 5.7 mm</td>
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<tr>
<td>mixing chamber length</td>
<td>l_3 = 57 mm</td>
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<tr>
<td>diffuser outlet diameter</td>
<td>d_d = 17 mm</td>
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<td>l_d = 82 mm</td>
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<table>
<thead>
<tr>
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<tbody>
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<td></td>
</tr>
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<td>d_c = 3.4 mm</td>
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<td>d_2 = 7.4 mm</td>
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</tr>
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<td>motive nozzle length of the divergent part</td>
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<td></td>
</tr>
<tr>
<td>mixing chamber diameter</td>
<td>d_3 = 10.3 mm</td>
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<td>mixing chamber length</td>
<td>l_3 = 103 mm</td>
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<td>diffuser outlet diameter</td>
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</tr>
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</table>

**TEST STAND AND EXPERIMENTAL RESULTS**

The schematic of an experimental rig presented in Figure 7 was designed to operate on isobutane (Butrymowicz et al., 2009). The main elements of the stand are listed in the figure caption. The geometry of the tested ejector is presented in Figure 8. The motive nozzle throat diameter was D_c = 3.5 mm. Other important factors of ejector geometry are: D_c/D_f = 1.71, L_n/L_f = 23.4, L_3/L_m = 0.84, α_1 = 8° and α_2 = 10°. The testing stand was equipped with the temperature sensors and pressure transducers installed at all locations of interest. The Coriolis mass flow meters with accuracy of 0.15% were used.

Sight-glasses were installed at various locations to observe the flow. The test rig was equipped with two additional loops: the first one for the thermal load for the evaporator and another for the condenser cooling. These systems allow for adjusting refrigerant flow rates as well as for changing of operation.
### Table 4. Performance of ejectors with geometries as shown in Table 3

<table>
<thead>
<tr>
<th>Ejector 1</th>
<th>Ejector 2</th>
<th>Ejector 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-600a</td>
<td>R-1234ze(Z)</td>
<td>R-245fa</td>
</tr>
<tr>
<td>Assumed $Q$</td>
<td>$Q = 10$ kW</td>
<td>$Q = 10$ kW</td>
</tr>
<tr>
<td>$m_0$ [kg/h]</td>
<td>$m_0$ [kg/h]</td>
<td>$m_0$ [kg/h]</td>
</tr>
<tr>
<td>91</td>
<td>186</td>
<td>166</td>
</tr>
<tr>
<td>$m_e$ [kg/h]</td>
<td>$m_e$ [kg/h]</td>
<td>$m_e$ [kg/h]</td>
</tr>
<tr>
<td>20.8</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>predicted $U$ - eq. (3.6)</td>
<td>predicted $U$ - eq. (3.6)</td>
<td>predicted $U$ - eq. (3.6)</td>
</tr>
<tr>
<td>0.237</td>
<td>0.240</td>
<td>0.246</td>
</tr>
<tr>
<td>predicted II</td>
<td>predicted II</td>
<td>predicted II</td>
</tr>
<tr>
<td>0.228</td>
<td>0.210</td>
<td>0.235</td>
</tr>
<tr>
<td>required II - eq. (4.2)</td>
<td>required II - eq. (4.2)</td>
<td>required II - eq. (4.2)</td>
</tr>
<tr>
<td>0.213</td>
<td>0.205</td>
<td>0.213</td>
</tr>
<tr>
<td>predicted $p_r$ [bar]</td>
<td>predicted $p_r$ [bar]</td>
<td>predicted $p_r$ [bar]</td>
</tr>
<tr>
<td>5.47</td>
<td>7.80</td>
<td>2.62</td>
</tr>
<tr>
<td>predicted $t_{p_r}$ [°C]</td>
<td>predicted $t_{p_r}$ [°C]</td>
<td>predicted $t_{p_r}$ [°C]</td>
</tr>
<tr>
<td>41.1</td>
<td>40.6</td>
<td>41.4</td>
</tr>
<tr>
<td>predicted $Q_r$ [kW]</td>
<td>predicted $Q_r$ [kW]</td>
<td>predicted $Q_r$ [kW]</td>
</tr>
<tr>
<td>9.85</td>
<td>9.73</td>
<td>10.36</td>
</tr>
<tr>
<td>predicted $Q_e$ [kW]</td>
<td>predicted $Q_e$ [kW]</td>
<td>predicted $Q_e$ [kW]</td>
</tr>
<tr>
<td>1.55</td>
<td>1.43</td>
<td>1.7</td>
</tr>
<tr>
<td>predicted $Q_c$ [kW]</td>
<td>predicted $Q_c$ [kW]</td>
<td>predicted $Q_c$ [kW]</td>
</tr>
<tr>
<td>11.40</td>
<td>11.16</td>
<td>12.06</td>
</tr>
<tr>
<td>Predicted COP</td>
<td>Predicted COP</td>
<td>Predicted COP</td>
</tr>
<tr>
<td>0.157</td>
<td>0.148</td>
<td>0.164</td>
</tr>
</tbody>
</table>
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Figure 7. Schematic diagram of testing stand: 1 – vapor generator, 2 – evaporator, 3 – secondary fluid mass flowmeter, 4 – primary fluid mass flowmeter, 5 – condenser, 6 – liquid refrigerant storage, 7 – glycol pump, 8 – refrigerant pump, 9 – glycol mass flowmeter, 10 – throttling valve, 11 – ejector, 12 – electrical heater

parameters in wide range. The condenser cooling system was equipped with an automatically controlled dry cooler. The thermal load system was equipped with automatically controlled electrical heater. The stand is also equipped with control valves enabling the adjustment of the operating parameters of the motive vapor at the inlet to the motive nozzle of the ejector. Standard data acquisition facility was used based on commercially available systems. The first one was a real time, Compact FieldPoint system, designed for industrial control. The second was modular SCXI system. This system logs all main parameters and controls valves, pumps, electric heaters and safety system. The computer uses a LabVIEW version 8.6.1 software with additional toolkits. In addition, software dedicated to experimental stand is capable to receive on-line data from software REFPROP, (Lemmon & Span, 2006; REFPROP, 2007).
The real time measurements are shown on the computer screen while all measured data are stored in a data file. During the experiments 100 readings at the steady-state conditions were taken and averaged to make one experimental run, shown in Table 5.

The experimental investigation were conducted in tworuns. The evaporation temperature was kept constant, $t_{eI} = 9.1 \, ^{\circ}\text{C}$ and $t_{eII} = 7.0 \, ^{\circ}\text{C}$. The condensation temperature was varied between approximately $t_{c} = 23 \div 33 \, ^{\circ}\text{C}$. The motive stream temperature at saturation condition was set as $t_{gI} = 77 \, ^{\circ}\text{C}$ and $t_{gII} = 63.7 \, ^{\circ}\text{C}$ for two runs, respectively.

Superheating of the secondary stream was $\Delta T_e = 6.5 \, \text{K}$ for Run No. 1, and $\Delta T_e = 5.9 \, \text{K}$ for Run No. 2. Superheating of the motive vapor was $\Delta T_g = 10 \, \text{K}$ for Run No. 1, and $\Delta T_g = 8 \, \text{K}$ for Run No. 2. The system efficiency COP is calculated as the ratio of the cooling capacity $\dot{Q}_c$ to the thermal energy $\dot{Q}_g$ delivered to the vapor generator and motive power of the mechanical liquid pump $P_p$:

$$COP = \frac{\dot{Q}_c}{\dot{Q}_g + P_p} \quad (22)$$

Motive power of liquid refrigerant pump is calculated as the product of the mass flow rate of refrigerant and the change of the specific enthalpy at the both sides of the pump:

$$P_p = \dot{m}_g (h_g - h_s) \quad (23)$$

In general, the motive power of the refrigerant pump is in most cases very small, usually 1÷2 percent of the thermal energy delivered to the generator and therefore can be omitted. Nevertheless this power was included in present investigations.

Experimental results for both runs are presented in Figure 9 to Figure 12. Entrainment ratio $U$ is defined as motive to secondary mass flow rates ratio, and compression ratio $\Pi$ is defined as ratio of the pressure lift produced by the ejector to the difference between motive pressure and suction pressure.

Figure 9 shows COP of the system as a function of condensation temperature for Run No. 1. It can be observed that up to $t_c = 28 \, ^{\circ}\text{C}$, the COP is constant and equal to 0.075 then begins to decrease for higher condensation temperatures. Similarly the mass entrainment ratio ($U$) shown also in Figure 4 starts

<table>
<thead>
<tr>
<th>Runs</th>
<th>Unit</th>
<th>Run 1</th>
<th>Run2</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure of motive vapor $p_g$</td>
<td>MPa</td>
<td>1.27</td>
<td>0.95</td>
</tr>
<tr>
<td>superheating of motive vapor $\Delta T_g$</td>
<td>K</td>
<td>10.0</td>
<td>8.0</td>
</tr>
<tr>
<td>saturation temperature of motive vapor $t_{gs}$</td>
<td>°C</td>
<td>77.0</td>
<td>63.7</td>
</tr>
<tr>
<td>suction pressure $p_s$</td>
<td>MPa</td>
<td>0.21</td>
<td>0.20</td>
</tr>
<tr>
<td>superheating of suction vapor $\Delta T_s$</td>
<td>K</td>
<td>6.5</td>
<td>5.9</td>
</tr>
<tr>
<td>saturation temperature of evaporation $t_{es}$</td>
<td>°C</td>
<td>9.1</td>
<td>7.0</td>
</tr>
<tr>
<td>Backpressure $p_b$</td>
<td>MPa</td>
<td>Variable (0.35 – 0.44)</td>
<td>Variable (0.33 – 0.43)</td>
</tr>
<tr>
<td>saturation temperature of condensation $t_{cs}$</td>
<td>°C</td>
<td>Variable (25.1 – 33.1)</td>
<td>Variable (22.8 – 32.0)</td>
</tr>
</tbody>
</table>
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Figure 9. Coefficient of performance and mass entrainment ratio ($U$) vs. condensation temperature for Run No. 1

![Figure 9](image)

Figure 10. Performance line of the ejector $\Pi = f(U)$ for Run No. 1

![Figure 10](image)

Figure 11. Coefficient of performance (COP) and mass entrainment ratio ($U$) versus condensation temperature for Run No. 2

![Figure 11](image)
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Figure 12. Performance line of the ejector $\Pi = f(U)$ for Run No. 2

The COP of the system as a function of condensation temperature shows that at $t_c < 30$ °C, ejector operates at on-design mode and COP is constant at 0.15 then starts to decrease as condensation temperature rises above 30°C. For on-design operating regime, the mass entrainment ratio is at 0.19 and starts to decrease for condensation temperatures over 30°C. This relationship is illustrated in Figure 11. The performance line of the system in co-ordinates: compression ratio $\Pi$ vs. mass entrainment ratio $U$ is presented in Figure 12. It is seen that Run No. 2 covers both on-design and off-design conditions. The maximum reported compression ratio is $\Pi = 0.30$ and corresponds to $U = 0.15$.

NUMERICAL MODELING OF MOTIVE EJECTOR

Considering the general goal being experimental verification of the stable operation of the ejector under required operation conditions, the manufacturing of an ejector prototype with required accuracy is essential. For that purpose, special fabrication technology (Kapayeva et al., 2017; Usubamatov et al., 2015) to assure high accuracy and close tolerances was used. In addition, the main goal in this stage of research was the evaluation of the design procedure rather than estimation of the maximum capacity of the ejector. This required CFD calculations for one proposed geometry in order to analyze the operation of the ejector in the whole range of the operation parameters (Smierciew et al., 2009). The compression process by the shock wave should be also analyzed on the basis of the numerical calculations results along with predicted pressure profile produced inside the ejector. The ejector geometry as shown in Figure 8 was analyzed by means of CFD modeling.

The numerical calculations were carried out with use of ANSYS FLUENT 14. Two numerical models were built, namely:
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- 2D axi-symmetric model shown in Figure 13 that was discretized by means of structural mesh with the density 46 612 cells (48 931 nodes);
- 3D model (Fig. 14), discretized by means of structural mesh with the density 42 714 cells (50 800 nodes).

The numerical calculations were carried out using SST turbulence model that belongs to family of $k-\omega$ as well as $k-\varepsilon$ realizable models (Dvorak & Vit, 2005; Furlong et al., 2010). The standardized wall function was applied for the case of $k-\varepsilon$ model along with default model constants for both of the above models. The velocity and pressure distributions were calculated with application of coupled algorithm. The discretization scheme second order of the type upwind were chosen. Numerical calculations were

Figure 13. Calculation mesh for the case of the axi-symmetric 2D model of the ejector

Figure 14. Calculation mesh for the case of 3D model of the ejector
carried out for the operating conditions corresponding to the experimental values – specifically the ejector being is powered (motived) with superheated vapor at the average temperature of 60°C.

Calculations results obtained for the case of the axi-symmetric model are presented in Table 6 below while Tables 7 and 8 show the results obtained for 3D model. As seen, the reasonably good agreement between the prediction and experimental data is achieved in terms of the pressure distribution. However, for 3D model, a numerical prediction of mass entrainment ratio is less accurate and this requires further analysis. Note that the accuracy of the mass entrainment prediction is affected also by the measurement error.

The static pressure distributions along the length of the ejector for two analyzed cases of 3D model are presented in Figures 15 and 16 below. The location of the shock wave compression is clearly visible. Note that the compression in the diffuser may be thought as only a supplementary since vapor compress-

---

**Table 6. Numerical predictions compared with experimental data for 2D axi-symmetric model**

<table>
<thead>
<tr>
<th>$t_g$[°C]</th>
<th>$p_g$[MPa]</th>
<th>$t_e$[°C]</th>
<th>$p_e$[MPa]</th>
<th>$m_{exp}$[kg/s]</th>
<th>$m_{CFD}$[kg/s]</th>
<th>$m_{exp}$[kg/s]</th>
<th>$m_{CFD}$[kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.4</td>
<td>0.689</td>
<td>8.60</td>
<td>0.175</td>
<td>0.020</td>
<td>0.0231</td>
<td>0.001963</td>
<td>0.00198</td>
</tr>
<tr>
<td>60.9</td>
<td>0.736</td>
<td>10.0</td>
<td>0.176</td>
<td>0.021</td>
<td>0.022</td>
<td>0.004395</td>
<td>0.004378</td>
</tr>
</tbody>
</table>

**Table 7. Numerical predictions compared with experimental data for 3D model, Run No. 1**

<table>
<thead>
<tr>
<th>$p_{exp}$</th>
<th>$p_{CFD}$ (total/static)</th>
<th>$p_{exp}$</th>
<th>$p_{CFD}$ (total/static)</th>
<th>$p_{exp}$</th>
<th>$p_{CFD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar</td>
<td>Bar</td>
<td>Bar</td>
<td>Bar</td>
<td>Bar</td>
<td>Bar</td>
</tr>
<tr>
<td>$t_g$[°C]</td>
<td>$t_e$[°C]</td>
<td>$t_c$[°C]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>72.1</td>
<td>12.78</td>
<td>53.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{exp}$ [kg/s]</td>
<td>$m_{CFD}$ [kg/s]</td>
<td>$CFD - EXP - EXP \cdot 100%$</td>
<td>$m_{exp}$ [kg/s]</td>
<td>$m_{CFD}$ [kg/s]</td>
<td>$CFD - EXP - EXP \cdot 100%$</td>
</tr>
<tr>
<td>0.027</td>
<td>0.0252</td>
<td>6.707</td>
<td>0.005162</td>
<td>0.0065</td>
<td>-27.7</td>
</tr>
</tbody>
</table>

**Table 8. Numerical predictions compared with experimental data for 3D model, Run No. 2**

<table>
<thead>
<tr>
<th>$p_{exp}$</th>
<th>$p_{CFD}$ (total/static)</th>
<th>$p_{exp}$</th>
<th>$p_{CFD}$ (total/static)</th>
<th>$p_{exp}$</th>
<th>$p_{CFD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar</td>
<td>Bar</td>
<td>Bar</td>
<td>Bar</td>
<td>Bar</td>
<td>Bar</td>
</tr>
<tr>
<td>$t_g$[°C]</td>
<td>$t_e$[°C]</td>
<td>$t_c$[°C]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75.53</td>
<td>12.44</td>
<td>53.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{exp}$ [kg/s]</td>
<td>$m_{CFD}$ [kg/s]</td>
<td>$CFD - EXP - EXP \cdot 100%$</td>
<td>$m_{exp}$ [kg/s]</td>
<td>$m_{CFD}$ [kg/s]</td>
<td>$CFD - EXP - EXP \cdot 100%$</td>
</tr>
<tr>
<td>0.0269</td>
<td>0.0262</td>
<td>2.3175</td>
<td>0.0052</td>
<td>0.0067</td>
<td>-29.3642</td>
</tr>
</tbody>
</table>
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...sion in the analyzed ejector is obtained mainly by a shock wave. For all CFD calculations, the properties of real vapor were applied according to NIST thermodynamic and thermo-kinetic properties models.

PRELIMINARY DESIGN OF SOLAR-DRIVEN COLD STORAGE CHAMBER

As a result of previous cycle modeling (Smierciew et al., 2009), along with presented here CFD analysis of the ejector operation - confirming a reliable ejector operation over wide range of operating conditions - plus systematic experimental investigations, authors were able to perform a preliminary design and component selection for the ejection refrigeration unit. The configuration of the prototype is shown in Figure 17 below. The required surface area of thermal solar collectors for 3 kW of cooling power is approx. 10 m². The adequate amount of electric power to drive the liquid pump can be supplied by less than 1 m² of photovoltaic panel surface.

CONCLUSION

The described research addresses a refrigeration concept that uses low quality heat (below 100°C), either solar or waste as energy source without need for electricity from power grid and does not pollute the environment. A significant energy saving is realized by a modified thermodynamic cycle that pressurizes a liquid instead of vapor. Extensive laboratory tests and CFD modeling were conducted in order to provide the design background for effective cooling system prototype for post-harvest preclooling and field storage of fruits and vegetables. There is also a great potential of using this technology for refrigeration and air-conditioning in the Third World countries and in remote areas where electric energy is

Figure 15. Static pressure distribution on the ejector wall for the test Run No. 1 (see Table 6)
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Figure 16. Static pressure distribution on the ejector wall for the test Run No. 2 (see Table 7)

![Static pressure distribution graph](image)

Figure 17. Configuration of solar cooling system prototype

![Solar cooling system diagram](image)
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unavailable. Small solar-based units can be developed for storage of medicines, perishable food, and to cool field clinics.

Significant progress has been achieved in developing a methodology to design ejector geometry capable to adjust the cooling system to varying load conditions. The three-dimensional CFD modeling followed by extensive laboratory experiments had clearly demonstrated a reliable ejector operation under a broad range of changing load and power input. Further, out of many refrigerants under consideration, it was found that isobutane provides highest efficiency and, being a natural substance does not pollute the environment. With technical feasibility being fully confirmed, it can be reasonably expected that an attractive commercial product will emerge.

ACKNOWLEDGMENT

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DISCLAIMER

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REFERENCES


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ENDNOTES

1. The fluid is called as „dry” when the ejector operates with superheated vapor only under condition of no superheating at the generator outlet; the fluid is called as “wet” if at least part of the processes in the ejector occur in wet vapor region under the same generator condition.

2. The ejector operates under on-design conditions when both motive flow and the secondary flow are chocked.
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APPENDIX

Nomenclature

\[ p \] – pressure [bar],
\[ t \] – temperature [°C],
\[ Q \] – heat capacity [W]
\[ h \] – enthalpy [kJ/kg]
\[ w \] – velocity [m/s]
\[ m \] - mass flow rate [kg/s]
\[ \Delta T \] - superheated of fluid [K]
\[ U \] – mass entrainment ratio
\[ d \] – diameter [mm]
\[ A \] - area [m²]
\[ l \] – length [mm]

Greek Symbols

\[ \rho \] – density [kg/m³]
\[ \Pi \] – compression ratio
\[ \eta \] – isentropic efficiency

Subscripts

\[ g \] – generator
\[ e \] – evaporator
\[ c \] – condenser
\[ m \] – mixing chamber
\[ d \] – difuser
\[ n \] – nozzle
\[ cr \] - critical
\[ s \] – isentropic
\[ 1,2,… \] - state of refrigerant at the essential points

Superscripts

\[ ' \] – saturated liquid conditions
\[ '' \] - saturated vapor conditions
Chapter 6

Thermal Technologies and Systems for Food Preservation

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Anna University, India

Imran Hussain Showkath Ali
Anna University, India

ABSTRACT

Thermal technologies for food preservation prevent the degradation of desired properties of the perishable food items for a longer duration to fulfill the needs of the consumers in the aspects of nutrition, safety, and price. Each freezing method has its distinct characteristics on quality of frozen food products. The major physical and chemical changes observed during the freezing process were freezer burns, recrystallization, protein denaturation, color, flavor, release of enzymes, etc. These will be detailed with appropriate examples. The comparative analysis of the aforementioned thermal technologies based on the quality of food products will be discussed with the recommendations for the selection of appropriate thermal technologies. It will guide the practicing engineers and researchers to understand the drawbacks of conventional thermal technologies and how they affect food qualities along with the advancements made to overcome the drawbacks.

INTRODUCTION

Increasing demand for the packaged food products without degrading the fresh taste and nutritional content has become the important concern among the consumers in this competitive environment. The shift in time between the production and utilization of food products reduces its freshness, color and nutritional content, organoleptic desirability. Nowadays, consumers are more aware of common food-borne diseases in the packaged food products due to their exposure to various food technologies introduced by food corporations in the world. The competition among companies in the food industry
for the intensively populated countries has led to introduction various popular dishes from all around
the world had created a requisite for the efficient food processing and preservation. Food preservation
means preventing the degradation of desired properties of the perishable food items for a longer duration
to fulfil the needs of the consumers in the aspect of nutritional, safety, and price. The progress in thermal
and non thermal technologies by the researchers has become the promising approach for ensuring the
food with nutritionally well with completely eliminated food borne diseases. During past few decades,
most of the industrial food preservation syndicates rely on thermal technologies for reducing the growth
of microorganisms inactivating enzymes. There is various thermal food preservation like heating, cool-
ing, drying to prolong shell life enhance palatability; reduce pathogens in the food by maintaining the
economic climatic conditions of the food products. The degree of microbial growth in the perishable
food items depends on temperature (Aste, 2017; Amit, 2017). This assurance committed and fulfilled
by these technologies establishes the safe food industries. The spoilage of the food products can be
postponed by the preserving it in the optimum storage temperature.

This chapter provides the brief description about the categories of the thermal technologies involved
in the food preservation and their effects of various technologies over food products. This chapter would
help the end user to select the appropriate thermal systems along with their degree of achievable food
quality for different food products in the food preservation sectors. It will guide the practicing engineers
and researchers to understand the drawbacks of conventional thermal technologies and how it’s affect-
ing the food qualities along with the advancements made to overcome the drawbacks in the emerging
technologies.

**OBJECTIVES OF THERMAL PRESERVATION**

The goal of food preservation by thermal technologies is to slow down the growth of microorganisms
along with reduction of enzymatic action in the food products by applying external thermal load. Even
though thermal food preservation techniques prevent the spoilage of food products but also have an
adverse effect on the texture leading to wastage of food products. Several microorganisms could cause
detrimental changes in the food products. The main objectives of thermal preservation techniques are to
obtain the suitable temperature of the food products to stop the detrimental changes like microbiological,
physical, physiological and biochemical within the optimal limit in the food products (Ganguly, 2013;
Seetaramaiah, 2011; Leistner, 2000).

**EFFECT OF TEMPERATURE ON THE DETRIMENTAL CHANGES**

**Microbiological Changes**

The growth of microorganism in the food products increases the decaying of the food products. The
growth of microorganisms in the food products depends directly on temperature. Whenever the food
products are exposed to certain environmental conditions, the microbial number shows no longer increase
in microbial activity is known as lag phase. The microorganisms grow exponentially during certain pe-
riod is known as generation time. Each pathogenhas optimal temperature at which the microbial growth
no longer exists. The minimum growth temperature is found to be the optimal temperature at which the
lag phase and generation time became infinitely long. Few of the pathogens reportedly known to cause various intestinal infections are listed in the Table 1 along with the minimum growth temperature (Wills, 2016; James, 2000; Chattopadhay, 2014).

**Physical Changes**

The most important loss affecting the physical appearances of the meat are drip loss. Its starts after slaughtering of the meat followed by the denaturation. Denaturation of the meat is commonly known as the drip loss. It also reduces the soluble nutrients and forms unattractive appearances of the meat results in decrement of economic value of the food products. The drip loss increases with the increase in the temperature of the food. Rapid chilling reduces the drip loss in meat and pork by half for reducing the temperature from 14 ºC to 5 ºC in 10 hrs. While in slow freezing of meat causes rupture in the meat fibers causes excessive water loss and reduced juiciness in the meat. Faster the freezing of the food results in the formation of small ice crystals which tends to reduce drip loss depending on the presence of protein and carbohydrate content in the meat (Brennan, 2006; Fischer, 2007).

**Physiological and Biochemical Changes**

Temperature plays a predominant role in increasing the economic value to the perishable fruits. During maturization of the fruits, it under goes aerobic respiration process. The exponential change in the respiration rate of the fruits during ripening is known as respiratory climacteric. Fruits like apple, mango, plum, olive, tomato etc., undergoes respiratory climacteric process. Internal ethylene concentration in the fruits causes ripening of the food products. Higher temperature promotes ripening of the food faster than the lower temperature due to increase in the internal ethylene concentration in the fruits. For example, in guava fruit, during ripening stage, the color of the guava fruit changes from green to yellow due the chlorophyll degrading enzymes like peroxidase, chlorophyllase tends to reduces the economic value of the fruits during off session period (Abreu, 2012; Deepthi, 2017; Pavasi, 2005).

**CATEGORIES OF THERMAL TECHNOLOGIES**

The heat treatment of the food products is categorized based on the temperatures in which the process is operated (Rahman, 2007). It is categorized into two types,

1. Pasteurization
2. Freezing

**Pasteurization**

Pasteurization is one of the most reliable method of food preservation for long term storing of fluidized food products like milk and bottled fruit juices to eliminate the food spoilage by both enzymes and microorganisms. It is also known as the mild heat treatment to kill high sensitive microorganisms without degrading the nutritional properties of the food products. The pH of the food products is used to determine the effect of heat treatment process. Mostly acidic carbonated fruit juices at the pH of < 4.5
Table 1. Optimal growth temperature of various species

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Species</th>
<th>Minimum growth temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pink yeast</td>
<td>-34</td>
</tr>
<tr>
<td>2</td>
<td>Unspecified molds</td>
<td>-12</td>
</tr>
<tr>
<td>3</td>
<td>Campylobacter spp.</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>Vibeio spp.</td>
<td>-5</td>
</tr>
<tr>
<td>5</td>
<td>Clostridium perfringens</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>Yersinia enterocolitica</td>
<td>-2</td>
</tr>
<tr>
<td>7</td>
<td>Clostridium botulinum</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>Unspecified coliforms</td>
<td>-2</td>
</tr>
<tr>
<td>9</td>
<td>Brochothrix thermosphacta</td>
<td>-0.8</td>
</tr>
<tr>
<td>10</td>
<td>Aeromonas hydrophila</td>
<td>-0.5</td>
</tr>
<tr>
<td>11</td>
<td>Staphylococcus aureus</td>
<td>7</td>
</tr>
<tr>
<td>12</td>
<td>Pathogenic Escherichia</td>
<td>7</td>
</tr>
<tr>
<td>13</td>
<td>Entrococcus spp.</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>Leuconostoc carnosum</td>
<td>1.0</td>
</tr>
<tr>
<td>15</td>
<td>Grifidam</td>
<td>1.0</td>
</tr>
<tr>
<td>16</td>
<td>Escherichia coli O157:H7</td>
<td>6.7</td>
</tr>
<tr>
<td>17</td>
<td>Salmonella spp.</td>
<td>5</td>
</tr>
<tr>
<td>18</td>
<td>Bacillus cereus</td>
<td>5</td>
</tr>
<tr>
<td>19</td>
<td>Listeria monocytogenes</td>
<td>1.0</td>
</tr>
<tr>
<td>20</td>
<td>Leuconostoc sp.</td>
<td>2.0</td>
</tr>
<tr>
<td>21</td>
<td>L. sakelcurvatus</td>
<td>2.0</td>
</tr>
<tr>
<td>22</td>
<td>Clostridium botulinum</td>
<td>3</td>
</tr>
<tr>
<td>23</td>
<td>Clostridium botulinum B, E, F</td>
<td>3.3</td>
</tr>
<tr>
<td>24</td>
<td>Pantoea agglomerans</td>
<td>4.0</td>
</tr>
<tr>
<td>25</td>
<td>Salmonella panama</td>
<td>4.0</td>
</tr>
<tr>
<td>26</td>
<td>Aeromonas hydrophila</td>
<td>-0.1 to 1.2</td>
</tr>
<tr>
<td>27</td>
<td>Serratia liquefaciens</td>
<td>4.0</td>
</tr>
<tr>
<td>28</td>
<td>Vibrio parahaemolyticus</td>
<td>5.0</td>
</tr>
<tr>
<td>29</td>
<td>Listeria monocytogenes</td>
<td>-1 to 0</td>
</tr>
<tr>
<td>30</td>
<td>Yersinia enterocolitica</td>
<td>-2</td>
</tr>
<tr>
<td>31</td>
<td>Salmonella Heidelberg</td>
<td>5.3</td>
</tr>
<tr>
<td>32</td>
<td>Pedobacter sp.</td>
<td>6.0</td>
</tr>
<tr>
<td>33</td>
<td>Lactobacillus brevis</td>
<td>6.0</td>
</tr>
<tr>
<td>34</td>
<td>L. viridescens</td>
<td>6.0</td>
</tr>
<tr>
<td>35</td>
<td>Salmonella typhimurium</td>
<td>6.2</td>
</tr>
<tr>
<td>36</td>
<td>Staphylococcus aureus</td>
<td>6.7</td>
</tr>
<tr>
<td>37</td>
<td>Klebsiella pneumonia</td>
<td>7.0</td>
</tr>
<tr>
<td>38</td>
<td>Bacillus spp.</td>
<td>7.0</td>
</tr>
<tr>
<td>39</td>
<td>Salmonella spp.</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Source: (Wills, 2016; James, 2000; Chattopadhay, 2014)
are pasteurized at 60 to 65 ºC to kill the yeast and molds. While, in case of non-carbonated fruit juices at pH > 4.5 are pasteurized at 80 ºC for clear pasteurization. Based on the technologies applicable for the pasteurization of food products are classified in accordance to packed and unpacked food products (Frazier, 1992; Panchal, 2017; Sarkar, 2015). Severe pasteurization of the apple juice to destroy Alicyclobacillus acidoterrestris spores has caused 35% reduction in the inhibiting capacity of apple juice (Alongi 2018). Pasteurization of the packed food products like beer, fruit juices, milk wines are treated with the thermal technologies like water bath and steam pasteurization.

Pasteurization of the unpacked food products like wines, dairy products and fruits are treated with vat pasteurization technology, heat exchanger pasteurization technology, high temperature short time pasteurization technology, flash pasteurization technology, and ultra-high pasteurization technology (Rahman, 2007).

**Water Bath Pasteurization**

Water bath pasteurization is the method of heating and cooling the acidic food products like milk, hard cider, beer, juice etc. The water bath pasteurizer consists of the heating section, cooling section, water circulation system with PLC control unit. The bottled or packed food products mounted in the conveyor belt which carry them across the heating section for particular pasteurizing period and then into cooling section for effect pasteurization of the food products. Research work carried out on pasteurization of the milk in water bath pasteurizer for inactivation of mycobacterium paratuberculosis found that the longer holding time of 25 sec at 72 ºC effectively inactivates mycobacterium paratuberculosis present in the milk than using 90 ºC for pasteurization (Grant, 2002). Where as in steam pasteurizers it consists of moving cabinets housed with the steam pipes and chiller unit. Once the meat carcases enter the cabinet, the doors of the cabinets are closed. The steam generated and stored in the pressure vessel is opened and allowed to fill the cabinet. The steam present in the cabinet treats the side walls of the meat carcases for 6 to 8 sec. After the sterilization process, the meat enters the cooling section where the meat carcases are cooled down with the help of 4 ºC water for 10 sec. This improves the shelf life of the products for longer storage duration along with increase the antibiotic-resistant pathogenic E. coli in the meat carcases and without degrading the nutritional and palatability. Bath pasteurization of milk products to study the bacillus spore’s activation for various processing temperatures. It is concluded that the growth of bacillus spores at 74 ºC is significantly higher than that the other processing temperatures and causes sweet curdling of fluid milk (Phebus, 1997; Nutsch, 1996). The schematic representation along with the water bath pasteurizer for pasteurizing the tempeh cake are shown in the Figure 1 (Pfaff, 1996).

**Vat or Batch Pasteurization**

Vat pasteurization is one of the important method of preserving unpacked food products with the pH greater than 4.5, where high temperature is required for inactivation of enzymes. The vat pasteurization method pasteurizes products like milk, sour cream, egg nog, frozen dessert mixers, etc. The vat pasteurization method consists of the vat for storing the food products with the heating coil at the outer liners of the inner surface of the vat. The heating coils are powered by the hot water and steam so that, it can maintain the food products at the pasteurization temperature for longer duration provided with the mechanical stirrer for continuous agitation during the processing. Than the pasteurized food products will be allowed to flow through the cooling sections. Hence it is a batch pasteurization technique, increasing
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Figure 1. Schematic diagram of water bath pasteurizer (Pfaff, 1996)

Figure 2. Schematic and process diagram of vat pasteurizer (Goff, 2013)

the number of vats might increase the flow of the flow products. It requires high level of attention for the food preservation to eliminate over loading, burning, churning due to irregular agitation. Continuous flow of food products is not possible with the vat because of expensive automation systems. Beet root juice pasteurized with thermal batch pasteurization for 720 seconds at 96 ºC reduces the flavor, Betacyanin and Betaxanthin content along with the complete inactivation of micro flora in the juice (Kathiravan, 2014). The colostrum immunoglobulin concentration is reduced upto 23% after on farm commercial pasteurization (Godden, 2003). The on farm batch pasteurization of the waste milk pasteurized at 65 ºC for 30 min provides the incubation period of 28 weeks with no viable mycobacterium paratuberculosis (Stabel, 2001). Inadequate space limits, the use of batch pasteurization for continuous flow of unpacked food items leading to the formation of heat exchanger pasteurization method. The schematics of vat pasteurizers are shown in the Figure 2 (Goff, 2013).
Plate Heat Exchanger Pasteurization

Plate heat exchanger pasteurization is introduced into the market to provide the uninterrupted flow of food products as experienced in the open boiling pan vat pasteurization method. The plate type heat exchangers consist of the series of both side grooved plates connected with the help of metal frames. Each plates are separated from one another with the help of rubber gaskets. The products to be pasteurized flows at one side of the plates. The heat transfer fluid flows through the other side of the plates. Plate type heat exchangers are compact and flexible to increase the capacity of the plant. The cleaning and sterilizing process of the plate heat exchangers are ease after every batch comparatively with the batch pasteurization process. The commercially available plate heat exchanger pasteurizers can pasteurize up to 80,000 liters per hour in a compact area comparatively with the batch and continuous pasteurization process. The initial and operating cost of the plant are low owing to less labor cost and automation required only for regulating the flow and providing heat regeneration in heat transfer fluids. In case of high viscous fluids like dairy products, tomato ketchup, mayonnaise etc., the concentric coil heat exchangers are preferred owing to the high pumping power (Holanowski, 2018). The schematics of plate heat exchanger for milk processing are shown in Figure 3. The plate heat exchanger pasteurization unit pasteurizes the milk by passing the milk into the plate heat exchanger where the milk exchanges heat with the heat transfer fluid. In order to increase the holding time in the plate he exchanger, the values are provided. The plate heat exchanger is capable to be extended by adding number of plates.

Source: Holanowski, 2018
Flask or High Temperature-Short Time Pasteurization

Flash pasteurization is the same as that of the heat exchanger type of pasteurization with additional equipment like deaerator, regenerative heating and cooling systems with control units for temperature and flow control systems. It uses direct steam for heating the food products in the heat exchangers. It is also known as the continuous pasteurization process but found to be more expensive than other pasteurization processes. The study on milk pasteurization by microwave flash pasteurization method at 100 °C for 0.01 sec has reduced the thiobarbituric acid (TBA) and fatty acid content in the milk. The flash pasteurizers rapidly rising the temperature of the products just above the pasteurization temperature and seal it in the air tight containers. The whole system is maintained at positive pressure in order to eliminate the entry of oxygen into the food products like fresh fruit juices like tomato, pine apple etc. The deaerator is a special equipment coupled with the flash pasteurizer to remove the oxygen from the fruit juices before packing it in the containers. It is highly preferred in cases like high flavor without degrading the nutritional content of the food products (Aguiar, 2014). The schematics of HTST pasteurization system for donor milk in human milk bank setting are shown in Figure 4 (Escuder-Vieco, 2018).

Ultra High Temperature Pasteurization

The ultra high temperature pasteurization method is utilized for the emergency situations where the refrigeration systems are not available but it is more similar as that of high temperature short time pasteurization method. It can operate up to 137 °C for a short duration of 2 to 3 sec. It is mainly used to destroy the heat resistance spore forming bacteria like B. licheniformis and B. subtilis and Geobacillus stearothermophilus. These type of processing help us to store the milk in room temperature for longer duration up to 12 months (Campbell; Datta, 2002). The schematic diagram of the ultra high temperature pasteurization system for processing the milk are shown in the Figure 5 (Bylund, 1995). The UHT pasteurization techniques preheats the supplied products to the certain temperature followed by pressurization to about 4 to 6 bar to eliminate the boiling of the product during further heating of the product. After post heating, the product is flash cooled in the vacuum chamber where the flash vapor equalizes the amount of steam previously injected during post heating process.

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Freezing Food Preservation Techniques

Freezing food preservation technique is one of the ancient methods of food preservation for storing long term basis. It is also the least time consuming method of food preservation but require high initial cost. Freezing food preservation technique does not kill the spoilage organism in the food products but it reduces the microbial growth with minimal changes the color, texture and flavor. It also slows down the enzymatic activity in the food products leading to reduction in the fast changing of maturization of the food products. So the enzymatic activities are to be stopped before freezing by using blanching or using chemical components. The change in the texture of the food products were also been observed during freezing is due to crystallization of the water content. So, most of the high water containing food products like celery and salad greens are not preferred for freezing. Temperature is one of the most important governing parameter in the spoilage of food products. Increase in the temperature of the food products quickly degrades the food. Slow freezing of food products provides the sufficient time for dripping of water from the food causing damages to the cell wall due to osmotic pressure. Increase in the solute concentration owing to the drip loss from the food products kills the polymeric cells (Li, 2018; Evans, 2016). The major methods in freezing food preservation techniques are categorized based on the contact medium utilized by the freezing technologies. Based on the contact medium used, it is divided into three types. They are solid, liquid and gases medium based freezing techniques (Rahman, 2007).

Solid Medium Based Freezing Techniques

Solid medium based freezing food preservation techniques works with the plate type food freezers. Plate type freezers are used only for the regular shaped food items. Plate type freezers utilizes series of parallel flat powered by hydraulic press mounted either vertically or horizontally. The series of flat plates are coupled with the refrigerating circuit for freezing the food products. The food products processed here are of meat, fish, chopped products, vegetables etc. The hot air defrost systems are attached with the flat plates to defrost the frozen ice after the freezing process. Based on the vertical and horizontal arrangements of the flat plates in the freezers it is classified in to vertical plate freezers and horizontal flat plate freezers (Hui, 2004; Johnston, 1994). In horizontal flat plate freezers, the flat plates are arranged in the shelves. The packaged fish products of homogeneous regular shapes are processed here. The hot gas defrosters are used after every freezing process to maintain the performance of the horizontal flat plate freezers because of the formation of the ice crystals over the flat plates reduces the surface contact between the flat plate and the products. The products with irregular shapes also affect the performance of freezing process. Contact area plays a major role in the performance of the horizontal plate freezers. The pictorial representation of horizontal plate freezers is shown in Figure 6 (Jiang, 2004). In the vertical plate freezers, the flat plates form the bin where the fishes are loaded directly from the top without wrapping. The loaded fishes are frozen completely and formed into cubical blocks after the defrost process completes. In absence of the defrost process, high load is required to separate the frozen food cubical from the flat plates could cause damage to the food products (McGowan, 2012).

Liquid Medium Based Freezing Techniques

The food products freezed by this method use refrigerated liquid capable to remove more heat per unit volume of the products than the air type freezing technique. The refrigerated liquid will be in direct
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contact with the food products. The refrigerated liquid used in this methods are liquid carbon dioxide, liquid nitrogen, brine solution. In the liquid nitrogen freezing technique, the fish products freezed by this method travel in the conveyor belt into the tunnel. The vapor nitrogen formed during the freezing of food products used for precooling of the food. After precooling process, the liquid nitrogen is sprayed over the food products to cool the food products to -50 °C. It is also called as spray type of liquid medium freezing process. It is found to be the most compact type of food preservation techniques than the air blast type of food preservation technique. The size of the system is small and no refrigeration systems are required but the system requires the vacuum chamber for processing the food products. The other type of frozen food preservation technique involves the carbon dioxide as their refrigerated liquid. It is same as that of liquid nitrogen freezing preservation techniques but the carbon di oxide can be easily recovered from the processing plant. The other type of liquid based freezing technique is the immersion freezing technique using brine solution like sodium chloride. Mainly fishes like tuna with thick skins are preferred for processing by this technique because of low salt absorption. This degree of absorption salt by the food products reduces the flavor and taste of the food products. The investigation on the freezing rate in immersion potato preservation by the ultra sound has significantly reduces the freezing time (Johnston, 1994; Li, 2002; Delgado, 2009).

Gas Medium Based Freezing Techniques

These type of food preservation method transfer the heat from the food products with the help of cooled air. Forced convective heat transfer from the food products are helps to transfer large amount of heat. The air is cooled by refrigeration systems. Freezing rate of the food products increases with the increasing air flow rate. There are different types of air blast freezing in the commercial sectors. They are batch continuous air blast freezing, belt continuous air blast freezing, fluidized bed freezing. In the batch continuous air blast freezing method, the irregular shaped food products are processed by arranging them
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in the trays and placing the trays one over the other with the wooden spaced placed alongside with the air. The trays arranged in series are moved into the cabinet in which the cooled air flows over the food products in the cabinet. This type of freezing method is the batch wise freezing method so it is called as the continuous batch wise freezing method. In the belt continuous freezing process, the irregular shaped food products like the fish meats are arranged in the conveyor belt passes through the tunnel. The air flows through the tunnel with the velocity of 5 m/s cools the food products. It is a continuous and fast process than the batch continuous process. The conveyor belt moves into the tunnel in the spiral path is called as spiral freezing method. In the fluidized bed air blast freezing technique, the food products like peas, cut corns, carrot, strawberry etc., are placed in the mesh conveyors belt. When the food product passes the freezing zone, the air blown through the mesh turn round the food products and it helps to increase the heat transfer surface area of the food products (Johnston, 1994; Kondratowicz, 2002). The schematics of air blast freezing techniques are shown in the Figure 7 (Dempsey, 2012).

Effects of Freezing Temperature on Biological Properties

The freezing temperature significantly influences the color, flavor and nutritional content in the food products. The convective heat transfers co efficient of the food products using various freezing food preservation techniques ranging from 5 to 1200 W/m²K whereas air blast freezing shows least and liquid immersion shows higher. The list of food products affected by the various freezing methods is illustrated in the Table 2.

EMERGING FOOD PRESERVATION TECHNOLOGIES

Pulsed Electric Field Food Preservation Technologies

The pulsed electric field food preservation technologies process the fluid and semi fluids are treated. It is categorized under non thermal type of food preservation technique. During processing the food products, the food products are pre heated to certain temperatures and then cooled down to improve the efficiency

Figure 7. Schematic of air blast freezer (Dempsey, 2012)
Thermal Technologies and Systems for Food Preservation

Table 2. Food products affected by the various freezing methods

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Products</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Red swamp cray fish (Shi, 2018)</td>
<td>Higher freezing temperatures with liquid nitrogen and storing at high temperature than the freezing temperatures causes drip loss in the fish and reduces the SSP content in the fish.</td>
</tr>
<tr>
<td>2</td>
<td>Salmon fillet (Kono, 2017)</td>
<td>Higher freezing rate affects the color of the salmon fillets within 0.3 mm from the outer surface.</td>
</tr>
<tr>
<td>3</td>
<td>Parfried frozen potatoes (Adedeji, 2018)</td>
<td>Freezing at -82 °C reduces the oil intake of potato than the liquid nitrogen freezing method.</td>
</tr>
<tr>
<td>4</td>
<td>Nectarines (Zhao, 2018)</td>
<td>Near freezing temperature storage of nectarines at -1.5 °C extends the storage period. It also improves the post- harvest quality and anti-oxidant capacity.</td>
</tr>
<tr>
<td>5</td>
<td>freeze-dried soybean curd (Hamkarnsujarit, 2016)</td>
<td>Liquid nitrogen freezing and -90 °C freezing retains the color of the soybean curd than freezing at higher temperatures.</td>
</tr>
<tr>
<td>6</td>
<td>Egg yolk (Huang, 2016)</td>
<td>Freezing the egg yolk at -18 °C and storing it for 60 days increases the hardness of the mayonnaise without affecting the acceptability than producing mayonnaise from the fresh yolk.</td>
</tr>
<tr>
<td>8</td>
<td>Carrot slices (Xu, 2014)</td>
<td>High pressure carbonic immersion freezing reduces drip loss and nutritional content along with reduces tissue damage than the ultra low freezing methods.</td>
</tr>
<tr>
<td>9</td>
<td>Bakery product (Kougelhopf) (Meziani, 2012)</td>
<td>Higher freezing rate shows lower specific volume in frozen doughs along with loss of yeast in the freezing process and shows textural defect.</td>
</tr>
<tr>
<td>10</td>
<td>Cat fish fillets (Rodezno, 2013)</td>
<td>Higher freezing rate of 1.29 °C/min and energy removal rate of 10.29 J/s achieved by cryogenic freezing technique than air blast freezing techniques shows better quality after 6 months.</td>
</tr>
</tbody>
</table>

of the pulsed electric field technology. In the pulsed electric field techniques, small electrical pulses are applied to the food products. The potential difference formed between the inner and outer surfaces of the microorganisms kills them. It has minimal impact on the color, taste and nutritional content in the food products (Mohamed, 2012; Haan, 2002).

**Dielectric Heating Technique**

The conversion of high frequency electromagnetic field produces from the high frequency waves like microwave (between 300 MHz to 300 GHz) and radio wave (300 GHz to as low as 30 Hz) is converted to thermal energy is called as dielectric heating. Based on the frequency range, it is divided into microwaves and radio waves. The basic principle behind the dielectric heating process is the oscillating electromagnetic field causes the polar molecules to align themselves in the electromagnetic field and produces the molecular friction and migration of ionic species generates heat energy. These type of heating processes are used in the places where rapid and volumetric heating is applicable (Rahman, 2007; Jones, 1992). The effect of temperature, moisture content, salt content in the dielectric properties of the dielectric heating techniques are illustrated in the Table 3.
**Thermal Technologies and Systems for Food Preservation**

**Table 3. Effect of temperature, moisture content, salt content in the dielectric properties of the dielectric heating techniques**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Product</th>
<th>Results</th>
</tr>
</thead>
</table>
| 1     | Rice Bran (Ling, 2018)                                                                        | 1. Electromagnetic penetration depth decreases with the increasing moisture content and temperature.  
2. Increasing salt content in the rice brand increases the heating rate in the rice brand. |
| 2     | Lasagna containing meat balls, mozzarella cheese, noodles and sauces (Wang, 2009)           | Uniform heating rate by radio frequency heating is not affected by the dielectric properties of the food products but influenced by the shape, size and heat transfer properties of the ingredients. |
| 3     | Pumppable food products like skim milk, carrot purees, green pea and Salsa con queso (Kumar, 2007) | 1. The homogeneous pumppable food products like skim milk, carrot purees, green pea similar results like  
a. Dielectric constant decreases with the increasing temperature.  
b. Dielectric loss factor increases with the increasing temperature.  
2. In case of multi-phase heterogeneous food products like Salsa con queso shows different results which will be helpful in designing continuous flow microwave heating process. |
| 4     | Ground beef                                                                                  | Increase in the fat content in the food products has significantly reduces the dielectric constant and dielectric loss but below 0 ºC fat content does not varies the dielectric properties of the food items. |
| 5     | Stem and florets of broccoli                                                                | 1. The presence of water molecules in the stem and florets of broccoli decreases the dielectric loss factor above the freezing temperature.  
2. Below the freezing temperature, dielectric loss factor increases with the increasing temperature. |
| 6     | In shell egg (Dev, 2008)                                                                     | Faster heating rate achieved by the egg with microwave heating is due to presence of albumen in the egg.                                                                                                  |
| 7     | Raw Milk (Hamid, 1969)                                                                       | Microwave pasteurization of the raw milk shows that the microorganism decreases exponentially for the increasing irradiation period.                                                                       |

**Ohmic Heating Techniques**

Ohmic heating is also known as the electric resistance based heating process, it works on the principle of ohmic electrical resistance offered by the food product for heating. The internal resistance offered by the food products generates the heat in the products. In this technique, the electrode comes into direct contact with the food products for the induction of eddy current into the food products. It works well with the liquid food products with good conductance to electrical current. Various types of electrode arrangements in the ohmic food preservation technique are parallel, parallel rod, collinear, staggered rod (Sakr, 2014). The advantages of ohmic heating in the food preservation sector are,

1. Quick rise in the processing temperature without any moving parts.
2. Faster heating rate with uniform temperature distribution in the liquid food items are possible.

The effect of ohmic heating on the enzymatic and nutritional content for various food products are illustrated in Table 4. The feedback control systems are required for the ohmic heating process to regularly maintain the power input to the system. Ohmic heating could cause oxygen and hydrogen evaluation in the food products owing to the low frequency ohmic heating. The ohmic heating study has been conducted with the fish mince wash wash water to remove the proteins from the water. The results of
Thermal Technologies and Systems for Food Preservation

Table 4. Effect of ohmic heating on the enzymatic and nutritional content for various food products

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Products</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Enzyme in activation (Castro, 2004)</td>
<td>The presence of electric field significantly affects the lipoxygenase and polyphenoloxidase kinetics and reduces the inactivation time.</td>
</tr>
</tbody>
</table>
| 2.     | Orange juice (Leizerson, 2005) | 1. Low initial heating with ohmic heating process in the orange juice retains the flavor of the food products.  
2. The spores are inactivation are caused by the thermal treatment of ohmic heating but not attributed by the flow of current.  
3. The residual pectin esterase activity was reduced to 5%. |
| 3.     | Carrot puree with starch and salt (Zareifard, 2003) | The electrical conductivity of the food products increased with the increasing temperature and it found to decreases for the increasing particle size and concentration. |
| 5.     | Acerola pulp (Mercali, 2013) | Monomeric anthocyanins degradation in acerola pulp for both the ohmic and conventional heating process show a similar rate constant of 6.1 to 1.97 x 10⁻³ min⁻¹ for all temperatures. |

The investigations conclude that the 30% fish proteins are removed from the wash water for the ohmic heating of water to 70 °C (Huang, 2007).

CONCLUSION

The thermal technologies for food preservation techniques utilizes various parameters like freezing rate and freezing temperatures for inactivation of enzymes causing spoilage of food products. The process of heating and cooling the food products at various temperatures slightly degrades the nutritional content in the food products along with the decrement in storage time. Some of the novel combined method of freezing food preservation techniques like cryo-mechanical freezing, dehydro-freezing methods

1. Reduces the refrigeration load  
2. Maintains the moisture content of the high moisture containing food products  
3. Improves texture and flavour of the food products

Future research work needs to be focused on the heat transfer behavior of food products along with the food properties prediction for optimizing the equipment design in terms of energy conservation.

ACKNOWLEDGMENT

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REFERENCES


Thermal Technologies and Systems for Food Preservation


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Thermal Technologies and Systems for Food Preservation


KEY TERMS AND DEFINITIONS

**Air Blast Freezing:** The process of non-contact type of freezing by maintaining the air temperature.

**Cryo-Mechanical Freezing:** The combined method of utilizing the cryogenic freezing technique with the air blast freezing techniques in the single food preservation systems.

**Dehydro-Freezing:** Combined method of dehydration of high moisture containing food products before freezing.

**Denaturation:** The consequence of cell death under applied external applied load in the food products.

**Drip Loss:** The weight loss in the meat after slaughtering due to dripping of pink proteinaceous fluid in the meat.

**Pasteurization:** The process of rapid heating followed by rapid cooling for enzymatic inactivation.

**Respiratory Climacteric:** The exponential change in the respiration rate of the fruits during ripening.
Chapter 7

Uses of Non–Thermal Treatment Technologies in Liquid Foodstuff

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ABSTRACT

Heat treatments are the most basic methods used to provide microbiological and enzymatic inactivation of food. However, the applied high temperature affects important parameters such as color, nutritional value, taste, and sensory characteristics of foods in the negative direction. Therefore, in recent years, producers and consumers have sought to obtain healthy food with little deviation in quality parameters, and new techniques of non-thermal emerged from this point. In this chapter, non-thermal food such as accented electric fields, ultrasonic waves, high-pressure application, microfiltration, X-rays, ionizing radiation, high voltage electrical discharge, pulsed light, ultrasound, magnetic field heating, and information on conservation methods are given.

INTRODUCTION

Microbial activities in food can cause food spoilage and food poisoning. These microbial activities vary according to the pH, water activity, temperature, chemical and physical properties of the food. Pathogenic microorganisms have a number of causes that cause quality losses such as color loss, enzymatic and oxidative reactions in the products resulting from the development of pathogenic microorganisms, as well as the emergence of compounds called toxins which will adversely affect the health of people and consequently the economic losses (Jalili, Jinap, & Noranizan, 2010).

Mycotoxins; They are toxic metabolites of molds such as Aspergillus, Penicillium, Alternaria and Fusarium. These toxins, which are formed in various foodstuffs, reach people with the food they are in. These metabolites, which have frequent contact in daily life, still threaten public health and also cause economic losses by returning the exported products from the customs gates. These molds increase the quality and quantity of the products by multiplying in unprocessed foods under favorable conditions and cause deterioration on human health. (Şahin, Ünüvar, & Baydar, 2011).

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**Uses of Non-Thermal Treatment Technologies in Liquid Foodstuff**

In food industry, heat treatment technology, which has a very common usage area, is a very effective method for inactivation of microorganisms. The negative effects of heat treatment applications on the product increased the interest in new technologies. In recent years, it has been treated at the minimum level in line with the preferences of the consumer and with the increase in the demand for high quality foods in terms of natural and nutritional physiology, the interest in food products which have not lost their fresh or fresh characteristics has increased. Pathogenic microorganisms, both in the final stages of production, as well as in the development of the pathogen during storage, causing decay and product processing difficulties caused by severe economic damage causes.

For this reason, it provides a good potential for pasteurization of liquid foodstuffs such as fruit juice by providing inactivation of pathogenic microorganisms with the combination of non-thermal technologies and other applications. In this study, the application of nonthermal food such as stressed electric field, ultrasonic, high pressure application, microfiltration, X rays, ionized radiation, high voltage electrical discharge, pulsed light, ultrasound, magnetic field heating, information about preservation methods.

In this study, non-thermal food preservation methods which can be used and used in fluidized foods such as accent electric field, ultrasonication, high pressure application, microfiltration, X-ray, ionized radiation, high voltage electrical discharge, pulsed light, ultrasound, magnetic field heating, moderate magnetic field methods explained.

**NON-THERMAL TREATMENT OF LIQUID FOODSTUFF**

**High Hydrostatic Pressure**

High Hydrostatic Pressure (HHP) application is the process of exposing solid and liquid foodstuffs in the range of 100 - 1000 MPa with or without packing. (Hygreeva & Pandey, 2016). It is a method that provides microbiological and enzymatic inactivation without any change in nutritive value of taste and food products when compared with heat treatment. In the HBP process, the HHP process can be applied in two forms, with or without food (Ohlsson & Bengtsson, 2002). The main principle of the High Hydrostatic Pressure process is based on the principle of compressing the liquid with the pressure force applied to the liquid surrounding the food (Baptista, Rocha, Cunha, Saraiva, & Almeida, 2016). Nowadays, this technique has found a wide range of applications in the food industry. Some important areas of use; It is used in applications such as microorganism inactivation, protein denaturation, enzyme inactivation or activation, gel formation, preservation of sensory quality elements such as color, taste-odor, increasing the efficiency in extraction (Muntean et al., 2016; Patterson, 2014; Saroya, 2017; Tao, Sun, Hogan, & Kelly, 2014). HHP treatment; marmalade products such as fruit juice, fruit jellies, fruit yogurts, various meat and meat products, mussels, oysters and other shellfish (Ohlsson & Bengtsson, 2002).

Mechanism of action on microorganisms; compression of the gas cofula under pressure, changes occurring in the cell, intracellular matter infiltration and intracellular organelles as a result of the change occurs. At the same time, there are important effects on quality and inactivation of important enzymes that cause food spoilage. (Patterson, 2014; Tao ve ark., 2014).

High hydrostatic pressure application is used in vegetable products, fruit juice and beverage industry, meat products and crustaceans in order to prevent microbial growth and increase shelf life at room temperature, 100-900 MPa pressure range (F. Liu, Li, Wang, Bi, & Liao, 2014; Tao et al., 2014).
Pulsed Electrical Field

Pulsed electrical field (PEF) is a non-thermal process used for the protection of foodstuffs with the application of high voltage electric field for a very short time. PEF is an innovative strategy for introducing innovative processing technologies for traditional technology areas, introducing new products in the market, increasing food quality and reducing energy costs, and thus leading to increased competitiveness of the food industry. (Tiwari, O'Donnell, & Cullen, 2009). It can be applied at very low temperatures to prolong shelf life by allowing microorganisms to become inactive, with little or no change in the properties of foods such as taste, flavor and nutrients. In the PEF process, the electric field in the range of 12-35 kV cm\(^{-1}\) is interrupted by short pulses (1-100 μs), providing an inactivation mechanism on the enzymes and microorganisms (Kaletunç, 2009; Vega-Mercado et al., 1997). Generally, PEF applications use exponential or square wave pulses (Álvarez, Condón, & Raso, 2006). This system is generally used in the food industry for the pasteurization of food such as milk, fruit juice, sausages and liquid egg (Toepfl, Siemer, Saldaña-Navarro, & Heinz, 2014). In PEF technology applications, it is composed of rectangular pulse model, logarithmic decreasing pulse model, sudden reversible pulse model and vibratory pulse model (Barbosa-Cánovas, Góngora-Nieto, Pothakamury, & Swanson, 1999).

When the inactivation mechanism of PEF technology is examined, the theory of dielectric breakdown is explained. It is the result of the deterioration of the system between the electrostatic clamping force and the elastic counter force of the cell membrane. Thus, the thickness of the cell membrane wall decreases and the cell membrane under this pressure with the structure of the non-suppressing cell membrane area and the increase in the ratio between the fat layers takes place. Therefore, the phase balance of the cell fatliquors is deteriorating. As a consequence of application of 1-10 kV/cm 10-15 μs cell, the cells are irreversibly degraded. The formation of large diameter pores by electroporation is due to the increase of the electric current intensity and the application time and the decrease of the ionic resistance of the medium. In the PEF applications of the researchers, bacteria, yeasts and molds and enzymes that produce degradation effect have been found to be successful and it would be appropriate to apply them to liquid foodstuffs (Lelieveld, Notermans, & Haan, 2007; Singh, Singh, Bansal, SangwanRajender, & Nayak, 2016).

Magnetic Field Heating and Moderate Magnetic Field Treatment

Magnetic field is a method that has a potential effect on microbial inactivation in foods. Magnetic field, static magnetic field (SMA) and mobile magnetic field (HMA) are two different methods of microbial inactivation in foods. The magnetic field density can vary in the SMA as well as constant waves in the SMA while in the HMA it may vary in sinusoidal waves. The magnetic field effect causes a change in the rate of cell proliferation by altering biomembranes or biomolecules, altering the ionic movement between DNA synthesis and the plasma membrane. It is applied in the processing of liquid and packaged solid foodstuffs (Filipić, Kraigher, Tepuš, Kokol, & Mandic-Mulec, 2012; Y. Liu, Jia, Ran, & Wu, 2010; Zhao, Yang, Zhang, Luo, & Li, 2018). In one study, PEF and SMF were used in combination for food freezing and gave successful results (Mok, Choi, Park, Lee, & Jun, 2015).

The moderate magnetic field (MEF) is based on the principle of electrical current passing through the electrical circuit by the food. It is often used by breaking the cell wall to effect fruit juice efficiency (Baysal, İçier, Rayman, Coşgun, & Petek, 2013; El Zakhem, Lanoisellé, Lebovka, Nonus, & Vorobiev, 2007). Escherichia coli has been reported to be used successfully in the inactivation study. (Machado ve
Uses of Non-Thermal Treatment Technologies in Liquid Foodstuff

Ark., 2010). In researches, it has been used in the studies such as increasing the shelf life of microorganisms by using the extraction of component, fermentation efficiency and other methods (Jaeschke, Menegol, Rech, Mercali, & Marczak, 2016; Mattar et al., 2015; Vallverdú-Queralt et al., 2013; Walkling-Ribeiro, Noci, Cronin, Lyng, & Morgan, 2010).

High Voltage Electric Discharge and Gliding Arc Discharge Discharge

Recently, new technologies such as high-voltage electrical discharges (HVED) have been used to extract valuable components such as polyphenols, which are mostly derived from vegetable matter (Boussetta & Vorobiev, 2014; Delsart et al., 2015). The electrical and mechanical effects of HVED technology cause damage to cell walls and tissues, causing it to break down. In one study, high voltage electrical discharges (0-400 kJ / kg) and solid liquid ratio (1: 5-1: 20, w / w) were used to minimize the loss of high component (rapeseed, and successful results were obtained (Barba, Boussetta, & Vorobiev, 2015). One of the new methods of protection in gravity is the gliding arc discharge (GAB) technology, which is used by means of electric arc discharge (Wright et al., 2014). In one study, shear arc discharge, water contaminated with Escherichia coli, was treated with GAB for the first 10, 13, 16 and 25 minutes and the best result was inactivated by 16 minutes of plasma treatment (approximately 2.7 log reduction) (Lee, Kim, Cadwallader, Feng, & Martin, 2013).

Ionize Radiation

By the continuous disintegration of their atoms, radioactive substances emit some radiation around them. Ionized radiation (ionizing radiation) impinging on the material creates electrically charged ions. In the safety of food, X-rays, gamma rays and accelerated electron beams are used. X-rays with a power of 5 MeV (millions of electron volts) are produced from sources with lower energies (Berk, 2018; Harder, Arthur, & Arthur, 2016). The effect of ionizing radiation on living cells is either directly on the cellular genetic material, or indirectly on non-genetic molecules. Ionized radiation causes breakage or fragmentation on genetic material. The level of this disintegration depends on the radiation dose. Radiation increases as the desire increases (Varlık, Erkan, Özden, Mol, & Baygar, 2004).

Successful results have been obtained in studying against norovirus and Tulane viruses in strawberries (Hossain et al., 2014). As a result of the studies, it is suggested that instead of irradiation with sterilization of food, it is better to apply hurdle technology with other food preservation methods, even though successful results are obtained in microbial inactivation (Bounial, Salmieri, & Lacroix, 2016). The effect of ionizing radiation on living cells is either directly on genetic material in the cell, or indirectly on non-genetic molecules. Ionizing radiation causes breakage or fragmentation on the genetic material. The level of this disintegration is dependent on the dose of radiation. The higher the dose, the higher the lethal effect of radiation.(Atasever & Atasever, 2007).

Plasma Sterilization

Plasma technology was first discovered in 1928 by Irving Langmuir. The first step in plasma sterilization was taken in 1968 and the first plasma application was made in 1989. The microbial inactivation mechanism of plasma has begun to be investigated since the 1990s, but it is still not fully understood (Stoica, Alexe, & Mihalcea, 2014). The material has quite different properties than solid, liquid and gas
Plasma is regarded as the fourth state of matter. Plasma is regarded as the fourth state of matter by some physicists and is also defined as a gas composed of ions and free electrons (Evelyn, Kim, & Silva, 2016; Fernández, Shearer, Wilson, & Thompson, 2012). Plasma used for sterilization also contains uncharged particles such as atoms, molecules and radicals. It is formed by the release of a gas or gases between a fixed (direct current) or two electrodes. Inactivation occurs by affecting the cell walls on the microorganism with electrons and ions released during plasma production and helps sterilization. In the studies done, many foods such as vegetables, fruits and meat products gave positive results in microbiological terms. It is used in food packaging systems. Classification of plasma is defined as hot plasma and cold plasma. The cold plasma ion temperature is more convenient to use at room temperature and at temperatures (Niemira, 2012; Pasquali et al., 2016; Yangılar & Oğuzhan, 2013)(Niemira, 2012; Pankaj et al., 2014; Pasquali et al., 2016; Yangılar & Oğuzhan, 2013).

Pulsed Light

The pulsed light uses wave lengths (200 nm-1 mm) close to the broad-spectrum infrared region in the UV region. In the surface sterilization process, application of at least one pulse of energy with an energy density of approximately 0.01-50 J/cm² is performed on the surface. Pulsed light systems used for food decontamination can broadband the spectrum from ultraviolet to infrared, with a few strokes applied at a time, each pulse can last from 100 ns to 2 ms. Pulsed light is a method of sterilization which FDA (Food and Drug Administration) uses in food, which has antimicrobial effect and which can be used to reduce the use of disinfectant and chemical preservative without damaging the contents and surface of the applied product. In some studies, the duration of the pulses varies from 1 μs to 0.1 s and 1-20 flashes are applied at the moment. In these applications, microbial inactivation occurs by various mechanisms such as microorganisms’ proteins, chemical changes on the cell membrane, disintegration of the DNA chain. This technology also uses intense, short-time signals of broad-spectrum light from UV to infrared (100 to 1100 nm) It causes germicidal effects due to UV light (100-400 nm), visible light (400-700 nm) and near infrared light (700-1100 nm), photochemical, photothermal and photophysical exposure (Condon, Alvarez, & Gayan, 2014; Elmnasser et al., 2007). In studies conducted with high intensity and energy pulsed light method, it has been determined that the cell is damaged in such a way that it cannot repair itself. However, in conventional UV applications, the cell can repair itself under certain conditions. According to Bacteria, the resistance of mold spores to pulsed light was found to be stronger. In recent years, successful results have been obtained in food safety and nutritional changes in fresh fruits. Food is most commonly used in meat industry. (Abida, Rayees, & Masoodi, 2014; Bhavya & Hebbar, 2017; Cacace & Palmieri, 2014; Duarte-Molina, Gómez, Castro, & Alzamora, 2016; Saroya, 2017). The bactericidal effect of pulsed light is limited to a low penetration degree. Suitable for inactivation of microorganisms on solid surfaces, however, the availability in liquid foods is limited to clear liquids. However, the penetration depth is quite small depending on the optical properties of the media (Delgado, Kulisiewicz, Rauh, & Wierschem, 2012).

Microfiltration

Microfiltration from membrane separation techniques is an alternative method used to prevent the negative effects of various components, primarily proteins, especially high-grade heat treatment applied by bacteriological causes in the dairy industry. Microfiltration separates micron and larger size particles
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in solution. The pore diameter of the microfiltration membranes ranges from 0.05 to 5 mm. Since the membrane resistance is low, they are operated under low pressure and are operated at pressures up to 2.0 bar on average. Microfiltration is a technique capable of distinguishing molecules with molecular weights greater than 200 kDa by pressure from 0.1-0.5 bar. The pore diameters of the membrane used range from 0.1 to 10 μm (Rosenberg, 1995; Urošević ve ark., 2017). It is used for selective separation of large molecule particles such as pathogenic microorganisms, somatic cells, fat globules, phospholipids in milk and dairy technology. According to the milk produced from pasteurized milk, the storage time of milk and milk products is shorter than the milk produced by subjecting to microfiltration method (Avalli ve ark., 2004; Raghavarao ve ark., 2005).

Ultrasound

The sound is determined by the frequency range which our ear can hear (16-20 kHz). “Infra-ses” for sound waves with frequencies less than 20 Hz and “Ultrases” for sound waves with frequencies greater than 20 kHz. Another definition is the generation of energy by 20,000 or more sound waves at the moment (Carovac, Smajlovic, & Junuzovic, 2011). Ultrasound; can be defined as frequencies of sound waves having the ability to pass through solids, liquids, gases and which can not be perceived by the human ear (Mason, Paniwnyk, & Chemat, 2003; Torley & Bhandari, 2007).

In 1880, Pierre Curie (with the discovery of piezoelectric effect), which brought the development of sound wave technology for the first time, has been. As a result, motion is being used with the aid of motion devices in a loud environment. In 1942, medical ultrasound was identified by Austrian Thedore Dussik. II. After World War II, modern sound wave technology has begun to develop. For the first time, Ludwig and Struthers showed the stones in the bile duct with the help of sound waves (Günaydın, 2011; Mason, 1999). The use of ultrasound technology as a microbial inactivation method has been shown in the 1960s when sound waves from submarine swimmers killed fish (Piyasena, Mohareb, & McKellar, 2003).

Ultrasound applications are divided into 2 groups according to their energy status. Low-energy (<100 kHz, <10 W.cm2) ultrasound is applied at frequencies between 5-10 MHz and at low densities below 1 W / cm2. Low intensity ultrasound does not cause a physical or chemical change in the affected area. Higher energy (<100 kHz, <10 W. cm2) ultrasound is applied at a density greater than 1 W / cm2 and frequencies in the range of 18-100 kHz in general. Ultrasonics is used in a variety of industrial sectors such as chemical, biological processing, food processing, pharmaceutical, medical and defense. In Table 1 below, some low-energy and high-energy ultrasound applications are classified (Ashokkumar et al., 2010; Awad, Moharram, Shaltout, Asker, & Youssef, 2012; Muthukumarappan, Tiwari, O'Donnel, & Cullen, 2010; Ojha, Mason, O'Donnell, Kerry, & Tiwari, 2017; Paniwnyk, 2017).

The theory of the inactivation mechanism of microorganisms is based on the effects of bursting of bubbles due to the influence of the press. Micro shocks that occur during this explosion are effective on microorganisms (Piyasena et al., 2003). In another explanation, asymmetric explosion of the bubbles formed by the temporary cavitation causes many damages in the outer parts of the cells by rapid jetting of the resulting liquids (water jet), and also provides inactivation by breaking the structure of the polymeric substances in the cell walls (Chandrapala, Oliver, Kentish, & Ashokkumar, 2012; H. Feng & Yang, 2011).
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Table 1. Examples of low-energy and high-energy ultrasound applications

<table>
<thead>
<tr>
<th>Low Energy Ultrasound</th>
<th>High Energy Ultrasound</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Uninterrupted monitoring of the production process</td>
<td>• Extraction</td>
</tr>
<tr>
<td>• Determination of fat percentage in meat</td>
<td>• In the homogenization process</td>
</tr>
<tr>
<td>• Surface cracks in cheese</td>
<td>• Emulsification</td>
</tr>
<tr>
<td>• Milk coagulation</td>
<td>• Sanitation</td>
</tr>
<tr>
<td>• In the characterization of fruits and vegetables</td>
<td>• Shorten the freezing time in foods</td>
</tr>
<tr>
<td>• Determining the quality of the eggs</td>
<td>• During the filtration phase</td>
</tr>
<tr>
<td>• Controlling wine fermentation</td>
<td>• Drying, crystallization</td>
</tr>
<tr>
<td>• The rheological properties of the dough</td>
<td>• In solving of frozen products</td>
</tr>
<tr>
<td>• Determination of sugar content</td>
<td>• In the removal of gas from liquid wastes</td>
</tr>
<tr>
<td>• Determination of different physicochemical properties (acid etc.)</td>
<td>• Quality control in packaged foods</td>
</tr>
</tbody>
</table>

Ultraviolet Light

UV irradiation technology is a process used as an alternative to thermal methods in food processing. In order to ensure microbial inactivation in food applications, the use of UV in the process and the need to use any chemicals in the process ensures that the UV process is environmentally friendly (Guerrero-Beltrán & Barbosa-Cánovas, 2004). Ultraviolet (UV) light is a type of radiation that has a wavelength in the electromagnetic spectrum of wavelengths between 10-400 nanometers. There are three ultraviolet light regions in the electromagnetic spectrum. These are UV-A (315-400 nm), UV-B (280-315 nm) and UV-C (200-280 nm). UV light has the ability to inactivate pathogenic microorganisms in the UV-C region. Inactivation efficiency follows a range in which maximum inactivation occurs at a range of about 254 to 264 nm. It is known that the use of UV-C light in food affects microorganisms in a wide spectrum, while it also has many advantages over foodstuffs in other aspects. The use of short wave ultraviolet (UV-C) in food processing can also extend the shelf life of food products and reduce the health risks associated with the presence of pathogens. This application can be applied to prevent foodborne diseases in fresh fruits and vegetables, fresh fruit juice drinks, fresh meat, poultry and seafood (Choudhary & Bandla, 2012; T. Koutchma, Forney, & Moraru, 2009).

In some studies, ultraviolet light showed antimicrobial effects in the wavelength range of 100-280 nanometers. In general, in a variety of studies it has been shown that the destruction of microorganisms is caused by the penetration of the UV-C light into the outer membranes of the cells, which leads to enormous damage to the DNA due to the formation of thymine dimers, which prevents the microorganisms from undertaking DNA transcription and replication, by causing death. The efficacy of ultraviolet light application varies according to the characteristics of the light, the properties of the food, the wavelength, the microorganism species, the process conditions and the mechanism of action according to many properties such as whether the food is solid or liquid. Studies on the application of microorganism inactivation on food surfaces are increasing and many studies have found that UV light technology is successful. (Gómez-López, Koutchma, & Linden, 2012; Keklik, Krishnamurthy, & Demirci, 2012; T. Koutchma, 2014; T. Koutchma et al., 2009).
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CONCLUSION

In food industry, heat treatment technology, which has a very common usage area, is a very effective method for inactivation of microorganisms. The negative effects of heat treatment applications on the product increased the interest in new technologies. In recent years, it has been treated at the minimum level in line with the preferences of the consumer and with the increase in the demand for high quality foods in terms of natural and nutritional physiology, the interest in food products which have not lost their fresh or fresh characteristics has increased. Therefore, it provides good potential for the pasteurization of liquid foods such as fruit juice by providing inactivation of pathogenic microorganisms with non-thermal technologies.

REFERENCES


Uses of Non-Thermal Treatment Technologies in Liquid Foodstuff


Uses of Non-Thermal Treatment Technologies in Liquid Foodstuff


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Keklik, N. M., Krishnamurthy, K., & Demirci, A. (2012). Microbial decontamination of food by ultraviolet (UV) and pulsed UV light. In A. Demirci & M. O. Ngadi (Eds.), *Microbial Decontamination in the Food Industry* (pp. 344–369). Elsevier. doi:10.1533/9780857095756.2.344


Uses of Non-Thermal Treatment Technologies in Liquid Foodstuff


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Vallverdú-Queralt, A., Odrizoza-Serrano, I., Oms-Oliu, G., Lamuela-Raventós, R. M., Elez-Martínez, P., & Martín-Bellos, O. (2013). Impact of high-intensity pulsed electric fields on carotenoids profile of tomato juice made of moderate-intensity pulsed electric field-treated tomatoes. *Food Chemistry*, 141(3), 3131–3138. doi:10.1016/j.foodchem.2013.05.150 PMID:23871069


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Chapter 8

Pinus Pinaster Bark
Composition and Applications: A Review

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ABSTRACT

The food market is demanding natural antioxidants either to be applied to food or cosmetic and nutriceutical purposes. Plants are very rich in polyphenols that have diverse biological functions, such as defending plants against microbiological attacks, becoming essential to plant life. The bark of Pinus pinaster Aiton subsp. atlantica is known to have a great amount of polyphenols with antioxidant and antimicrobial properties. P. pinaster has a large area of distribution in the northwest of Portugal, making this source a biomass feedstock of great interest for the food industry in Portugal. Therefore, embarking on the trend of circular economy, polyphenols are being extracted aiming for the exploitation of their antioxidant and antimicrobial properties as a food additive in a variety of food matrices. This chapter aims to provide a more insightful view of the chemical composition, extraction methods, and food applications of pine bark of Pinus pinaster Aiton subsp. atlantica polyphenols.

INTRODUCTION

Consumers are active agents in the food chain and are increasingly demanding for natural foods, with greater nutritional value, beneficial for health, rich in bioactive compounds, and, if possible, that contribute to sustainability (Falguera, Aliguer, & Falguera, 2012; Ruggeri, Straniero, Pacifico, Aguzzi, & Virgili, 2008).

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Pinus Pinaster Bark Composition and Applications

Food additives, such as antioxidants, are frequently used to control lipid oxidation during food processing and storage. However, even if consumers are aware of the benefits of using additives, they have a strong expectation of foods with the fewest or lowest possible level of additives. If the additives must exist, then consumers’ prefer them to be from natural origin (Balzan et al., 2017).

With sustainability in mind, the reduction of wastes as well as their valorisation, transforming waste into a resource is a new world tendency which is called circular economy (Seabra, Dias, Braga, & de Sousa, 2012). “Bioeconomy” and “circular economy” are keywords in the Horizon 2020 as well the Horizon Europe – the next European Union research and innovation framework programme. Plants are being used for various purposes i.e. food, fuel, fodder, goods, and to extract bioactive compounds, namely polyphenols, alkaloids, anthocyanins, flavonoids, phenolic acids, carbohydrates, polysaccharides and essential oils, which are found effective against a vast number of health complications and have impact on lower risk of cancer, cardiovascular and other diseases (Belwal et al., 2018; Jablonsky et al., 2017). Plant derived ingredients possessing antioxidant and antimicrobial properties have the advantage of being readily accepted by consumers, as they are considered natural (Hayes, Stepanyan, Allen, O’Grady, & Kerry, 2011).

Pine bark is an abundant residue of the wood industry, since it represents 10–20% of the pine tree trunk. Due to large availability of pine bark on a global scale, there is an increasing interest in its use (Ronda, Della Zassa, Biasin, Martin-Lara, & Canu, 2017). Bark presents several favourable features such as some important phytochemical constituents, low price and long-term stability that together make the usage of this residue highly attractive (Braga et al., 2008; Seabra et al., 2012). The pine bark extracts have been reported to have several bioactivities including antioxidant, compounds with cardiovascular benefits, and anti-diabetic effects (Aspé & Fernandez, 2011; Chupin et al., 2015).

This review paper aims to provide a more insight view of the chemical composition, extraction methods and food applications of polyphenols from pine bark of Pinus pinaster Aiton subsp. atlantica.

PINE BARK AS A POTENTIAL BIOMASS FEEDSTOCK

Pinus pinaster, also called maritime pine, is the conifer occupying the most extended area in Europe and Asia forest surface, and it is the species with the most extended dissemination in the West of the Iberian Peninsula, where it covers more than 28% of the whole forest surface, mainly Portugal (Figure 1) (Ronda et al., 2017). This wide distribution is due to its ability to grow on poor soil that provides minimal nourishment (Tümen, Akkol, Taştan, Süntar, & Kurtca, 2018).

Due to large availability of pine bark on a global scale, there is an increasing interest in its use (Ronda et al., 2017). Pinus pinaster bark is an abundant residue of the wood industry, since it represents 10–20% of the pine tree trunk. Trees are cut down with different ages/trunk diameters according to their use (from 7 to 53 cm or more). For the paper industry, one of the main destinations of these pine species nowadays in Portugal, the cut down occurs with a trunk diameter of about 7-14cm (Centro Pinus, 1999). Bark presents several favourable features such as some important phytochemical constituents, low price and long-term stability that together make the usage of this residue highly attractive (Seabra et al., 2012). The pine bark extracts have been reported to have several bioactivities including antioxidants, compounds with cardiovascular benefits, and anti-diabetic effects (Aspé & Fernandez, 2011; Chupin et al., 2015). Consequently, great interest has been recently focused on the addition of polyphenols to foods and biological systems, due to their well-known abilities to scavenge free radicals, i.e. antioxidant power.
Pinus Pinaster Bark Composition and Applications

Figure 1. Distribution map of Maritime pine (Pinus pinaster) (EUFORGEN, 2009)

Pinus pinaster

This distribution map, including both natural and naturalized occurrence of Pinus pinaster was compiled by members of the EUFORGEN Programme
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(Pinelo, Rubilar, Sineiro, & Núñez, 2004). They have received considerable attention in the fields of nutrition, health, and medicine owing to their physiological and biological activities, namely antibacterial, antiviral, anticarcinogenic, anti-inflammatory and cardiovascular system diseases prevention (Seabra et al., 2012). Several studies pointed out the influence of the age of the plants, among other factors, on their polyphenol content (Hassegawa, Stevanovic, & Achim, 2016; Meena & Asrey, 2018; Talhaoui, Taamali, Gómez-Caravaca, Fernández-Gutiérrez, & Segura-Carretero, 2015).

Literature reports validate that there is continued interest in bark characterization with the ultimate objective of developing chemical products such as nutraceuticals, adhesives, and biofuels (Eberhardt, 2012).

CHEMICAL COMPOSITION

There is a lot of information about wood but not about pine bark. The chemical composition of the latter is different from wood, extractives being the most abundant compound group (Feng, Cheng, Yuan, Leitch, & Xu, 2013). Bark differs from other lignocellulosic materials mainly by the presence of polyphenols and suberin (Fengel & Wegener, 1984b). The different components of bark depend not only on the natural variability associated with its origin, age of tree, location and growing conditions, but also on its anatomic origin (Vázquez, Freire, González, & Antorrena, 2000). When compared to wood, bark
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has higher content of water and organic solvent extractives and ashes, and lower amount of polysaccharides, which represents only 35% of the bark against the 75% of wood (Fradinho et al., 2002; Vázquez, Antorrena, & Parajó, 1987). Besides carbohydrates and extractives (20-40%), pine bark also contains other minor substances such as lignin, suberin and ash. Table 1 presents the chemical composition of various *P. pinaster* barks reported in literature.

**Carbohydrates**

The carbohydrate fraction of bark includes cellulose and the hemicelluloses (Fengel & Wegener, 1984b). Cellulose is an important cell wall structure basic component and accounts for 20.2% of unextracted pine bark (Fengel & Wegener, 1984a, 1984b). Cellulose is insoluble in most solvents including strong alkali. Thus, it is difficult to segregate from bark in pure form because it is powerfully connected with other substances from the cell wall, namely the hemicelluloses and lignin (Fengel & Wegener, 1984a; Pettersen, 1984). Other compounds such as fats, waxes and proteins can easily be removed by extraction with organic solvents and dilute alkali (Fengel & Wegener, 1984b). Hemicelluloses contribute to the alkali fraction and are also easily hydrolysed by acids (Fengel & Wegener, 1984e; Fradinho et al., 2002; Pettersen, 1984).

**Table 1. Chemical composition of Pinus pinaster bark**

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>0.5</td>
<td>1.2</td>
<td>0.8</td>
<td>3.5</td>
</tr>
<tr>
<td>Extractives</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>41.8</td>
<td>11.4</td>
<td>16.6</td>
<td>-</td>
</tr>
<tr>
<td>Hexane + benzene</td>
<td>2.5(^{a})</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dichloromethane</td>
<td>-</td>
<td>2.3</td>
<td>3.1</td>
<td>-</td>
</tr>
<tr>
<td>Ether</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ethanol</td>
<td>11.6</td>
<td>6.5</td>
<td>10.3</td>
<td>2.5(^{a})</td>
</tr>
<tr>
<td>Water</td>
<td>4.1</td>
<td>2.6</td>
<td>3.2</td>
<td>16.0</td>
</tr>
<tr>
<td>NaOH</td>
<td>22.7(^{b})</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alkaline extract</td>
<td>-</td>
<td>-</td>
<td>10.8(^{f})</td>
<td>-</td>
</tr>
<tr>
<td>Aromatic content</td>
<td>59.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Suberin</td>
<td>1.0</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lignin</td>
<td>29.6(^{c})</td>
<td>43.7(^{e})</td>
<td>33.2(^{h})</td>
<td>37.5</td>
</tr>
<tr>
<td>Polysaccharides</td>
<td>28.9(^{d})</td>
<td>41.7</td>
<td>48.4(^{b})</td>
<td>48.1</td>
</tr>
</tbody>
</table>

\(^{a}\)Corresponds to waxes; \(^{b}\) 1% NaOH; \(^{c}\) measured by Klason method; \(^{d}\) approximately half corresponding to cellulose; \(^{e}\) lignin + polyphenols; \(^{f}\) tannins and other polyphenols insoluble in water and ethanol, 2% NaOH, 0.5 h, 100 °C, 1 g/10 mL (alkaline extraction after solvent extraction); \(^{g}\) Klason lignin determined after solvent extraction and alkaline extraction with 2% NaOH (0.5 h, 100 °C, 1 g/10 mL); \(^{h}\) Holocellulose determined after solvent extraction and alkaline extraction with 2% NaOH (0.5 h, 100 °C, 1 g/10 mL); \(^{i}\) ethanol-benzene extractives.
Holocellulose estimation is an analytical procedure that ascertains the total polysaccharide (cellulose and hemicelluloses) and methods for its determination seek to remove all the lignin from wood without disturbing the carbohydrates (Pettersen, 1984). The holocellulose or total polysaccharide content in P. pinaster bark can vary from 28.9 to 48.4% in dry bark (Table 1).

**Lignin**

After cellulose, lignin is the most important component in plants (Fengel & Wegener, 1984d). It is a strengthening material for the plant cell wall, which acts as a matrix for cellulose microfibrils. Lignin represents a vast reservoir of aromatic materials, mainly untapped because of the difficulties associated with release of these metabolites (Pereira, Valentão, Pereira, & Andrade, 2009). Extracts of coniferous barks contain compounds deriving from the lignin metabolism, such as shikimic acid, ferulic acid, coniferylaldehyde, vanillin and others (Fengel & Wegener, 1984b). The lignin content of barks can only be determined after alkali extraction, because the polyphenol fraction is resistant to hydrolysis, and thus contributes to the lignin value (Fengel & Wegener, 1984b). A new method was developed and the lignin isolated by this treatment is referred to Klason lignin (Dence, 1992). The variation of these compounds in P. pinaster bark goes from 29.6 to 43.7% dry bark (Table 1). Occasionally, total lignin content is overestimated due to the condensation reaction between lignin and polyphenol in the presence of sulfuric acid (Ku, Jang, & Mun, 2007).

**Suberin and Ash**

Suberin is an insoluble constituent of the outer bark and is found in the phellem layer of plants (Fengel & Wegener, 1984b; Nunes et al., 1996). Two studies (Nunes et al., 1996; Vázquez et al., 1987) reported low amounts of suberin in P. pinaster bark (1.0-1.5% dry bark) (Table 1).

Ash is the inorganic residue remaining after combustion, which mainly contains metal oxides (K₂O, MgO, Na₂O, CaO, and Fe₂O₃, etc.), windborne soil or sand particles (Feng et al., 2013). Ash content in P. pinaster bark studies vary between 0.5-3.5% in dry residue (Table 1).

**Extractives**

Other pine bark components obtained by solubility of bark in various solvents are named extractives. These components do not contribute to the cell wall structure, and most are soluble in neutral solvents (Pettersen, 1984). In P. pinaster bark the extractives concentration is between 11.4-41.8% of the dry weight (Table 1). They include many different compounds like fats, waxes, alkaloids, proteins, simple and complex phenolics, simple sugars, resins, terpenes and glycosides which can be extracted from bark by means of polar and non-polar solvents (Fengel & Wegener, 1984c; Pettersen, 1984). However, the number of extractives depends not only on the species but also on the solvents used, and usually requires a sequential extraction, the yields from which give a preliminary characterization of the composition. Its composition can be widely variable even within one genus (Fengel & Wegener, 1984b). Some studies have been made of several tree barks, however, their comparison is restricted because of the different extraction methodologies.
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Polyphenols

Polyphenols are among the most widespread class of metabolites in nature, and their distribution is almost ubiquitous. It is estimated that 100,000 to 200,000 secondary metabolites exist and some 20% of the carbon fixed by photosynthesis is channelled into the phenylpropanoid pathway, thus generating the majority of the natural-occurring phenolics, such as flavonoids and stilbenes (Pereira et al., 2009). They are a big group of molecules characterized by having an aromatic ring and a hydroxyl group but also include molecules with one phenol ring, such as phenolic acids and phenolic alcohols (Belščak-Cvitanović, Durgo, Hudek, Bačun-Družina, & Komes, 2018; Oliveira, Carvalho, & Melo, 2014). These are compounds of the plant secondary metabolism that can accumulate in certain plant organs such as leaves, fruits, roots and stems. As a large group of bioactive chemicals, they have diverse biological functions. Because they are essential to plant life, they can provide defence against microbiological attacks and make food unpalatable to predators and other herbivores (Oliveira et al., 2014).

Others

The total content of both lipophilic and hydrophilic extractives usually corresponds to 20–40% of the dry weight of bark. The lipophilic fraction consists mainly of fats, waxes, terpenoids, and higher aliphatic alcohols. Terpenoids, resin acids, and sterols are in the resin canals present in the bark and also occur in the cork cells and in the pathological exudate of wounded bark (Yang & Jaakkola, 2012).

Lipophilic extractives like fats and waxes are extractable with organic solvents with low polarity such as diethyl ether, petroleum ether, acetone, hexane and dichloromethane (Fengel & Wegener, 1984c; Soon & Chiang, 2012). As ether is relatively non-polar it can also extract resins, oils, sterols and terpenes. Ethanol/benzene is more polar and extracts most of the ether-soluble compounds plus most of the organic materials insoluble in water. Hot water extracts some inorganic salts and low molecular weight polysaccharides including gums and starches. Water also removes certain hemicelluloses (Pettersen, 1984; Soon & Chiang, 2012). In some studies, the obtained yield for lipophilic fraction from P. pinaster bark was 2.3-3.1% and 0.9% in dry bark, with dichloromethane and diethyl ether, respectively (Table 1).

POLYPHENOLS CLASSIFICATION

Polyphenols differ in polarity (from the very hydrophilic simplest phenolic acids to the lipophilic alkylresorcinols), molecular weight (from small phenolic acids to polymeric hydrolysable tannins), and molecular structure, such as isomers (e.g. cis-resveratrol and trans-resveratrol). In addition, they present different forms of associations with food matrices (they may appear free, associated with weaker bonds or strongly linked with covalent bonds) (Sáyago-Ayerdi, Mercado-Mercado, Ramos-Romero, Torres, & Pérez-Jiménez, 2016). Biogenetically, phenolic compounds proceed of two metabolic pathways: the shikimic acid pathway where, mainly, phenylpropanoids are formed and the acetic acid pathway in which the main products are the simple phenols (Belščak-Cvitanović et al., 2018).

Figure 2 shows a scheme of the classification of polyphenols based on chemical structure. These aromatic compounds are divided in alkali soluble and alkali insoluble phenolic compounds. The former belongs to the flavonoid family. The later has a complex structure that appears to be related with the lignin of wood (Vázquez et al., 1987).
These compounds are soluble in methanol, hot water and ethyl acetate (Fengel & Wegener, 1984b). Many phenolic compounds are soluble in polar solvents. The choice on the solvents to be used depends on the number of hydroxyl groups and sugars in the molecules. For crude total phenolic extracts, aqueous alcohols and acetone have often been used as solvents (Julkunen-Tiitto, 1985). In bark, the main fraction of polyphenols is composed by tannins, which are divided in two different classes, hydrolysable tannins and condensed tannins. The former are mixtures of simple phenols such as pyrogallol and ellagic acid, and esters of a sugar, mainly glucose, with gallic and digallic acids. Condensed tannins consist of flavonoid units (essentially flavan-3-ols and flavan-3,4-diols) which have suffered varying degrees of condensation, and are associated with carbohydrates and traces of amino and imino-acids (Fradinho et al., 2002). The bark of many conifers consists mainly of condensed tannins, also called proanthocyanidins (Fengel & Wegener, 1984b).

Most of flavones and flavonols are obtained in the dichloromethane fractions and ethyl acetate extract of pine because of their low polar nature. The presence of flavonoids and phenolic acids in various species of pine has been variously reported (Kahlouche-Riachi et al., 2015). To extract flavonoid glycosides and higher molecular weight phenolics, solvents of higher polarity like ethanol or ethanol–water mixtures can be used, resulting in higher yields of total extracted polyphenols. Due to such a huge group of aromatic phytochemicals, several solvents must be evaluated to yield the higher amount of molecules of interest and to decrease concomitantly the treatment costs (Ayala-Zavala et al., 2011). One study reported selective extraction of flavan-3-ol monomers, catechin and flavonols preferentially in the organic phase, whereas procyanidins were extracted in the aqueous phase (Bonilla, Mayen, Merida, & Medina, 1999). The proanthocyanins, which are oligomers of catechin and epicatechin, are highly soluble in ethyl acetate (Thorat et al., 2013). Considering the ethanol and water extractives in *P. pinaster* bark, the extractives yield varies between 2.5-11.6% and 2.6-16.0% dry bark, respectively (Table 1).

Proanthocyanidin in pine bark is composed of flavan-3-ol subunits linked mainly through C4-C8 bonds (Ku et al., 2007).

The methods applied to analyse polyphenols are usually carried out in the supernatants of the extractions performed. However, in these extraction methods a fraction of polyphenols is left in the extraction residue, these are called the non-extractable polyphenols (NEP) or macromolecular antioxidants (Sáyago-Ayerdi et al., 2016). Studies of NEP are scarce when comparing with studies on extractable...
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polyphenols (EP). NEP are mostly proanthocyanidins, hydrolysable tannins and, phenolic acids (Pérez-Jiménez & Torres, 2011).

**EXTRACTION METHODS**

The extraction of components from plants due to its therapeutic effect has been practiced since ancient times, using decoction, maceration, infusion, digestion and percolation methods. With the modernization of the 19th and 20th century, an improved solid-liquid technique was introduced, named “Soxhlet extraction”, which is a form of digestion and decoction methods and is still a reference technique for extraction (Belwal et al., 2018; Jensen, 2007). Table 2 presents yields of extractions of *P. pinaster* components. Vázquez, González-Alvarez, Freire, López-Suevos, and Antorrena (2001) obtained 30.7% (w/w) when extracting *Pinus pinaster* bark from Spain with 5.0% NaOH at 90 °C for 30 min with 1/6 solid/liquid ratio (S/L). Also Fradinho et al. (2002) extracted Portuguese pine bark with 2% NaOH at 100 °C for 30 min with a S/L ratio of 1/10 and obtained a yield of 33.6% (w/w). Vieito, Fernandes, Vaz Velho, and Pires (2018) extracted the bark from *Pinus pinaster* Aiton subsp. *atlantica* of Northwest of Portugal, from trees with 15 years. They performed Soxhlet extractions with water, ethanol and a mixture of both (1:1), for 4 hours with a 1/17.6 S/L ratio. A higher yield was obtained with the water/ethanol mixture (1/1) (17.55% w/w). Braga et al. (2008) also extracted *Pinus pinaster* by Soxhlet with ethanol, for 120 min with a S/L ratio of 1/50 and obtained 9.7% (w/w) dry basis. Nevertheless, these techniques have the disadvantage of using larger volumes of solvent and also taking a long time for extraction (Belwal et al., 2018). Thus, the global environmental concern and also the demand for natural products led to the development of “green extraction techniques” and non-hazardous solvents. Commonly used solvents in extraction of food components are water, ethanol (or ethanol-water mixtures), hexane, and carbon dioxide, however there is a growing interest for using green extraction solvents, which is devoted to the environmental friendly nature and can meet both industrial and economical demand (Aguilera, 2003; Belwal et al., 2018). In recent years, extraction techniques employing water as the extracting agent have been under development, with a view to reduce the environmental impact. In these cases, it is necessary to employ high extraction temperatures to facilitate the recovery of the less polar compounds (Liazid et al., 2010); therefore, work is being directed towards high-pressure techniques, such as microwave-assisted extraction (MAE) or extraction with pressurised liquids (PLE), because they allow for working at temperatures above the boiling point (Liazid et al., 2010). The more notable “green techniques” besides MAE and PLE are ultrasound-assisted extraction (UAE), pulsed electric field assisted extraction (PEF) and enzyme assisted extraction (EAE), due to the relative simplicity with which they can be scaled up to industrial levels (Belwal et al., 2018; Liazid et al., 2010). Aspé and Fernandez (2011) compared conventional maceration, Soxhlet extraction, MAE and UAE, for extraction of *Pinus radiata* bark in one and three more stages. They concluded that with one-stage extraction, Soxhlet extraction scored the highest yield, and with three more stages only MAE and UAE could increase their yield, total phenols and tannin concentration, without damaging the sample. Nevertheless, MAE was the best technique. Chupin et al. (2015) extracted *Pinus pinaster* bark from France by microwave-assisted extraction with ethanol/water (80/20) and obtained 13.16% (w/w). Seabra et al. (2012) applied high pressure extraction (HPE) to pine bark using CO₂/EtOH (30/70) as solvent at 30 °C for 210 min and obtained 6.51% (w/w). For efficient extraction outcomes, not only the type of extraction methods used is important to ensure high extraction yield but also the sample preparation, namely particle size and drying conditions, selected
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solvent, solid-liquid ratio for each solvent, temperature and time of contact between sample and solvent (Belwal et al., 2018; Pinelo et al., 2004). Chupin et al. (2015) reported that the particle size influenced the amount of polyphenols extracted, being that the smaller the particle size of ground bark (up to 400 µm), the more is extracted. A smaller particle size allows a larger area of contact between particle and solvent. Regarding the sample drying, it is necessary because it influences the final concentration of the compound in the extract. It also helps if the sample is to be stored for an extended period of time, since it prolongs the shelf life by reducing the microbial growth and enzymatic activity (Belwal et al., 2018). Regarding the selected solvent, Vázquez et al. (2001) verified that the extract yield from *Pinus pinaster* bark increased between 2.5 and 6-fold when alkaline extractant solutions were used.

When assessing the success of an extraction method, the total phenolic compounds and antioxidant activity should also be taken into account. Jerez, Pinelo, Sineiro, and Nunez (2006) studied the influence of some critical extraction variables, such as temperature, time of contact and solid-liquid ratio, on the phenolic yield and antiradical activity of resultant extracts and found the following models:

\[
C_{\text{polyphenols}} = 11.3 - 4.1 \frac{L}{S} + 0.6T \\
\text{IP} = 54.5 - 18.4 \frac{L}{S} + 4.0t + 3.3T - 3.3 \frac{L}{S}t
\]

where \(C_{\text{polyphenols}}\) is the concentration of polyphenols in g GAE/L (gallic acid equivalent/L), IP is the inhibition percentage, \(L/S\) represents liquid-solid ratio in mL/g, \(T\) the extraction temperature in °C and \(t\) means time of contact in min. The optimum extraction conditions with respect to phenolic compound yields (equation 1) for *Pinus pinaster* bark in ethanol were determined at 50 °C for 90 min at the solid-liquid ratio of 1:5 (w/w). The authors found that the antiradical activity was higher when the extraction temperature was higher. On the other hand, they concluded that the contact time had no significant influence, indicating that the structure of the pine bark matrix allows the release of phenolic species more easily than do other natural matrices, which avoids long extraction times (Jerez et al., 2006). Also, Meullemiestre, Petitcolas, Maache-Rezzoug, Chemat, and Rezzoug (2016) who extracted *Pinus pinaster* sawdust by UAE obtained the following model regarding total phenolic content (TPC) expressed in mg of catechin equivalent per 100 g of dried pine sawdust:

\[
\text{TPC} = 309.67 - 13.15UI + 68.89T + 19.21t - 14.49T^2 - 16.41t^2
\]

where UI is the ultrasonic intensity (W/cm²), \(T\) is the temperature (°C) and \(t\) is the time (min).

Sometimes, the methodologies used for extraction, extract other non-phenolic substances, such as sugars, organic acids and proteins, requiring subsequent purification processes (Ignat, Volf, & Popa, 2011).
Table 2. Yields of extractions of P. pinaster components

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
<th>Operation conditions</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Pinus pinaster</em> sawdust from La Coruña, Spain</td>
<td>8.19% (w/v)</td>
<td>rotary shaker; 96% ethanol; 25 °C; 30 min; S/L: 1/10</td>
<td>Pinelo et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>2.86% (w/v)</td>
<td>rotary shaker; methanol; 25 °C; 30 min; S/L: 1/10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.32% (w/v)</td>
<td>rotary shaker; acidified water w/ HCl (pH=4); 50 °C; 90 min; L/S: 5/1</td>
<td></td>
</tr>
<tr>
<td><em>Pinus pinaster</em> bark from Santiago de Compostela, Spain</td>
<td>30.7% (w/w)</td>
<td>Water bath in reactor with stirring; 5.0% NaOH; 90 °C; 30 min; S/L: 1/6</td>
<td>Vázquez et al. (2001)</td>
</tr>
<tr>
<td><em>Pinus pinaster</em> bark from Viana do Castelo, Portugal</td>
<td>17.55% (w/w)</td>
<td>Soxhlet; water/ethanol (50/50); solvent boiling point; 240 min; S/L: 1/17.6</td>
<td>Vieito et al. (2018)</td>
</tr>
<tr>
<td></td>
<td>17.08% (w/w)</td>
<td>Soxhlet; 96% ethanol; solvent boiling point; 240 min; S/L: 1/17.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.84% (w/w)</td>
<td>Soxhlet; water; solvent boiling point; 240 min; S/L: 1/17.6</td>
<td></td>
</tr>
<tr>
<td><em>Pinus pinaster</em> bark from Landes of Gascony, France</td>
<td>13.16% (w/w)</td>
<td>Microwave-assisted extraction; ethanol/water (80/20); ------; 3 min; S/L: 1/10; 100 W</td>
<td>Chupin et al. (2015)</td>
</tr>
<tr>
<td><em>Pinus pinaster</em> bark from Portugal</td>
<td>33.6% (w/w)</td>
<td>Maceration; 2% NaOH; 100 °C; 30 min; S/L: 1/10</td>
<td>Fradinho et al. (2002)</td>
</tr>
<tr>
<td><em>Pinus pinaster</em> bark from Beira Litoral, Portugal</td>
<td>9.7% (w/w)</td>
<td>Soxhlet; 99.5% ethanol; solvent boiling point; 120 min; S/L: 1/50</td>
<td>Braga et al. (2008)</td>
</tr>
<tr>
<td><em>Pinus pinaster</em> bark from Beira Litoral, Portugal</td>
<td>6.58% (w/w)</td>
<td>Soxhlet; 99.5% ethanol; solvent boiling point; 120 min; S/L: 1/50</td>
<td>Seabra et al. (2012)</td>
</tr>
<tr>
<td></td>
<td>6.51% (w/w)</td>
<td>High Pressure Extraction (HPE); CO₂/EtOH (30/70); 30 °C; 210 min; S/L: 170 ± 10:1; 25.1 MPa; 7.6x10⁵ kg/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.86% (w/w)</td>
<td>High Pressure Extraction (HPE); CO₂/EtOH (90/10); 30 °C; 360 min; S/L: 254 ± 28:1; 25.1 MPa; 7.6x10⁵ kg/s</td>
<td></td>
</tr>
</tbody>
</table>

Note: Operation conditions are: method; solvent; temperature; time; solid/liquid ratio (S/L); power; pressure; flow rate.

IDENTIFICATION OF EXTRACTIVES

As mentioned in the sub-section “Polyphenols”, these include a very diverse family of compounds. Hence, to analyse them, many methods have been developed, namely the Folin-Ciocalteu assay which is widely used for determining total phenolics, the vanillin and proanthocyanidin assays that have been used to estimate total proanthocyanidins and pH differential assays for anthocyanins (Ignat et al., 2011; Pérez-Jiménez & Torres, 2011). The main disadvantage of the spectrophotometric assays is that they only give an estimation of the total phenolic content. They do not separate nor do quantitative measurement of individual compounds (Ignat et al., 2011). Then there are specific methods directed at individual phenolics, such as High Performance Liquid Chromatography (HPLC) or Gas Chromatography (GC) techniques (Pérez-Jiménez & Torres, 2011). HPLC is the preferred one for separation and quantification of polyphenols. The chromatographic conditions usually include the use of a reversed-phase C18 column, UV-Vis diode array detector, and a binary solvent system containing acidified water (solvent A) and a polar organic solvent (solvent B) (Ignat et al., 2011). Also, HPLC is often combined with Mass Spectrometry (MS) (Sáyago-Ayerdi et al., 2016). Nonetheless, due to the disadvantages in detection limit
and sensitivity, HPLC methods present limitations especially in complex matrix, such as crude plant extracts and environmental samples (Ignat et al., 2011).

**EXTRACTIVES APPLICATIONS**

The antioxidant compounds obtained from biomass sources can be used to increase the stability of foods by preventing lipid peroxidation and also protect against oxidative damage in living systems by scavenging oxygen radicals (Moure et al., 2001). Moreover, the food market is demanding natural antioxidants, free of synthetic additives (Tomović, Jokanović, Šojić, Škaljac, & Ivić, 2017).

There is a polyphenol concentrate extracted from the bark of *P. pinaster* in France, Pycnogenol (US Pat. No. 4,698,360), which is used throughout the world as a food supplement with a protective effect against chronic and degenerative diseases (D’Andrea, 2010). Although the pine bark water or ethanolic extracts have not been completely elucidated, the main constituents described in the literature for Pycnogenol indicate that it contains catechin, epicatechin and taxifolin (Packer, Rimbach, & Virgili, 1999). Some studies have been published on the utilisation of Pycnogenol in meat products (Ahn, Grün, & Mustapha, 2004, 2007; Hameş-Kocabaş, Yeşil-Çeliktaş, İşleten, & Vardar-Sukan, 2008) and yoghurt (Ruggeri et al., 2008).

Hameş-Kocabaş et al. (2008) observed that the addition of 1% of Pycnogenol to meat reduced the growth of *S. aureus* during storage when compared to control. Ahn et al. (2007) verified that Pycnogenol retained the redness of cooked beef during storage as well as reduced the numbers of *Escherichia coli* O157:H7 and *Salmonella typhimurium* and retarded the growth of *Listeria monocytogenes* and *Aeromonas hydrophila*. Ruggeri et al. (2008) observed that the enrichment of yoghurt with Pycnogenol did not promote any fermentative activities of the lactic acid bacteria, nor did it affect the protein and lipid contents. This suggests the utilization of Pycnogenol as a valuable ingredient to enrich yogurt preparation. Regarding the statements above, P. pinaster bark extract has the potential to be used as a natural preservative in the food industry. However, when applying a natural antioxidant in a food product, the extract must comply with some criteria such as be absent of any toxic or physiological effect, do not give any strong odour, flavour, or colour to the food product, and have significant antioxidant activity in small concentrations in the food product (Oreopoulou, 2003).

**FUTURE RESEARCH DIRECTIONS**

The influence of tree age and edaphoclimatic conditions on polyphenols content and antioxidant properties should be ascertained, together with comparison of extractions methodologies for maximum yield and antioxidant efficacies.

Testing these new extractives compounds on their toxicity towards different target cell lines is essential for the development process of a food additive or a food supplement or for cosmetic applications. Studies on antimicrobial properties against target microorganisms causing food-borne diseases should be performed to widen its application potential.
Pinus Pinaster Bark Composition and Applications

CONCLUSION

Characterization of compounds present in bark of Pinus pinaster Aiton subsp. atlantica of Northwest of Portugal, together with identification of their biological activity represents a key tool in determining the choice of suitable methods for obtaining these compounds and testing them for further development at a commercial scale, either as a food additive as well for cosmetics or nutraceutical applications.

ACKNOWLEDGMENT

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REFERENCES


Pinus Pinaster Bark Composition and Applications


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Chapter 9

Technologies for Monitoring the Safety of Perishable Food Products

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ABSTRACT

Food safety and eradication of food waste are current concerns of society and governments due to health, ethics, and sustainable economics. There are multiple technologies for monitoring food safety at different chain stages, among them, time-temperature integrators (TTI). Temperature is a major factor affecting food quality and safety during its life cycle. This parameter can be monitored using TTI devices on food packages, allowing users to know the thermal exposure. This chapter addresses food safety issues, namely factors related to microbial growth responsible for food deterioration. Moreover, TTI monitoring technologies are also described, focusing on features, advantages, disadvantages, applicability, and product examples. Analysis of the current state of TTI and technological evolution, a prediction is provided for future TTI devices designed for more assertive, traceable, safe, and quality food products.

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INTRODUCTION

Food waste is a persistent reality in the actual society. This is an upmost issue with substantial relevance, not only by the intrinsic ethical questions, but also to the relation between food consumer and producer (APIC, 2006). Food shortage in the world are due to lack of socio-economic conditions of parts of the population, this causes an immorality that condemns the existence of food waste, specially that 925 million people suffer of malnutrition in the world (APIC, 2006). Additionally, food waste is translated into costs to final consumers, distributors and producers. Lastly, food waste leads to degradation of natural resources such as water, soil, or energy consumption, affecting biodiversity preservation and air quality (ANCIPA, 2005). In recent years, a major priority for distributors is to provide high quality food (in a good state of conservation) to consumers, which became more aware and concerned with food quality standards (ANCIPA, 2005).

The Food and Agriculture Organization of the United Nations (FAO) estimates that one-third of the total food produced for human consumption is lost or wasted, approximately 1.3 billion of tons. This corresponds to annual costs of 750 billion dollars (FAO, 2011). The economical impact is significant due to loss of product value, nevertheless the environmental impact has to be accounted too, food waste leads also to waste of natural resources, such as water, land, energy, and unnecessary green gas emissions leading to global warming and climate change. This, in turn, affects agriculture and food production. Moreover, the FAO CEO, Graziano da Silva, reported during the Global Green Grout Forum (3GF) realized in Copenhagen (Denmark) in October of 2013, that food waste reduction to zero could provide sufficient food for 2 billion people. Thus, the FAO appeals for innovative ways to control and reduce this global food waste problem. FAO indicates that the major food waste happens in post-production phase, as well as during the harvest, transportation and storage. In developing countries, food waste is related with inadequate infrastructures, while in developed countries is a problem between commercialization and consumption phases (Gogou et al., 2013).

In the 27-member states of the European Union (EU), annual food waste is about 89 million tons, with a prediction of a rise to 126 million tons in 2020. In the case of perishable food products, such as the horticultural products, 30% of the European production is wasted after harvest (FAO, 2013). According to 2012 data, only in Portugal, about 1 million tons of food is wasted, i.e., about 17% of the total production (O’Connor, 2014).

The European Parliament declared 2014 as the European Year against the Food Waste, in order to take measures to solve this problem.

This is a worldwide problem, from agricultural field to consumers. Significant part of the problem is due to consumer behaviour, i.e. avoiding to buy “imperfect” horticultural products or with “small dimension” or products with closer expiry date.

To overcome this problem with serious ethical, social, environment and economic consequences, the European Parliament called a collective and urgent action to reduce food waste in half until 2025. Nonetheless, European Commission hopes to reach this target by 2020, since the “Roadmap to a Resource Efficient Europe” has been given a priority (Baptista et al., 2012) This ambition involves an assertive effort between all food chain parties. Additionally, many initiatives and campaigns have started to sensitize producers, sellers and consumers for the food waste problem.

Alternatively, ensuring food safety will reduce waste in the production, transportation and food display, and will help consumers to change their behaviour (APIC, 2006).
The time span, under storage conditions, which food remains acceptable for human consumption (in terms of safety, nutritional attributes, and sensory characteristics) is known as shelf life (Bell & Labuza, 1992; Corradini & Peleg, 2006; van Boekel, 2009; Jedermann et al., 2014). Food progressively deteriorates leading to loss of quality and safety, this is accelerated by inadequate storage and distribution conditions, such exposure to high temperatures or humidity (Taoukis et al., 1997; Labuza, 2001; van Boekel, 2008).

Perishable food products have high quantity of water and nutrients, essential elements for microorganisms to develop. This type of products requires special conditions to its conservation, storage and transportation (EU, 2015). Low temperature conservation is constantly required to extend lifespan and avoid deterioration. Examples of perishable products are all the fresh products of meat, fish, fruits and vegetables as well milk and its derivatives. Non-perishable foods, on the other hand, have low water content. Most of these products are vegetables, which can be stored in a dry environment at room temperature (for example: rice, beans, etc.). This type of food is a concern for production and distribution companies because they do not need specific conditions of preservation to be maintained. Fundamentally, conditions are harsh for microbial development (ANCIPA, 2005). Thus, the lifespan is longer and conservation requirements are lower.

Researchers focus towards creating new tools and improving the tracking capability/food safety in situ monitorization, in particular, the refrigerated chain, where quality and contamination risk is higher (FAO, 2011). At the retail stores around 15% of perishable foods are wasted as a consequence of damage and spoilage (Ferguson & Ketzenberg, 2006). This increases to approximately 35% when proper temperature conditions are not applied (Zoller et al., 2013). Therefore, monitoring food distribution and storage is critical to avoid food deterioration and waste, and ensuring the costumer on the product freshness (Annese et al., 2015). Hence, developing technologies to monitor quality of food products during all stages, from production to consumer, is crucial to reduce food safety outbreaks and lower food waste (ANCIPA, 2005).

**HYGIENE AND FOOD SECURITY**

The Role of Food Hygiene in Ensuring the Viability/Food Security

Food hygiene is the upmost important method to maintain product safety. Consisting on a set of measures that ensures safety and healthiness during food production: processing, manufacturing, packaging, storage, distribution, handling and sale (ANCIPA, 2005). Food contamination during preparation can lead to quicker food deterioration or worse, by jeopardizing safety causing diseases to consumers. The most infamous food contamination case was Typhoid Mary. In the 19th century Typhoid fever was identified and *Salmonella enterica* serovar Typhi was isolated. At that time, no antibiotics were available and mortality rate was at least 10%. Mary Mallon, named Typhoid Mary, carried the disease but never had any symptoms. In multiple occasions she was forbidden to practice cooking with enforced isolation, but anyway she constantly found a way to handle food for other people. Only Mallon infected 51 people, 3 of whom died. This stubbornness made society aware and started to protect itself (Brooks, 1996).

addition, the traceability and consequent contact between foods within packing is governed by the EC Regulation n.º 178/2002 and it should be rigorously followed.

**Food Hazards**

Besides physical (harmful materials, such as sharp metals) and chemical hazards (harmful toxic chemicals, such as cleaning agents), biological hazards are the source most concerns. Avoiding biological hazards is difficult and complicated due to the dependence of several factors. The food processing and the development of pathogenic bacteria rely heavily on the exposure. This can be caused by a macro-biologic agent (presence of flies or other insects) or microbiological agent (pathogenic bacteria, viruses and parasites).

Hazard severity and frequency classification is achieved by implementing a Hazard Analysis and Critical Control Point (HACCP) certification (Venâncio & Batista, 2003). This determines which hazards are more significant (Ellouze & Augustin, 2010).

**Microbial Growth Factors**

Microbial development is dependent of favourable conditions. The rate of microbial growth becomes exponential after cell adaptation to the environment. When nutrients are depleted or inhibitory metabolites are accumulated, growth reaches the stagnation phase or stationary phase.

Regarding the factors that affect the rate of microbial growth in food, these have the ability to determine the nature of the damage and thus have some risks to health. Some of these factors affecting the rate of microbial growth in food product are shown in Table 1 (Venâncio & Batista, 2003).

**Extrinsic Microbial Growth Factors**

Extrinsic factors are environmental conditions for storing food products that affect microbial growth. These factors are relative humidity, temperature and atmospheric composition (Venâncio & Batista, 2003).

**Relative Humidity**

Humidity is the moisture content of air, being the mass ration of water vapor to dry air. Relative humidity is the ratio as a percentage of the partial pressure of water vapor in air to the vapor pressure of liquid water at a given temperature. This is an essential measure of water activity of the gas phase. In regions where the water activity is low and the food is stored in atmospheres with high relative humidity.

Water can be transferred to the gas phase in foods and promote the growth (germinate and grow) of microorganisms that remained viable until the point, but unable to develop themselves.

*Table 1. Factors affecting the rate of microbial growth in food products (Venâncio & Batista, 2003)*

<table>
<thead>
<tr>
<th>Microbial Growth Factors</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>Physicochemical food properties</td>
</tr>
<tr>
<td>Extrinsic</td>
<td>Storage environment conditions</td>
</tr>
<tr>
<td>Processing factors</td>
<td>Disregard for proper food manufacture (time and temperature)</td>
</tr>
</tbody>
</table>
Technologies for Monitoring the Safety of Perishable Food Products

Temperature

Microbial growth can occur at a wide temperature range depending on the microbe. Growth can be explained as simple as by the cell enzymatic activity. Enzymes are designed by biological organisms to have an optimum activity to allow the best adaptation to the environment temperature, pressure, pH, aw, etc. Temperature affects activity and can even lead to enzymatic denaturation (microbial inactivation). Low temperatures, slow down enzymatic reactions, growth rate is low (this is what happens in freezing or refrigerating temperatures). High temperatures, also inhibit enzyme activity, but it can lead to denaturation, growth is inhibited and microbes are inactivated (i.e. cooking food, pasteurization, sterilization). Higher temperature and longer exposure time will determine the amount of microbial inactivation. Microbial growth occurs when optimum temperature range is met, at lower temperatures growth rate is lower, at high temperature growth is also lower but if temperature is too high growth can be completely inhibited. An important requirement is the presence of liquid water as a basis that supports the growth.

Atmosphere Composition

Oxygen presence in the atmospheric composition and its potential influence on the oxidation/reduction allows the development of microbes. The common methods to reduce the microbial growth based in modified atmosphere packaging consist in: inhibitory effect of atmosphere enrichment with carbon dioxide CO₂ (with the consequent reduction of oxygen, O₂, and pH change on the food surface); oxygen impoverishment in the atmosphere (reducing respiratory intensity and consequent delay in maturation); and atmosphere modification with an inert gas such as the nitrogen, N₂. Though, lowering or removing completely oxygen from the atmospheric composition can lead to anaerobic microbial growth. Pathogenic bacteria such as Clostridium species are anaerobic and can lead to serious infections, for example, the ingestion of botulinum toxin produced by Clostridium botulinum. Increasing CO₂ can help inhibiting bacterial growth by lowering the pH.

Intrinsic Factors of Microbial Growth

Microbial growth also depends on factors related with the food itself.

Nutrients

For microbial growth to occurs the right carbon and nitrogen source need to be present. If the right nutrient is present in the food composition, growth will occur, i.e., key nutrients concentration, in some cases, can determine the rate of microbial growth. Examples of nutrients that promote microbial growth are: carbohydrates, proteins, fats, minerals and vitamins.

pH

Depending on the food type, pH can be optimum for microbial growth. Food pH has an important effect on growth and viability of microorganisms. This is also explained by stability of biomolecules, cells need to maintain an intracellular pH above a critical limit, otherwise denaturation of proteins occurs. Therefore, each microbe has a specific pH range which they can grow. In general, most microbes grow best around neutral pH values (6.5 - 7.0). However, different microorganisms resist to different pH’s, some can resist in extreme pH conditions (pH as low as 1 and high as 9), yet these microbes are found in
Technologies for Monitoring the Safety of Perishable Food Products

extreme conditions in the nature. In food environments, Yeasts and Moulds and some bacteria are more resistant to lower pH (low as 3.0), due to the production of acidic compounds from their metabolism, such as lactic acid (lactic acid bacteria) and acetic acid (yeasts and others). Generally bacterial pathogen growth is inhibited at pH lower than 4, that is the case of some preserves and fermentation processes.

Naturally acidic type of foods are fruits, been the reason why yeasts and mould are more susceptible to develop and cause spoilage. Neutral pH, such as meat, are more prone for pathogenic bacteria to grow.

Carbohydrate rich food tend to deteriorate by acid hydrolysis, reducing pH (reducing the risk of pathogens), protein-rich food, the pH increases, when spoiled, meaning its less safe with a higher risk of a pathogen to grow.

Oxidation/Reduction Potential

Chemical composition of foods influences the oxidation/reduction potential (Eh), thus affecting microbial growth. Positive redox potential is required for aerobic microorganisms, whereas anaerobes need a negative potential. Oxygen plays an important part in the redox potential due to our oxidizing atmosphere, however, oxygen presence is not an utter prerequisite for redox reactions since other compounds can accept electrons.

Plant origin foods have a typical Eh of +300 to 400 mV, aerobic growth is favoured. On the other hand, anaerobic growth is favoured on meat products due to the redox potential of -200 mV

Water Activity ($a_w$)

Free water in the food is required for microbial growth, in other words, for all cellular biochemical reactions to occur: transport nutrients, remove released products of enzymatic reactions for the synthesis of cellular materials and participate in other biochemical reactions. Each microbial species (or group) has an optimum level, maximum and minimum of water activity for growth. When $a_w$ is reduced until a minimum level for microbial growth, the cells remain viable temporarily. However, if the water activity is dramatically reduced, the microbial cells lose their viability, usually more quickly at first and then slowly. Most enzymatic reactions require $a_w$ levels higher than 0.85, bacterial growth does not occur at $a_w$ levels lower that 0.9, and for moulds and yeasts the $a_w$ limit of growth is between 0.8 to 0.9. However, food cannot be all converted to low $a_w$ levels to ensure microbial inhibition, for example, fresh fruits need to be stored with other means because high air moisture will preserve the texture and the $a_w$ will remain higher than 0.95.

Antimicrobials

Natural antimicrobial substances are present in food, these substances are able to inhibit microbial growth. Some examples are lysozyme in eggs, essential oils, lactoferrin from cows’ milk, among others.

Common Bacteria Responsible for Food Contamination

In a review about food hazards, microorganisms are those that provide greater danger (Surak, 2003; Ellouze & Augustin, 2010).

The attention given by the producers to food hazards focus primarily on microbiological hazards that represent a significantly higher number of cases than the other types of contamination.
Technologies for Monitoring the Safety of Perishable Food Products

Among the microorganism variables that are possible to identify are:

- The variability expression of the many pathogenic mechanisms;
- The microorganism potential to cause disease;
- The sensitivity of the microorganism to the food substrate characteristics and with the surrounding environmental conditions;
- The nature of the interactions with other organisms.

Table 2 includes examples of common bacteria in food contamination and the main conditions to the occurrence of some of the biological dangers (Venâncio & Batista, 2003).

Bacteria in a certain concentration can be considered as having an infective dose, because has the minimum number of microorganisms necessary to cause a disease. This can change from individual to individual due to the fact that is necessary to have in consideration that there is a set of physiological nature factors that influence the level of minimum infective dose (degree of gastric acidity, intestinal flora, immunity, nutritional status and individual stress, ...).

Preventive Measures

To prevent the contamination of food is essential to implement some good practices that support this goal. In the food industry, the food products mixing and heat supply is made simultaneously to ensure safety and to avoid physiological damage to the consumer.

Processes Used in Minimizing Food Contamination

The mixture of certain levels of nutrients, oxygen and favourable pH are necessary conditions to provide the microorganism growth. Perishable foods are the foods most susceptible to deterioration by microbial growth (Mehauden, 2009; Li & Wang, 2012).

Table 2. Examples of common bacteria in food contamination and the main conditions to the occurrence of some of the biological dangers (Venâncio & Batista, 2003)

<table>
<thead>
<tr>
<th>Bacteria</th>
<th>$T_{\text{min}}$ ($^\circ$C)</th>
<th>$T_{\text{max}}$ ($^\circ$C)</th>
<th>$pH_{\text{min}}$</th>
<th>$pH_{\text{max}}$</th>
<th>$a_w_{\text{min}}$</th>
<th>$NaCl_{\text{max}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacillus cereus</td>
<td>5</td>
<td>55</td>
<td>4.9</td>
<td>8.8</td>
<td>0.93</td>
<td>10</td>
</tr>
<tr>
<td>Campylobacter jejuni</td>
<td>32</td>
<td>45</td>
<td>4.9</td>
<td>9.0</td>
<td>0.98</td>
<td>2</td>
</tr>
<tr>
<td>Clostridium perfringens</td>
<td>12</td>
<td>50</td>
<td>5.5</td>
<td>9.0</td>
<td>0.943</td>
<td>7</td>
</tr>
<tr>
<td>Escherichia coli</td>
<td>7</td>
<td>46</td>
<td>4.4</td>
<td>9.0</td>
<td>0.95</td>
<td>6.5</td>
</tr>
<tr>
<td>Listeria monocytogenes</td>
<td>0</td>
<td>45</td>
<td>4.39</td>
<td>9.4</td>
<td>0.92</td>
<td>10</td>
</tr>
<tr>
<td>Salmonella spp.</td>
<td>5</td>
<td>47</td>
<td>4.2</td>
<td>9.5</td>
<td>0.94</td>
<td>8</td>
</tr>
<tr>
<td>Shigella spp.</td>
<td>7</td>
<td>47</td>
<td>4.9</td>
<td>9.3</td>
<td>0.97</td>
<td>5.2</td>
</tr>
<tr>
<td>Vibrio parahaemolyticus</td>
<td>5</td>
<td>43</td>
<td>4.8</td>
<td>11</td>
<td>0.94</td>
<td>10</td>
</tr>
<tr>
<td>Yersinia enterocolitica</td>
<td>-1</td>
<td>42</td>
<td>4.2</td>
<td>9.6</td>
<td>0.97</td>
<td>7</td>
</tr>
</tbody>
</table>
Technologies for Monitoring the Safety of Perishable Food Products

By microorganisms’ growth, there is a consumption of nutrients and the production of enzymes that contribute for the loss/contamination of flavours or synthesis of compounds, which will cause the food to become unsuitable to consumption, ultimately could cause disease. However, not all microorganisms are pathogenic, this parameter depends on its concentration in the food product (infective dose).

Effectiveness of Thermal Treatments (Production of Food Safe)

Due to consumer pressure, regulations have been created and applied on food safety and quality to ensure consumer protection. The food producers are responsible for the safety of their products. To ensure this security, the food products are submitted to different techniques that allow the reduction of the number of microorganisms or eliminate pathogenic microorganisms in food (Mehauden et al., 2007). Table 3 describes several food preservation techniques.

Heat Treatments

The quality requirements on food manufacturing became increasingly demanding over the last 20 years. Fundamentally, the product may not cause damage to the consumer. To ensure food safety, manufacturers have been using different techniques for preservation (Mehauden et al., 2007).

Table 3. Food preservation techniques

<table>
<thead>
<tr>
<th>Preservation Technique</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hygiene</td>
<td>• The microorganisms’ growth can be delayed or prevented by the fulfilment of hygiene rules for food production.</td>
</tr>
<tr>
<td>HACCP</td>
<td>• The food security methodology can be applied to reduce contamination;</td>
</tr>
<tr>
<td></td>
<td>• Depends on the identification of Critical Control Points (CCP) in the food production and preparation process;</td>
</tr>
<tr>
<td></td>
<td>• The food products are strictly monitored in order to ensure the food safety for consumption.</td>
</tr>
<tr>
<td>Chemistry preservation</td>
<td>• Chemicals such as salt or acid can be added on foods to reduce its pH or reduce the water activity ($\omega_w$), thus limiting the growth of microorganisms.</td>
</tr>
<tr>
<td>Biological fermentation</td>
<td>• The fermentation purpose is to allow the growth of unwanted microorganisms. These are added on food in order to compete with the unwanted and harmful microorganisms causing its annulation;</td>
</tr>
<tr>
<td></td>
<td>• It is the oldest method of food preservation.</td>
</tr>
<tr>
<td>“Smart packing”</td>
<td>• Used in order to extend the food product shelf life, through oxygen removal, capturing of carbon dioxide and mixing with control agents or antimicrobial agents inside of the product packaging.</td>
</tr>
<tr>
<td>Microorganisms removal by microfiltration</td>
<td>• Considered a “cold” pasteurization;</td>
</tr>
<tr>
<td></td>
<td>• Used for liquid products such as milk and beer.</td>
</tr>
<tr>
<td>Thermal treatment</td>
<td>• Unlike the heat treatment, the cold preservation does not eliminate the microorganisms present, but slows their growth;</td>
</tr>
<tr>
<td></td>
<td>• Low temperature methods include refrigeration and freezing.</td>
</tr>
<tr>
<td>Irradiation</td>
<td>• In this technique, electromagnetic waves or electrons are applied in food;</td>
</tr>
<tr>
<td></td>
<td>• Ionization and UV radiation causes damages on microorganism DNA and lethal injuries;</td>
</tr>
<tr>
<td>High pressure (Pascalization)</td>
<td>• The pressures in the range of 200 MPa to 800 MPa are applied to food causing the damage in cell membrane of the microorganism and denaturation of its proteins;</td>
</tr>
<tr>
<td></td>
<td>• This technique (recent) is very appealing in the food production industry.</td>
</tr>
<tr>
<td>Pulse electric field</td>
<td>• The application of an electric field in food usually causing damage on the membrane of microorganism during the voltage application;</td>
</tr>
<tr>
<td></td>
<td>• Can only be applied to liquid food such as orange juice.</td>
</tr>
</tbody>
</table>
The food treatment by heat consists in an operation that aims cooking/food producing and simultaneously reduce/prevent the microbial growth responsible for the “poisoning”. The impact of these preservation techniques in food safety and quality is quantified by its effectiveness. Table 4 describes thermal treatments ranked according to their temperatures (Mehauden, 2009).

Theoretically, the duration of treatment by heating depends on several parameters (Surak, 2003):

- Thermal resistance of the microorganisms and spores hypothetically present in the food;
- Thermal characteristics;
- The food pH and characteristics of its nutrients;
- Shape and size of the package;
- Physical conditions of food (liquid, solid or mixture).

The thermal processes used can be determined from mathematical modelling. Mathematical models depend on the product time-temperature profile and the elimination kinetics of the desired microorganism. The thermal process calculation is based on the amount of destruction of the heat-resistant bacterium, *Clostridium botulinum* (Mehauden, 2009).

### MONITORING TECHNOLOGY OF FOOD SAFETY OF PERISHABLES FOOD PRODUCTS

Food monitoring allows, to some point, to improve the distribution and supply of these products to the sales centres and to evaluate quality at different phases/stages of the food chain (Gogou *et al.*., 2014).

To this end, electronic devices named Time-Temperature data logger are used to evaluate food quality. There are several types of these devices, depending on their operating principle (Taoukis *et al.*, 2010).

### Monitoring of Food Products

Perform the tracking of a product along all the food chain is the best way to evaluate the various steps or critical points (Taoukis *et al.*, 2010). This is also the best way to reduce food waste and maximize the producer profits (Mehauden *et al.*, 2007).

### Table 4. Thermal treatments ranked according to their applied temperatures (Mehauden, 2009)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasteurization</td>
<td>- Heating food process in order to eliminate the microorganisms endowed with the capacity to cause damage to the consumer (example: bacteria, virus);&lt;br&gt;- Does not eliminate all microorganisms present. Only reduces the number of sensitive microorganisms to heat for safe levels and stops the activity of most enzymes;&lt;br&gt;- Is a soft treatment and temperature applied does not exceed the 100 °C;&lt;br&gt;- Pasteurized products are constantly refrigerated and should be consumed before its expiry date.</td>
</tr>
<tr>
<td>Sterilization (Ultra High Temperature - UHT)</td>
<td>- Temperatures range between the 135 °C and 150 °C during 2 to 4 seconds;&lt;br&gt;- Treatment goal is to extinguish all pathogenic organisms and their toxins;&lt;br&gt;- Based on the destruction of the bacterium <em>Clostridium botulinum</em>, which can be lethal if swallowed.</td>
</tr>
</tbody>
</table>

Note: Clostridium botulinum - produces a botulinum exotoxin highly resistant to temperature. Its growth occurs in anaerobic environments and in conditions of pH > 4.5 allowing their growth after packaging of food products.
Technologies for Monitoring the Safety of Perishable Food Products

The consumer is aware that perishable foods products suffer quality and safety alteration when badly preserved (in not recommended environments). Thus, the consumer always chooses the product with longer expiry date (presuming to be fresher) or the one that presents most appealing organoleptic conditions. Therefore, producers become aware of the importance dynamics of the quality parameters after production of the food type, from preservation to transportation. This conscience improves the transportation, storage and sale quality standards, and clearly identifies the critical points of each key phase (Li & Wang, 2012).

Note that the lifespan or shelf-life of food products is a parameter that depends mostly on the temperature to which it is subjected. Consequently, producers consider this parameter to be crucial factor and aim to extend it to the maximum. Based on studies conducted in the food chain of Greece and France, the critical points where the food product is more subject/susceptible to thermal variations are in the transition phases along the distribution chain (small temperature oscillation) and, especially in the last stage of the chain, when consumer purchases the food product. Transition phase from supermarket to the domestic fridge/freezer and maintenance of food in this environment are the most critical points for food quality conservation (Gogou et al., 2013).

Electronic devices, such as mininOMAD, OM-84-TMP (Omega Engineering Inc., Stamford, USA) can be incorporated in the packaging monitoring effectively from food production line to consumers’ homes (Gogou et al., 2013).

As shown in Figure 1, we are able to through the analysis of results of this study it is possible understand where are the critical points on the chilled food chain. We can also conclude that food is maintained at a higher temperature and higher temperature variations during storage in domestic refrigerators (Figure 1). These thermal levels remain practically constant since the final phase of the step in which the food is placed in the supermarket display cabinets (at this stage food may be located closer to the display

Figure 1. Historical time-temperature that the perishable foods cross through a chilled chain (Gogou et al., 2013)

*For a more accurate representation see the electronic version.
Technologies for Monitoring the Safety of Perishable Food Products

cabinet door that can be opened several times a day, leading to higher temperature variations). Table 5 shows the average temperature/duration of food at each recorded stage in the study carried out on the chilled French supermarkets chain (Gogou et al., 2013).

Results presented in Table 5 show that although consumer food transportation phase (supermarket/domestic refrigerator) exposed food to higher temperatures, this is performed in a short period of time. However, this can be harmful to food integrity, such as the temperature relation of domestic refrigerator/duration (time before consumption).

Traditional Monitoring

Traditional monitoring consists in the verification of the thermal treatment effectiveness during food production phase. These treatments are used to eliminate any pathogenic agent during the production phase and the monitoring is realized in order to evaluate treatment effectiveness (Mehauden, 2009).

Thermocouples and Dataloggers

These electronic devices are incorporated on food products and used to check the thermal treatments validation/effectiveness (Mehauden, 2009).

They can be inserted into the food packaging and its objective is record the temperature inside the package during a period of time. Temperature records collected can be visualized using a graphical chart of temperature in function to time. This way of evaluating the effectiveness of thermal treatment is widely used and data analysis easier and fast (Gogou et al., 2013).

However, these electronic systems present some drawbacks in some thermal processes. For example, analysing fluid food, the electronic equipment may interfere with the proper motion of the fluid in the container, leading to an incorrect temperature recording. In many cases, it is impracticable to put it in the right place, preferably in the coolest zone of the package.

The equipment size is also a barrier that affects the recording effectiveness. A wireless datalogger, due to its big size (battery), may not be suitable for certain application cases, although this restriction has been a priority area of research and development (Mehauden, 2009).

Table 5. Average temperature/duration of food at each recorded stage in the study carried out on the chilled French supermarkets chain (Gogou et al., 2013)

<table>
<thead>
<tr>
<th>Phase of the chilled chain</th>
<th>Average temperature (ºC)</th>
<th>Duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production / Warehouse</td>
<td>3.4</td>
<td>2.7</td>
</tr>
<tr>
<td>Transportation / Distribution centre</td>
<td>3.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Distribution centre / Transportation / Market</td>
<td>3.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Supermarket</td>
<td>4.0</td>
<td>22.4</td>
</tr>
<tr>
<td>Transportation by the consumer</td>
<td>9.8</td>
<td>0.02 (48 min.)</td>
</tr>
<tr>
<td>Domestic refrigerator</td>
<td>6.8</td>
<td>16</td>
</tr>
</tbody>
</table>
Technologies for Monitoring the Safety of Perishable Food Products

Count of Microorganisms

The effectiveness of thermal treatments can also be analysed from the assessment of changes in quality and attributes of the food (counting microorganisms) before and after treatment. A food sample is collected before and after the thermal treatment and microorganisms are counted. However, this technique can be laborious, lengthy (takes days of incubation) and costly.

Due to the disadvantages of these two presented techniques led to the development of a new monitoring technique, the use of Time-Temperature Integrators (TTI) (Mehauden, 2009).

Monitoring for Time-Temperature Integrators (TTI)

TTI devices are shelf-life indicators, alternative to conventional temperature control systems and as potential replacement for conventional open labelling (Farquhar, 1977; Taoukis & Labuza, 1989; Fu et al., 1991; Shimoni et al., 2001; Taoukis et al., 2010; Taoukis, 2010). These devices have the purpose to measure the direct impact of storage conditions on the food product, allowing to quantify the impact of a certain temperature condition on a product attribute (Taoukis et al., 2010). Thus, the real freshness of the product is reported instead of a static label. Producers, retailers, and consumers can, instutively, visually verify the cumulative time-temperature history of a product (Sherlock et al., 1991; Giannakourou & Taoukis, 2002; Giannoglou et al., 2014). These simple devices are normally characterized of a label/sticker that changes coloration irreversibly, indicating the real food storage history. Degradation kinetics are temperature dependent, under an incorrect storage temperature, a chromatic change is triggered. This change can be quantified with a value of $P$ (statistical value that refers the probability of rejecting the null hypothesis when it is true, i.e., considers two different groups that are not) (Mehauden, 2009).

Features

The fundamental characteristics of any of these types of temperature monitoring devices are (Kim et al., 2012; Brizio & Prentice, 2015; Tsironi et al., 2017):

- Small;
- Resistant;
- The time-temperature history is not necessary to determine the impact of the thermal treatments on foods.

Types

TTI devices are classified depending on two parameters. These can be classified according to their origin/application in food or in accordance with the substance containing (Mehauden et al., 2007).

- Classification according to the origin/application:
  - **Intrinsic TTI:** Used in natural form in foods. The thermal treatments efficiency is evaluated through the specified quantification before and after the process. The most important advantage, is the homogeneously dispersed intrinsic TTI in the foods (Mehauden, 2009).
  - **Extrinsic TTI:** Used in artificial form in foods, and it can be subdivided into three groups:
    - TTI added directly to food, blended together with food;
Technologies for Monitoring the Safety of Perishable Food Products

- Permeable TTI, which are placed in separate units that contain a permeable barrier which allows exchanges between food and TTI;
- Isolated TTI, placed in a separate unit and the barrier is not permeable. Thus, no exchanges between device and food is made.

- **Classification according to the contained substance:**
  - Depending on the substance contained in the TTI, these can be subdivided into the types (Taoukis *et al.*, 2010):
    - Enzymatic TTI;
    - Microbiological TTI;
    - Chemical TTI;
    - Physical TTI.

Types of TTI Devices Depending on the Contained Substance

This section describes the basic principle, applications, advantages and disadvantages of different types of TTI classified according to type of contained substance.

**Enzymatic TTI**

The principle of operation is based on the quantification of the enzyme activity (Giannoglou *et al.*, 2014; Brizio & Prentice, 2015; Tsironi *et al.*, 2017). Accumulation of the substrate hydrolysis shows the impact of temperature variation suffered by the product. Having a high thermal stability allows its usage in a wide range of temperatures. These devices are best suited for pasteurization and sterilization (Mehauden, 2009).

The enzyme choice must satisfy certain conditions (Kim *et al.*, 2012):

- The isothermal enzyme inactivation has to follow a known kinetic order;
- The enzyme needs to be thermally resistant;
- The enzyme needs to have a Z value (the value of the accumulated probability) until a point that corresponds with the study of microorganisms rather than only be used as a security tool.

The most commonly used enzyme is *α-amylase* whose characteristics and properties that makes it suitable are:

- Belongs to microorganism *Bacillus spp*;
- Good thermal resistance;
- Z value roughly equivalent to the recipient organism (*Clostridium botulinum*);
- Denaturation follows a kinetic reaction of 1st order;
- Industrial application in the production of beer, processes of making paper and detergent;
- Produced to industrial scale by the microorganism *Bacillus spp*;
- Stable at pH values in the range of 5.5 to 8;
- The stability can be modulated by calcium addition. Hence, the enzyme can withstand high temperatures (up to 90 °C) during a specific time interval.
Technologies for Monitoring the Safety of Perishable Food Products

The most usual applications of these types of devices are on pasteurization and sterilization processes. In the pasteurization process its application are related with (Mehauden, 2009):

- The existence of enzymes thermally stable, common in pasteurization temperatures;
- Specific systems are not necessary to protect the enzyme.

The applicability in the case of sterilization processes results on:

- To find thermally stable enzymes in higher temperatures (sterilization temperatures) is more difficult.

The device response is characterized by:

- Quantifying enzyme denaturation due to the thermal treatment (enzyme activity decrease);
- The quantification of change between before and after treatment demonstrates the impact of enzymatic activity in the TTI device.

The utilization advantages of this type of devices are (Pavelkova, 2013):

- Small size;
- Low cost;
- Wireless;
- Shock resistant (available for processes where thermocouples and dataloggers cannot be used);
- Rapid analysis when compared with microbiological devices.

The application disadvantages of this type of device are (Mehauden et al., 2007):

- Inability to allow online monitoring;
- Its small dimensions can difficult their recovery between foods;
- Need to know the value of Dr² and Z value (value of the cumulative probability to data processing) - helps determine the monitoring effectiveness and comparing the data. Necessary to have some preliminary experiments and enzyme calibration before the device is ready to use (Maesmans et al., 1994).

Microbiological TTI

This is the mostly used type of TTI devices in the food industry, and it relies on the growth of microorganisms, such as yeast or lactic acid bacteria, which in turn release metabolites that change the environment pH leading to a colour change of a pH indicator (Kim et al., 2013; Choi et al., 2014; Zhang et al., 2016). It can be divided in two types of analytical principles. The first, analyses the process impact based on the quantification of the number of surviving microorganisms. The second one, only detects if there are or not the microorganisms growth (Sun, 2012).
The operation basic principle consists in a carrier system, inoculated with a determined microorganism concentration and a thermal resistance. The cutting level of activity of the microbiological integrators in the sterilization provides the magnitude/effect of the process (Sun, 2012).

The characteristics of the microbiological integrator can be summarized in:

- The organism must be stable in respect to its quantity and thermal resistance. The results must be reproducible with low variability;
- The microbiological system (microorganisms, carrier system and procedure used) need to be calibrated for specific sterilization conditions;
- The relationships between the microbiological integrator and the load of pathogenic microorganisms in food products must be known so that the validity of the sterilization process can be ensured.

Depending on the intended application, the microorganism that will serve as a biological indicator has to be chosen. The most resistant species are generally the most used in the process, however, under certain conditions, less resistant microorganisms, quite similar to natural microflora or easily detectable can be used. Examples are (Sun, 2012):

- *Bacillus stearothermophilus* spores are the more used as biological indicators in sterilization process in humid heat conditions;
- *Bacillus subtilis* spores are used to the dry heat treatment and in processes where the ethylene oxide is used;
- *Bacillus pumilus* spores are used to sterilization processes by pathways of ionic radiation.

To determine the impact of thermal treatment, it is necessary to use spores previously calibrated and valid in relation to physical parameters known.

The utilization advantage of this type of device is that the microorganisms are easily disseminated in the food product, while that the main disadvantage is the difficulty to provide high accuracy results (Mehauden, 2009).

**Chemical TTI**

These are employed as a label on the product packaging with a very simple and intuitive reading so that the end consumer is able to gather the information and decide by himself about his purchase (Sun, 2012).

This type of indicator is based on chemical reactions, such as polymerization, photochromic, or oxidation reactions (Mai *et al.*, 2011; Brizio & Prentice, 2014). The specific molecule has no colour in its basic state, becoming dark blue when is activated when exposed to ultraviolet radiation (UV). The molecule reverts to colourless depending on the temperature (based in the Arrhenius equation^3^).

The label should be hidden under an anti UV filter after its activation avoiding another colour change. Consequently, if in the package label there is a change from dark blue to blue standard, the indicator show that the product remains in conditions to be consumed, because the extrinsic conditions of the food safety are within limits. If the label has grey or white, the product should not be consumed.
Technologies for Monitoring the Safety of Perishable Food Products

The labels may be stored in a room with any temperature, but without light until its utilization. The support paper must be specified, whereas the printing on a plastic substrate is possible (Hightech Europe, 2014).

The thickness of the ink is not easy to measure, but this parameter is read indirectly through the activation and colour measurement. The distance between the product and the packaging is the minimum recommended. This should be reduced for that food temperature history and the TTI device are as identical as possible (Hightech Europe, 2014).

As limitation of this type of TTI devices, it can be noted that the reference colours used are not very appealing/instinctive to the consumer. Reference colours used: blue (good condition) and grey (poor condition). Additionally, may be subject to product adulteration activities, such as re-packaging in cases that the expiration date of foods has been exceeded and can be placed a new label of fresh reference (dark blue).

Nanoparticle TTI

Nanoparticles can change shape, size or surface morphology depending on the temperature exposure. This leads to alteration of the light absorption spectra by the particle (different wavelength absorption), characterized by visual chromatic shift (Wang et al., 2017).

Physical TTI

The operation basic principle of this type of TTI device is based on the phenomenon of diffusion. The system consists of a chemical coloured substance that can melt and be absorbed by an absorbent paper under the effect of moist heat (steam). Usually used as an indicator of thermal processes (Sun, 2012).

The response of this type of device is calculated by measuring the distance reached by the compound that is submitted to the diffusion process.

Its major disadvantage is the impossibility to use with dry heat thermal processes. Additionally, it cannot be included in the product because this device is only activated by steam.

TTI: INTEGRATORS TIME-TEMPERATURE

This section describes various TTI devices available on the market. Their specifications are described, as well as their advantages and disadvantages. Note that only some examples are shown. In the market, other TTI brands making use of the same concept are available.

TTI 3M MonitorMark™

Concept

Physical TTI device capable of indicating food products temperature over time, expressing this cumulative distribution by diffusion (3M, 2018). Consisting on accelerated diffusion of colored fatty acids at high temperatures (Jafry et al., 2017), this is an irreversible thermal exposure record.

This type of equipment is used for a wide range of temperatures and is typically applied near the food products sensitive to temperature variations (usually applied in the packaging).
As a disadvantage this device does not provide specific information about the product quality, but only the food thermal exposure is reported (parameter that is related to the quality). The equipment dimensions are approximately 95x19x2 mm³ (Figure 2).

Features

The main features are:

- Rectangular shape, with a pellicle or adhesive slick/laminate;
- The dispersion of the blue compound allows to quantify temporally the threshold temperature at which the product was subject;
- The pressure sensitive adhesive allows their aggregation (the dispersion of blue compound) in any clean and dry surfaces.

Advantages

The main advantages offered are:

- Low cost;
- Works as accessory (label) on the outside of product packaging;
- The results are visual, easy and intuitive to interpret, indicating immediately the occurrence of thermal mishandling.

Equipment Models

The 3M MonitorMar device presents several specific models (see Table 6) designed to function on different temperature ranges and several time intervals that the cumulative records.

Figure 2. TTI 3M MonitorMark (3M, 2018)
Technologies for Monitoring the Safety of Perishable Food Products

Table 6. Available models by the brand of the equipment (3M, 2018)

<table>
<thead>
<tr>
<th>Model</th>
<th>Activation temperature range $A_{\text{activation}}$ (°C)-Registration time</th>
<th>Typical temperature °C to not accumulate</th>
<th>Conditional temperature °C (minimum 2 hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9860*</td>
<td>-15°C - 48 hours</td>
<td>-20°C</td>
<td>≤ -25°C</td>
</tr>
<tr>
<td>9860B</td>
<td>5°C - 48 hours</td>
<td>0°C</td>
<td>≤ -4°C</td>
</tr>
<tr>
<td>9860C</td>
<td>10°C - 48 hours</td>
<td>7°C</td>
<td>≤ 5°C</td>
</tr>
<tr>
<td>9860D</td>
<td>10°C - 1 weeks</td>
<td>7°C</td>
<td>≤ 5°C</td>
</tr>
<tr>
<td>9860E</td>
<td>26°C - 48 hours</td>
<td>24°C</td>
<td>≤ 21°C</td>
</tr>
<tr>
<td>9860H</td>
<td>31°C - 1 weeks</td>
<td>29°C</td>
<td>≤ 26°C</td>
</tr>
<tr>
<td>9861*</td>
<td>10°C - 2 weeks (End point 34°C)</td>
<td>7°C</td>
<td>≤ 5°C</td>
</tr>
<tr>
<td>9864C</td>
<td>10°C - 24 hours (End point 17°C)</td>
<td>7°C</td>
<td>≤ 5°C</td>
</tr>
</tbody>
</table>

As can be seen by analysing the data presented in Table 6, the most suitable models to record temperature mishandling of perishable foods are the 9860B, 9860C (see Figure 3) and 9860D models, due to its activation and typical temperature characteristics described in Table 6.

These devices provide a general reference on exposure to a constant temperature and must be used with a combination of general knowledge about the terms of product display, in order to estimate the time-temperature exposure. The indicator verifies the exposure of temperature and not product quality. Its purpose is to visually indicate when the product quality should be checked (3M, 2018).

TTI Timestrips

Concept

The Timestrips is a unitary chemical indicator manually activated by the consumer in order to verify the elapsed time since the food package opening or since its first use (Timestrip, 2018).

In terms of dimensions, the standard size of this equipment is 19x40 mm².

This is designed to allow consumers to track down the time elapsed since label activation. This feature is particularly suitable for packaging, labelling of perishable foods or products that require maintenance and regular place relocation (chilled and frozen products).

Figure 3. The Model 9860C of 3M MonitorMark (3M, 2018)
Technologies for Monitoring the Safety of Perishable Food Products

The thermal monitoring tagged Timestrips is always available to be activated in the right time, because they are completely inert at the temperature at this stage and may be stored to the environment temperature, unlike other temperature recorders that need to be stored in controlled environments to ensure its functionalities.

Advantages

The main advantages offered by this indicator are:

- High accuracy and advantage cost/benefit;
- Easy handling and reading, being directly applied to the product or packaging.

This brand has two different types of devices with the same functionalities, but with different purposes. One type is used to monitor thermal mishandling in the ascending threshold recommended, and the other in descending threshold (Timestrip, 2018).

**Timestrips Plus**

This equipment works as indicator of the thermal exposures occurring in the ascending thresholds to the recommended or to its temperature range (Timestrip, 2018).

The specific features of this model are:

- “Button” which confirms the indicator activation to know when the device is in the cumulative record mode;
- Extensive validity;
- Water resistant.

Timestrips Plus type has several models that cover several temperature ranges (-20 °C to 38 °C). See some examples on Table 7. Once again, this diversity exists so that it is possible to cover a wider range of foods in which it can be included because the foods do not have the same range of conservation values recommended (Timestrip, 2018).

As showed in the Table 7, the choice of device to be applied depends on the range of recommended food temperature and the time intended to be measured.

These models have a unique serial number on the label to improve its traceability.

The models also include an activation button, which once pressed, measures the temperature violations. If the temperature falls below the threshold, a white circle changes to red colour irreversibly. This can be seen in the sequential process of images in Figure 4. The colour change is recognizable/appealing (from white to red) in order to be more effective to catch user attention (Timestrip, 2018).

These devices type, when following the food products, have the task to show if the perishable food was exposed to temperatures in its limit descending threshold. Low temperature values also impair the quality and freshness of perishable foods, if the freezing point is reached. Table 8 shows some of these models.

These models have each one its serial number (unique) on each label in order to improve its traceability.
Technologies for Monitoring the Safety of Perishable Food Products

Table 7. Description of the Timestrips Plus models (Timestrip, 2018)

<table>
<thead>
<tr>
<th>Model:</th>
<th>Timestrip Plus 058</th>
<th>Timestrip Plus 077</th>
<th>Timestrip Plus 076</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Frozen foods</td>
<td>Frozen foods</td>
<td>Chilled foods</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-14°C</td>
<td>0°C</td>
<td>5°C</td>
</tr>
<tr>
<td>Time scale</td>
<td>24 hours</td>
<td>12 hours</td>
<td>8 hours</td>
</tr>
</tbody>
</table>

Figure 4. Activation process of the temperature measurer equipment (Timestrip, 2018)

Table 8. Description of the Timestrips Minus models (Timestrip, 2018)

<table>
<thead>
<tr>
<th>Model:</th>
<th>Timestrip Minus 0°C</th>
<th>Timestrip Minus 2°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>0°C</td>
<td>2°C</td>
</tr>
<tr>
<td>Temperature range</td>
<td>Manual</td>
<td>Manual</td>
</tr>
<tr>
<td>Time scale</td>
<td>Solo</td>
<td>Solo</td>
</tr>
</tbody>
</table>

Figure
Technologies for Monitoring the Safety of Perishable Food Products

Timestrips Complete

Timestrip Complete provides an active monitoring of the boundaries above and below of environment temperature. The combination of Timestrip Plus (ascending temperature threshold) with the Timestrip Minus (descending temperature threshold), provides a viable alternative for monitoring food safety in the range of 2ºC-8ºC. Thus, this device prevents the two risk sources interfering in the food quality, i.e., high temperatures and low temperatures (Timestrip, 2018).

The normally used package contains:

- **Timestrip Minus**: Limit to 2 ºC
- **Timestrip Plus**: Limit to 8 ºC (other temperatures available).

TTI Fresh-Check®

The food exhibition at temperatures above the recommended is reflected in its freshness. Then these abuses have effects on taste, smell, texture, quality and bacteria proliferation in the food product. The Fresh-Check® indicators are used to prevent these effects by providing an indication of when the food products are subject to some mishandlings (Pavelkova, 2013).

Figure 5. Timestrips complete (Timestrip, 2018)
Technologies for Monitoring the Safety of Perishable Food Products

Concept

Its principle relies on a polymerization reaction in the solid state, resulting in a coloured polymer regarded as a temperature-sensitive ink that is invisible in its initial state, but in case of temperature excess, it darkens. The indicator consists on a polymer in a small circle surrounded by a printed ring of reference.

Features

The main features are:

- The chromic indicators is sensitive to temperatures since the -25 °C;
- Accuracy of +/- 1 °C;
- They exist on several sizes;
- The storage must be done at low temperatures;
- Its visual sensor is irreversible.

Operating Mode

The polymeric circle darkens if the product packaging was subjected to a thermal exposure outside of its range. The colour intensity is measured and compared to the reference colour on the label - on the reference ring (see Figure 6). Colour change of the polymer follows the temperature gradient, i.e., as higher the temperature variation, faster is the colour transition (Taoukis et al., 2010).

The indicator response is measured by decrease in reflectance quantification. This is due to the ratio between the electromagnetic flow radiation incident on a surface and the reflected flow. This indicator is used in different designs by different supermarkets. The principle is the same, the colour and display features are different depending on the supermarkets.

TTI CheckPoint (Vitsab L5-8 Smart TTI Seafood Label)

Concept

This enzymatic indicator allows a complete record of Time-Temperature (see Figure 7), i.e., responds continuously (accumulates) regardless of the temperature, unlike the partial history indicators, which accumulate when the temperature reaches the limit. Their cumulative is continuous (Kaur & Puri, 2017).

Figure 6. Label Fresh-Check (Taoukis et al., 2010)

*For a more accurate representation see the electronic version.
Technologies for Monitoring the Safety of Perishable Food Products

Figure 7. Representative graphs of the temperature as a function of time, of the two types of historical indicators that can provide (Kaur & Puri, 2017)

As indicated in Figure 7 b), the response of a full-history indicator does not alert, only when it reaches the temperature limit.

Operating Mode

This simple adhesive sticker has a basic enzymatic system principle: colour change caused by the pH decrease. After activation, the capsule is broken, substrate and enzyme are mixed, leading to an enzymatic hydrolysis of a lipid substrate by a lipase enzyme.

The substrate hydrolysis causes the acid release and the pH decreases, leading to a colorimetric change from dark green to bright yellow and then to red.

The combination of several types of enzymatic substrates at different concentrations can be used to provide a variety of responses depending on the temperature.

This indicator provides essentially the forecast percentage of load based on all temperatures that the equipment was subject over time, i.e., provides the remaining validity of the equipment or products where is inserted. As shown in the sequence of images displayed in Figure 8, initially, before being activated, the label has a background of neutral colour that is changing to green in its first phase of monitoring. Over time, the label changes shades of orange/red, indicating that the product is no longer in conditions to be consumed (see Figure 9) (Taoukis et al., 2010).

This device provides a progressive response of the product life instead of the final breaking point, after this be subjected to the above recommended temperatures.

Figure 8. Cumulative percentage relation/ring colour during the first phase after label activation, while still is viable (Taoukis et al., 2010)

*For a more accurate representation see the electronic version.
Technologies for Monitoring the Safety of Perishable Food Products

Figure 9. Cumulative percentage relation/ring colour during the last phase of monitoring (the label is no longer viable) (Taoukis et al., 2010)

*For a more accurate representation see the electronic version.

TTI OnVu

Concept

This indicator is based in photosensitive chemical compounds and organic pigments. Example: Benzylpyridines - changes its colour depending on the subjected temperature over time. The indicator substance is activated by UV radiation, which can be visualized by a dark blue coloration. After application on the package, this indicator has a UV filter to protect the substance to be reactivated to dark blue (Figure 10). Over time and temperature exposes the colour fades away, indicative of wrong temperature conservation or food product lifespan expiration (Figure 11). The indicator can be calibrated according to the temperature range and product lifespan (Pavelkova, 2013).

Response Analysis

The indicator is dependent of UV radiation to be activated, after that the indicator needs to be protected by a UV filter to prevent reactivation. Reference colour fades away due to two parameters, temperature and time, consequence of three different situations (Figure 11):

- Exposure to high temperature for a short time period;

Figure 10. Standard OnVu indicator (Taoukis et al., 2010)
Technologies for Monitoring the Safety of Perishable Food Products

- Exceeding the product life span by exposing to the recommended temperature during a long time period;
- Exposure to different temperatures and time (usual conservation experience).

In conclusion, this device has a unique property to relate time and temperature, giving a more detailed information of the food product conservation state.

Additionally, other models of the OnVu device are offered based on the same principle, but with different applications (see Figure 12) (Freshpoint, 2018). Since the reference colour can be calibrated to different temperature ranges, the different models can have applications to refrigerated products as well as frozen products. This TTI demonstrates to be very versatile and takes in consideration time and temperature, leaving consumers more informed on the food product conservation state.

CoolVu™ and BestBy™ TTI

OnVu new generation TTI, has similar performance changes colour from green or grey to red or white, respectively. These kinds of labels are used to follow conservation in the food chain (CoolVu™) and also as time from opening indicators (BestBy™), helping the costumer decide until when the product is safe to consume after opening (Freshpoint, 2018). The unique aspect of this label is to be very intuitive and simple to use, helping customer on the product freshness (Figure 13). Additionally, a mobile app was developed to help read these labels, enabling customers to have more information on the product.

Figure 11. Registration and tendency of discoloration in the relation exposure time elapsed/temperature (Taoukis et al., 2010)

*For a more accurate representation see the electronic version.*
**Technologies for Monitoring the Safety of Perishable Food Products**

**Figure 12. Detailed description of the OnVu models (Freshpoint, 2018)**

<table>
<thead>
<tr>
<th>Model (logo)</th>
<th>Description</th>
<th>Application</th>
<th>Advantages/benefits</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>OnVu Logist</td>
<td>The marker is dark blue colour after activation, colour fades away when product is subjected to temperature excess, the reference scale (by letters) helps determine if the refrigeration temperatures were respected during food logistics and distribution.</td>
<td>Refrigerated food products.</td>
<td>· Easy to apply; · Immediate visual indicator; · Flexible design and size; · Activated by UV radiation; · Low cost.</td>
<td></td>
</tr>
<tr>
<td>OnVu Ice</td>
<td>· Indicator that shows if the product suffered a thawing event after production; · The used marker offers the consumer a warranty seal certifying that the product was maintained frozen since its production.</td>
<td>Suitable for a wide range of frozen products (including ice cream, meat, fish, vegetables, ...);</td>
<td>· Can be calibrated to match with the recommended range of freeze/thaw temperatures; · Flexible design and size; · Low cost.</td>
<td></td>
</tr>
<tr>
<td>OnVu</td>
<td>· Product freshness indicator, after UV activation the marker is dark blue, over time and temperature differences colour fades; · Reference scale for comparison is below the marker.</td>
<td>Available for food with short expiration date that require refrigeration (meats, fresh produce, juices).</td>
<td>· High accuracy; · Size and flexible design; · Can easily be incorporated in the food package; · Can be calibrated according to the food lifespan.</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 13. Different customisable models of the Freshpoint labels (Freshpoint, 2018)**

**TTI (eO)**

This microbiological TTI is based on pH variations. Colour gradually changes when pH is lowered (from green to red, Figure 14) by a controlled microbial growth contained in the TTI marker gel (Chiellini, 2008; Pavelkova, 2013). Depending on the application, this device can be adjusted by selecting the right microorganism and gel composition (Chiellini, 2008). Before application, labels are stored frozen (-18 ºC) to prevent the bacterial growth.
Activation is very simple, since the device is very thin, the label can be thawed at room temperature for a few minutes (Pavelkova, 2013).

Once placed on the food package, by exceeding the temperature or the expiry date, the microbial growth occurs and causes a decrease in pH and an irreversible colour change (Taoukis et al., 2010).

FUTURE TRENDS/PROPOSED MODEL

There is no doubt that time temperature integrators are able to inform consumers and improves the whole food chain quality from production, distribution, sale and consumers, just by a simple, intuitive, clear and easy indication on the food product.

Consequently, consumers will purchase items with better quality, by a real-time result of good conservation conditions, instead of only focusing on the expiry date, which does not guarantee good conservation practices of the product.

Despite the extensive work that has been performed to advance this field and the valuable contribution that TTIs can bring in terms of eliminating consumer confusion and reducing food waste, there are still several limitations that hinder their extensive use in food products. Additionally, although the clear TTI application advantages, there are still improvements and limitations to overcome on future devices. Here we some issues that can be improved:

Price Dynamics

The consumer becomes increasingly aware of product life changes by indicators present in package, consequently this is a high priority to invest in a pricing strategy. Product prices become a dynamic parameter which decreases as the quality characteristics decreases. Therefore, food waste (before expiry date) will be reduced and producers’ profits will increase. By creating a price dynamic and having a quality assurance indicator will increase changes of consumers buying the product. Consumer decisions are based on quality but also on pricing. Thus, consumers will fell more confident and will rely on the conservation quality of food products under the expiry date (regardless if the product is the freshest).

To follow this dynamic strategy, a strategy has to be defined by pricing policies, i.e., one justification for the prices assignment and discounts, based on a detailed identification of the real time food product qualities.

Figure 14. eO indicator (Pavelkova, 2013)
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This change would not only improve the management of food safety, but also become an innovation in areas as marketing strategies, quality food management, consumers purchasing habits and refrigerated chain operations.

Reference Colours

As described before, consumer purchase intention is a variable parameter, very unpredictable and dynamic, this depends on the confidence that perishable food product package gives him. With the introduction of these monitoring technologies, reflecting the temperature history, consumer will have access to a detailed food conditions analysis, helping making the decision of a purchase.

However, in a general way and having as base the technological equipment studied, most of those that are applied in the product package follows a trend in their reference colours that describes the product characteristics or its condition. For example, the green colour reflects the good food conservation state and provides an idea of trust and safety to the consumer. By the other way, orange (middle term) and red (food safety limit) are appellative colours, which inform the consumer not to choose these foods items. When a food item contains a TTI with red indication, the commercial establishment has the responsibility of removing these products from the shelves. The problem arises when the TTI shows medium colours such as the smooth and dark orange. It must be highlighted that the consumer purchasing decisions, beyond being based in the price, are also based in the food quality. When the consumer faces a refrigerated display cabinet full of product packages with indicators reflecting a dark green colour or medium orange, he will manage his choice based on the product with better conservation state.

The food quality is in its maximum potential when arrives to the commercial establishment coming from the distributor, which does not mean that any foods indicator with a colour besides the green one is in bad conservation condition. However, knowing the consumer about the presence of indicators in food packages, his tendency will always search the entire display cabinet for a package with a green indicator. The consequences of these actions are the larger resident time of food items with less safety on display cabinet and the consequent accumulation of products which indicator will turn red. Thus, the food waste will not be successfully controlled. Thus, a new strategy for the aesthetics of the label is needed, specifically on the indicator reference. As example, the TTI OnVu has a reference scale not in colours but in letters (OnVu Logistic) or with several classification levels (OnVu active ink technology).

“Moment of Consumption” Scale

An alternative proposal only results if the consumer requires the food chain to comply strictly with the - uncontrolled parameter.

The products whose indicators are between the term of excellent conservation (green) and unacceptable food quality (red) are products that are still advisable to consumption. However, these suffer some unfair discrimination by the consumer. Depending on how purchase management is done, which varies from person to person, but always with the same principles (“last minute shopping” and “shopping to store in the storeroom”). Often, the consumer goes to a store knowing the food products what he needs to buy. Usually, he also knows when he will consume the products (in that day or in the next one or if he will store during some time). So, the reference scale of a label can be based in this idea.

Thus, a change in the reference scales used to identify the product state from a colours scale (“food preservation scale”) to a “consumption time scale” would help choosing the products that are in the middle
Combination of Features and Evaluation Parameters

Due to the extensive research, several TTI equipments were developed and are now available commercially with different functionalities and product organoleptic parameters evaluation.

Relatively to TTI functionalities, there are devices capable of indicating the consumer the product conservation status before its purchase, and others capable of evaluating the product state after package opening in a domestic environmental (or its remaining life time).

Thus, achieving the combination of these capabilities in a single equipment will increase slightly the average label size and its occupied space on the product package. However, on the other hand, this will become a lot more useful and versatile, since it includes two functions, one that evaluates the conservation state along the cold chain or in refrigerated location (either supermarket or domestic fridge) while the package is sealed, and other that starts operating when the package is opened.

Relative to evaluation parameters, several equipments have the capacity to evaluate, through microbiological, physical or chemical, organoleptic characteristics of foods. Nevertheless, other parameters can also be evaluated, such as, oxygen or humidity percentage present in the package. The development of an equipment with the ability to perform these three evaluations on the product, allows a better understanding of its conservation status.

Another perspective could pass through the inclusion of an antenna on the TTI device, making this device in a passive Radio Frequency Identification (RFID) tag. Based in an electrochemical process, the tag can provide the indication of conservation status when passing by an RFID antenna/reader. If these elements are located along all the cold chain, i.e., in the inputs/outputs of warehouses/stores, of transport/distribution vehicles, of commercial establishments (cash registers), it would be possible to obtain the real time data of each product (namely the temperature history along the cold chain), allowing to analyse the weaker links and act to promote the food security. Some studies demonstrate the efficiency of this kind of combined technology (Bibi et al., 2017; Lorite et al., 2017). This kind of device permits intelligent packaging which give more information on the product itself and its quality throughout the food chain. This device enables the package to be tracked down by GPS or mobile network, providing real time information. Depending on the type of RFID tag, the cost can vary between 40 to 50-euro cent per tag. This price can seem to be high, nevertheless when compared with temperature loggers, it is cheaper. With commercially available devices, this will lead the price to become lower and lower.

Potential Toxicity

Among some TTIs, there is a potential of migration of noxious reactants and the presence potential and actual toxic components. Some chemical TTIs use anthraquinone derivatives, which are structurally related to anthracene, which are potential carcinogenic and toxic (Wang et al., 2015; Zhang et al., 2016). Additionally, the usage of silver and gold nanoparticles, can lead to toxic effects to pulmonary cells (Ávalos et al., 2015).
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New TTIs need to take this into consideration, and replace toxic compounds with natural or generally recognized as safe (GRAS) indicators, subsequently diminishing user risk.

For example, Wei et al., reported the usage of the natural polyphenol anthocyanin (Wei et al., 2017) as an indicator for food freshness. Another study demonstrated the usage of the combination of laccase, guaiacol, and cysteine as O$_2$ concentration indicators (Won et al., 2016).

**CONCLUSION**

This chapter describes the literature of several technologies used for food safety monitoring of perishable products, which due to their susceptibility in losing nutritional qualities or organoleptic characteristics, deserve a special care by the producers/distributors and world organizations devoted to eradicate the world food waste.

The time-temperature indicators are used to optimize the product distribution and increase its lifespan, allowing a considerable waste reduction. The low cost, the trust that the consumer puts on the indicator and the record efficiency are the appointed criteria for the success of this type of equipment.

Currently, these systems provide a reproducible and assertive/precise answer according to their specifications. The TTI devices provide a visual summary of the product accumulated temperature.

This is a modern safety system of evaluation the food quality, preventing contamination through the monitoring, registration and control of the critical parameters during the entire food life cycle. There are devices commercially available to perform this evaluation, but for sure, the research and technological evolution will provide in the future new devices with extended functionalities that will develop this area, promoting its generalized use in the food chain.

**REFERENCES**


Technologies for Monitoring the Safety of Perishable Food Products


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ENDNOTES

1. *Kinetic reaction of 1st order* – Is one that occurs with speed directly proportional to the concentration of the reagent. For a reaction of this type to a constant volume (*mono-molecular, irreversible* and of 1st order – because the reagent concentration is elevated to the exponent 1) obtains the form: Reagent → Product.

2. *Dt* - Decimal value of the reduction time that corresponds to the amount of time required to reduce 1/10 the population of a microorganism subjected to a particular thermal treatment.

3. *Arrhenius equation:* In many cases, the observed speed of a chemical reaction increases as the temperature increases, but the extent of this increase varies a lot from reaction to reaction. In terms of the rate equation, the cause of variation of the reaction rate with temperature is in the constant *k* when this varies with the temperature changes. According to Arrhenius equation, the value of the constant of speed *k* increases with temperature. This means that an increase in temperature would produce an increase in the reaction speed, which is usually observed (Laidler, 1987).

The Arrhenius equation is useful because it expresses the quantitative relationship between temperature, activation energy and rate constant. Its greatest usefulness lies in determining the energy of a reaction, from the velocity measurements at different temperatures (Laidler, 1987).

*Note: Activation Energy:* Energy from the collision between molecules to form the activated complex, an unstable set of atoms weakly bound to each other and that can decompose into molecules of reactants or products.
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APPENDIX

Nomenclature

$a_w$: Water activity;
$CO_2$: Chemical symbol of carbon dioxide;
$Dt$: Decimal time reduction corresponding to the amount of time needed to reduce 1/10 of microorganisms’ population subject to a certain thermal treatment;
$Ea$: Activation energy;
$K$: Constant;
$N_2$: Chemical symbol of nitrogen;
$NaCl_{max}$: Maximum amount of saline concentration admitted;
pH: Physical-chemical quantity of the hydrogen potential that indicates the acidity, neutrality or alkalinity of an aqueous solution;
$T_{Activation}$: Activation temperature;
$T_{max}$: Maximum temperature;
$T_{min}$: Minimum temperature;
$P$: Statistical value of the probability to obtain a statistic test equal or more extreme than the observed in a sample, under the null hypothesis;
$Z$: Statistical value of the accumulated probability.

Abbreviation List

3GF: Global Green Growth Forum;
AND: Deoxyribonucleic acid;
CE: European Community;
CCP: Critical Control Points;
EU: European Union;
FAO: Food and Agriculture Organization of the United;
HACCP: Hazard Analysis and Critical Control Points;
MAP: Modified Atmosphere Packaging;
Redox: Chemical reaction of oxidation-reduction;
TTI: Time-Temperature Integrator;
UV: Ultra-Violet.
Chapter 10
Reference on Rice Quality and Safety

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ABSTRACT
Over the last decade, there have been massive investments and research to improve rice yield per hectare. Alongside successful stories of improved rice yields are corresponding concerns stemming from pre- and post-harvest rice quality- and safety-related issues. Such concerns in rice production, handling, and storage systems present public health and economic problems. To consumers and producers, a serious concern is the potential growth of toxigenic fungi on rice during storage leading to contamination of the rice with mycotoxins. That withstanding, diminished functional, sensory, and nutritional attributes hugely impact the investment returns. The author understands that discourse on rice storage is incomplete without reflections on nutritional related losses. In rendering a strong chapter to meet a wider readership, the above issues are discussed with deliberate effort to highlight technological advances making headway in the rice industry; these are outlined in the introduction, at first, and then expounded on in subsequent sections.

INTRODUCTION
Rice (Oryza sativa L.) is one of the leading food crops in the world and the staple food for more than half the world’s population. The United Stated Department of Agriculture (USDA) has established rice grade as U.S. No. 1 through 6, in which sample grade is based on quality discount factors. These factors include weed seed, red rice, seed mixture, damaged kernels, chalky kernels, etc. It is generally considered a semiaquatic, annual grass plant. Environmental conditions, such as drought, high nighttime temperatures, low sunlight intensity, disease, inadequate or excessive nitrogen and draining water early in hot weather, all intensify stress on rice kernels. The susceptibility of kernels to develop chalk or other kernel-weakening features in response to stress differs somewhat among cultivars. Cultivars of

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the two cultivated species, *O. sativa* L. and *O. glaberrima* Steud., can grow in a wide range of water-soil regimes, from deeply flooded land to dry, hilly slopes. Because of its long history of cultivation and selection under diverse environments, remarkable diversity exists in rice. The grain is grown in more than 100 countries on every continent except Antarctica, extending from 53° north to 40° south and from sea level to ranges of 2,500 m to 3,000 m above sea level. However, *O. glaberrima* is grown only on limited scale. The production practices for rice in various countries range from extremely primitive to highly mechanize.

Abnormally high nighttime air temperatures during kernel formation disrupt the starch formation process within the developing kernel. Thus, starch structure is altered and the general packing density of starch granules is reduced, creating chalky portions of kernels with associated changes in physico-chemical properties. Kernel smut disease anecdotally reduces milling yield and can sufficiently discolor rough rice to create quality reductions during parboiling. Field insects can also have detrimental effects on rice quality. Most notable is the stink bug, which bores into the kernel during development, resulting in a black spot on the kernel known as “peck.” Such kernels are typically removed after milling using color sorters.

The amount and timing of nitrogen fertilizer applied to rice during growth can impact milling yields. Greater nitrogen application rates at the beginning of kernel development are generally considered to increase head rice yield (HRY). One researcher surmises that a decline in HRY associated with reduced nitrogen application was a result of either decreased integrity of protein structural components of the rice kernel or of faster maturation and drying. Other data shows that topdressing nitrogen fertilizer at heading resulted in increased protein content for all cultivars tested and increased HRY for four of five cultivars evaluated, with the outlier being a cultivar with known high HRY potential.

Rice milling yield may be lower if rice is harvested at either very high or low moisture contents. At high moisture contents, many kernels can still be thin and immature and often break during the milling process. The ends of wet rice kernels grind off and become dust when they are processed. Rice may fissure if it dries in the field to below 15 percent moisture content and/or is rapidly rewetted (e.g., due to rainfall, heavy dew etc.). Rapid rewetting is a key cause for lowered head rice yields. Certain cultivars may be more susceptible to head rice yield reductions than others if rice drops below 15 percent moisture content (wet basis) and is rewetted in the field.

Laboratory milling systems are used throughout the rice industry to 1) estimate the milling yield that may be expected of rice lots when milled in large-scale milling systems and 2) produce milled rice samples from which visual, functional, sensory and nutritional assessments of the rice lot can be made. Laboratory-scale milling systems have long been used to estimate the milling performance that can be expected of a rice lot when milled in large, industrial scale systems. Laboratory systems comprise equipment that first removes the hull from the rough rice kernel, producing brown rice. Brown rice is typically milled to remove the germ and bran layers, leaving milled rice. The predominant measurements of rice milling yield are made using the endosperm, or milled rice kernel. The degree to which the bran layers are removed from brown rice, the degree of milling (DOM), plays a significant role in determining overall milling yield and functional quality of milled rice.

To achieve optimal milling yield and quality, long-grain rough rice is harvested at 19-21% moisture content wet basis (w.b.), and medium-grain at 23-25% moisture content. At such high harvest moisture contents, the grain is prone to heating which arises from respiration of the grain itself and associated microorganisms and pests; excessive respiration leads to rapid deterioration of the grain quality. Therefore, timely and proper drying of the grain from the relatively high harvest moisture contents to safe storage
moisture content of 12-13% is very important to minimize quality reduction and also arrest other issues related to microbial proliferation. In general, the rate of proliferation of microorganisms and pests in the grain storage ecosystem is dependent on the grain water activity, grain temperature, and storage duration.

High-temperature, cross-flow air drying and in-bin natural air drying are the most common methods used to dry rough rice. In developing countries, where the scale of production is large, the challenge rice producers have to face is to speed up the drying during relatively short harvesting “window”. With improved breeding programs to increase rice productivity and meet food demand, annual rice yields per acre have tremendously increased thereby calling for expansion of existing drying infrastructure. These infrastructure, however, have not expanded at the rate sufficient to meet the growing volumes of rice produced annually. Furthermore, developments in rice harvesting technology has increased the speed at which rice can be harvested; and along with larger and faster grain carts, trucks, and trailers for transporting rice from combines to driers, a much greater rice delivery rate to driers is realizable within the short rice harvesting “window”. It is not uncommon to see temporary “wet holding” (delayed drying) facilities for rice at commercial drying facilities. Moreover, the rice harvesting period is also characterized by warm and humid conditions that favor proliferation of microbes and pest within the grain storage ecosystem. There are new and emerging technologies such as chilling aeration, and infrared and microwave drying being developed for postharvest rice management.

Challenges related to rice safety therefore unfolds during harvesting periods. However, once rice drying is accomplished and microbial related deterioration arrested, the shelf life of rice could be improved significantly. The shelf life of the dried rice depend on the post drying process. For the different rice types, the more layers are removed in the rice milling process, the longer the shelf life of the rice. In practice, storage life of un-milled rough rice and brown rice is limited by the higher fat and protein contents. During milling or polishing of rice the silvery outer skin (the aleurone layer) and the nutritionally rich grain germ are removed; this increases the shelf life of rice. The downside of that milling process is that a large proportion of nutrients are lost. Parboiling of rice is a process that is generally used in attempt to reduce this loss. The process involves dehusking, soaking and steam treatment of rough rice with pressure applied in order to retain inside the grain the water-soluble nutrients, vitamins and minerals that are contained in the aleurone layer.

The goal of any storage system for rice is to provide safe storage conditions for the grain in order to prevent grain loss caused by adverse weather, moisture, rodents, birds, insects and microorganisms like fungi. The storage may take many forms depending of quantity of grain stored, the purpose of storage and the location of the store. The grain could be stored in rough rice or brown rice form. For food purpose, storage in rough rice form is better than milled rice because the husk on the rough rice provides extra protection against insects to help prevent deterioration of the rice quality during storage. When stored as brown rice, 20% less storage capacity will be needed compared to as rough rice. However, under tropical conditions brown rice has a very short shelf life, approximately two weeks. The grain could be stored in bins/silo, commercial warehouses, bags/vessels, bulk or hematic containers.

Rice can be fortified by adding micronutrients. In the past, commercial rice enrichment and fortification practices were accomplished through coating and dusting techniques. Although coating and dusting practices are still used, new and alternative methods using hot- and cold-extrusion techniques are gaining prominence. Rice can also be extruded and shaped into partially precooked grain-like structures resembling rice grains, which can then blended with natural polished rice. A technical challenge is to produce fortified rice that resembles natural rice and resists normal meal preparation and cooking processes.
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Microorganisms such as fungi and bacteria adhere to the surface of the grain kernel. The development of fungi depends on the temperature, humidity and the grain moisture content. Fungi on the grain can produce mycotoxins, some of which have toxic effects on humans and animals. One of the main mycotoxin contaminating rice grains is aflatoxin which is a toxic and carcinogenic compound produced mostly by Aspergillus flavus, Aspergillus parasiticus, and Aspergillus nomius. Without proper management, any rice storage system could result in bad rice with very negative consequences to consumers and processors. Problems could range from rice contamination with mycotoxins, discoloration, dry matter loss and other quality issues with adverse effects, not only on consumers but also on producers e.g., low returns on investments.

There is increasing pressure on crop production systems, rice included; especially, producers live with uncertainty of climatic conditions which impact the rice all the way from production to processing. These pressures in addition to the reducing natural resources (land and water) signals that increasing rice production at a rate that will meet rising demands will be challenging in the foreseeable future. At best, it is important that investments in production, processing and storage practices be improved; together, these will to maximize preservation of rice that could be produced and extraction of the highest value from the rice. Going forward, it will become very crucial to select through breeding program the best cultivars considering factors such as field history of disease and cultivar ratings: blast, sheath blight, smuts, stem rot, field history of weed species and herbicide program, soil texture and seedling-vigor, seeding method, susceptibility to lodging, maturity group and seeding dates, grain and milling yield performance, irrigation capacity, geographic location.

RICE QUALITY SAFETY

Definition

Rice “quality”, in its many definitions, can be affected at almost any point in the postharvest processing chain. The rice processing industry faces a continual challenge to prevent various forms of chemical and physical degradation in order to maintain quality at its highest level. Given the status of a rice lot delivered at harvest, overall quality can generally not be improved, short of specialized processes that improve particular quality attributes (e.g., parboiling can improve milling quality tremendously). It is more generally the case that processors are expected to maintain quality at the delivered levels. Given the volume of product typically handled by processing facilities, as well as the wide range of sources and production practices often experienced with rough rice, maintaining quality from the first point of delivery through final packaging is indeed challenging (Siebenmorgen & Meullenet, 2004).

Quality Assessment

Federal laws in the United States prohibit interstate commerce of contaminated grain. Contamination of grain is avoided by (1) preventing lodging of grain in the field, thus avoiding soil-borne microorganisms; (2) cleaning of grain at harvest to remove microorganisms which might be on foreign materials; (3) avoiding cracking or checking of grain during harvesting and handling; (4) protecting grain in storage from contamination by rodents and birds; (5) providing a storage environment such that microorganisms associated with grain will not grow; and (6) thoroughly cleaning granaries, storage, elevators, etc. after
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each storage season. The amount of filth can be quantified by the extent of hairs, dropping, feathers, etc. in the grain. Evidence of these materials can disqualify the grain for use as a food product. Sanitation practices in handling of the grain determine to a large extent the cleanliness of the products that are made from it. Insects may enter the grain, and do internal damage, often unnoticed by the casual observer. These insects are not removed by normal cleaning, although light kernels may be removed by a pneumatic or air separator. Old grain can serve as a place for insects to live, hibernate, or to deposit their eggs, and thus infect the next crop. Insects also may crawl or fly to a bin of grain to infest it, and they may move from one grain to another as harvest proceeds.

Mycotoxin

Several grain molds produce toxins called mycotoxins. The major mycotoxins are aflatoxins, Fusarium toxins, and ochratoxins. Of these, the aflatoxins are of greatest importance to the grain storage engineer. Aflatoxins are produced by certain strains of Aspergillus flavus and A. parasiticus; at least 12 aflatoxin derivatives have been identified. Aflatoxin B appears to occur most frequently in affected grain; it is a cyclic compound with chemical formula \( C_{17}H_{12}O_6 \). Because of the extreme toxicity, the tolerance at present (i.e., 1991) for aflatoxin in the United States is zero for food destined for human consumption and 20 ppb (parts per billion) for feed grains for animals. Aflatoxins are believed to be carcinogenic to humans, leading especially to liver cancer. Aflatoxins may occur in all grains, but are most commonly found in the United States on corn grown in the southeastern states where the growing conditions are optimal for A. flavus development (i.e., 27-30 °C or 80-86°F and 85-95% RH). Aflatoxin contamination appears to occur mainly in the field. In storage, the competition of other molds frequently negates the ability of A. flavus to develop aflatoxin (Brooker, Bakker-Arkema, & Hall, 1992).

The testing for aflatoxin in a grain sample can be conducted at three levels: by presumptive test, by screening procedures, and by quantitative test. Placing a mold-infected corn kernel in ultraviolet light is likely to produce a yellow-green fluorescence if aflatoxin is present (Shotwell & Hesseltine, 1981). This so-called BGYF (bright green-yellow fluorescence) test is presumptive in nature because it is only 50-80% reliable. A positive BGYF test of a grain sample should be followed by a more accurate screening or quantitative procedure.

Screening for different mycotoxins is done by minicolumn chromatography (Wilson, Tabor, & Truckess, 1976); the test requires a chemical laboratory and takes several hours. Quantitative tests are based on high-pressure liquid chromatography (HPLC) and are usually conducted in commercial laboratories (Pons & Franz, 1978). Screening and quantitative test for the detection of aflatoxins are obviously not practical at the farm or elevator level. However, they should be used at the feed mill or food processing plant if a presumptive test such as the BGYF procedures shows positive for a lot of grain.

Weidenboerner provides a list of mycotoxins found in rice and cites locality of incidence (Weidenboerner, 2001). Aflatoxins are of the most importance to rice safety, and therefore the most regulated in the U.S. grain industry. The major aflatoxins consist of aflatoxins B1, B2, G1 and G2; these are produced mainly by Aspergillus flavus, A. parasiticus or A. nominus (Miller, 1995; Richard, 2007). The aflatoxin B1 is considered to be the most potent naturally occurring carcinogen (Widstrom & Sparks, 1996), and is regarded as a quadruple threat because not only is it a potent toxin but is also hepatotoxic, teratogenic, and mutagenic. The World Health Organization has classified aflatoxins as a class 1 carcinogen (Moreno-Martinez et al., 2011).
The best way to control mycotoxins is to prevent their formation. Various strategies are presently being researched or used to control the risk associated with mycotoxin contamination of rice before harvest. These strategies include (1) selective breeding to advance the development of varieties resistant to mycotoxin-producing fungi; (2) proper cultural practices, such as choice of planting and harvest dates, tillage practices, crop rotation, plant population, irrigation, and sanitation; and (3) applying crop protection chemicals or biological controls. However, the spores of some pathogenic fungi such as A. flavus are prevalent in the air, making the fungus a common contaminant of grain even postharvest. The spores of such fungi are very heat tolerant and may survive the convective heating methods that are conventionally used to dry rice. That means that when viable spores that survived drying encounter favorable conditions of equilibrium relative humidity, the fungal spores may be activated, and their growth increases the risk of mycotoxin contamination.

Metal Contaminants

Although there is no clear definition of what a heavy metal is, density is in most cases taken to be the defining factor. Heavy metals are thus commonly defined as those having a specific density of more than 5 g/cm³. The main threats to human health from heavy metals are associated with exposure to lead, cadmium, mercury and arsenic (arsenic is a metalloid, but is usually classified as a heavy metal). Although adverse health effects of heavy metals have been known for a long time, exposure to heavy metals continues and is even increasing in some areas. Emissions of heavy metals to the environment occur via a wide range of processes and pathways, including to the air (e.g. during extraction and processing), to surface waters (via runoff and releases from storage and transport) and to the soil (and hence into groundwater and crops). Natural as well as anthropogenic sources of cadmium, including industrial emissions and the application of fertilizer and sewage sludge to farm land, may lead to contamination of soils, and to increased cadmium uptake by crops and vegetables, grown for human consumption. Long-term high cadmium exposure may cause skeletal damage, first reported from Japan, where the itai-itai (ouch-ouch) disease (a combination of osteomalacia and osteoporosis) was discovered in the 1950s. The exposure was caused by cadmium-contaminated water used for irrigation of local rice fields (Lars Jarup, 2003).

Pre-Harvest Factors

Irrigation

Irrigation water is one of the most precious resources for rice producers. Reports of diminishing supplies have prompted many producers to develop reservoir and/or tail water recovery systems to reduce the “waste” by collecting and re-using all available water. Simultaneously, producers have tried to implement other conservation techniques to preserve the resource vital to continued production. For instance, groundwater is used to irrigate 76.4% of the rice acreage in Arkansas with the remaining 23.6% irrigated with surface water obtained from reservoirs or streams and bayous. During the mid-1990s, the University Of Arkansas System Division Of Agriculture began educating producers on multiple-inlet irrigation which uses poly-tubing as a means of irrigating rice to conserve water and labor. As of 2015, rice farmers utilize this practice on 40.6% of the rice acreage. Stubble management is important for preparing fields for the next crop, particularly in rice following rice systems. Several approaches are utilized to manage the rice straw for the next crop, including tillage, burning, rolling, and winter flooding. In 2015, 43.5% of...
the acreage was burned in Arkansas, 39.0% was tilled, 26.7% was rolled, and 20.4% was winter flooded. Combinations of these systems are used in many cases. For example, a significant amount of the acreage that is flooded during the winter for waterfowl will also be rolled. Some practices are inhibited by fall weather, but in 2015 acreage where the stubble was burned noticeably increased as dry (Hardke, 2015).

Nighttime Air Temperatures

High nighttime air temperatures (NTATs) during reproductive growth stages (R-stages) are known to cause increased chalkiness and reduced head rice yields (HRYs) in susceptible rice cultivars. These effects have been clearly demonstrated in field trials conducted from 2007-2010 across the eastern Arkansas rice-growing region (Ambardekar, Siebenmorgen, Counce, Lanning, & Mauromoustakos, 2011; Lanning, Siebenmorgen, Counce, Ambardekar, & Mauromoustakos, 2011). Field trials continued from 2011-2014 in order to further verify these NTAT impacts on an expanded set of cultivars. Analysis of the 2012 and 2014 growing years indeed confirmed the trends of increasing chalk and decreasing HRY with increasing NTATs during critical R-stages. However, in 2011 and 2013 the trends were quite different among many cultivars. This was attributed to the abnormal growing environment in these years, when spring rains forced late planting, leading to significantly later heading dates and markedly reduced NTATs during later R-stages. These results demonstrate that during years of late planting with late heading of rice, NTAT is not an entirely accurate predictor of rice quality, as temperatures below a certain threshold may counterintuitively reduce quality.

Haydon, Siebenmorgen, & Counce (2015) reported that the trends of increasing chalk and decreasing HRY with increasing NTATs, may only be considered reliable predictors when rice is planted at recommended times, early in the year, as in 2012 and 2014. New models for understanding temperature effects on agronomic grain yields, HRY, and chalk should consider the effect of planting and heading dates on the growing environment. Agronomic grain yields tend to decrease with late planting and subsequent late heading dates (Siebenmorgen, Grigg, & Lanning, 2013). When weather forces delayed planting, it appears to be beneficial for some cultivars with respect to chalk and milling quality to experience relatively warmer NTATs during critical grain-filling stages. Though early seeding promotes greater agronomic yields, it also creates the conditions that maximize susceptibility to elevated NTAT effects. However, late planting and low temperatures during grain-filling may also contribute to quality and yield reductions.

Rice Cultivar Selection

During the course of development of a rice cultivar, a breeder selects for numerous traits (e.g., height, maturity, yield, milling yield, cooking quality, disease resistance, etc.), each of which may be controlled by a few or by many genes. The appearance of a trait is known as its phenotype and is a result of the presence of an allele (a form of a gene) under particular environmental conditions. Some genes are more sensitive to environmental conditions (e.g., genes for milling yield) than others (e.g., genes for pigmentation). In addition, traits can be influenced by interaction with other genes that are in the background of the cultivar (called “epistasis”). With each generation of self-pollination that occurs in rice, 50% of the segregating genes become fixed as one allele or another. Since rice is believed to possess more than 25,000 genes, it is clear that making significant genetic improvement can be difficult with so many “moving pieces”. This is one of reasons that breeders tend to focus on using narrow, improved germ plasm in their crosses so as to not disrupt the pyramid of desirable traits that they have spent years put-
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It can take 10 generations of selection to develop a cultivar that no expression of the trait under different environments, the number of genes involved, the interaction of allelic differences (additive, dominance, and epistatic effects), and the methods required to detect phenotypic differences (McClung, 2004).

The key to having an effective breeding program is the ability to evaluate large numbers of progeny to identify novel recombinants. Most breeding programs make 100-300 crosses and evaluate 20,000-40,000 breeding lines each year. Screening methods that are rapid, give clear results, and can be used on large numbers of progeny greatly enhance the progress that can be achieved from selection. Some traits, like height and maturity (days to heading), can be easily measured. Although these traits may be influenced by the growing environment to some extent, breeders typically include well-characterized varieties as repeated standards throughout the field to provide a quick visual reference. For some pathogens (e.g., P. grisea (Cooke) Sacc., causal agent of rice blast disease, and R. solani Kuhn, causal agent of sheath blight disease) for which propagation and inoculation methods are well established, screening nurseries are planted. For other disease, like narrow brown leaf spot and kernel smut, the breeder takes the opportunity to make selections when there is a natural incidence of the disease or by planting nurseries at sites that frequently have endemics. Screening for tolerance to insect damage is usually based on the latter method since there are no successful rearing methods or efficient screening techniques for insect pests common to the U.S. rice-growing regions (McClung, 2004).

Geographical Conditions

Rice is grown from the equator to 50°N and from sea level to 2500 m. It is grown in the hot, wet valleys of Assam and in the irrigated deserts of Pakistan. The soils on which rice grows are as varied as the climatic regime to which the crop is exposed: texture ranges from sand to clay, pH from 3 to 10; organic matter content from 1 to 50%; salt content from almost 0 to 1%, and nutrient availability from acute deficiencies to surplus. Productivity of land used for growing rice is to a large extent determined by soil and water conditions. Rice is the only major annual food crop (with the exception of aroids) that thrives on land that is water saturated, or even submerged, during part or all of its growth cycle (de Datta, 1981).

Rice will grow, under appropriate temperature regimes, wherever there is enough water to sustain a crop. That includes low-lying areas in coastal plains, floodplains, and valleys, where there is often more than enough water to maintain lowland rice and where water control must be practiced. Also included are rice fields (paddies) on steep and mountainous areas and vast upland areas where rice is grown in unbundled fields. Wherever conditions are favorable, lowland rice fields are formed into paddies that hold water during the land preparation and rice-growing periods. A number of land management systems for rice cultivation have evolved over the centuries to suit soil, climate, water supply, and socioeconomic conditions. Rice lands are categorized by Moormann and van Breemen (1978) who proposed a new terminology. Rice lands are categorized...
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into irrigated (where water supply is assured) and rained (where water supply is uncontrolled). Rained rice lands are grouped as: pluvial, phreatic, fluxial. Fluxial rice lands are located in lower aspects of the landscape or in flat areas and are flooded during the greater part of the growing season. These areas are currently known as lowland swamps in which the land could be either bunded or unbunded.

Cultural Management

In the late 1970s and early 1980s, U.S. breeding programs were successful in releasing short-statured, semi dwarf cultivars that produced high yields, resisted lodging, and showed a dramatic yield response to high levels of fertilizer. Rutger & Bollich (1991) called the development of semi dwarf rice cultivars one of the most important influences on rice improvement because it allowed increased fertilizer use and higher yields without inducing lodging. Although semi dwarf and tall cultivars can produce the same amount of aboveground biomass, semi dwarf cultivars have a higher harvest index, producing a greater portion of dry matter as grain instead of straw (Roberts, Carlson, & Farkas, 1980). The amount of timing of fertilizer application for the rice crop depends upon soil type, cultivar growth and development, and whether a ratoon crop (i.e., grain produced as a result of regrowth of tillers from stubble left in the field after the first crop is harvested) will be harvested. The amount of nitrogen required for optimization of the main crop yield tended to be higher than that required for optimization of milling yield. The amount of nitrogen required for maximum yield and milling quality depended on the cultivar. Seetanum & De Datta (1973) determined that milling quality was generally improved when nitrogen was applied in split (multiple) applications, rather than all at planting. A nitrogen application at heading was associated with an increase in grain protein content, grain hardness, and milling quality. Higher nitrogen applications have been reported to influences the viscosity profile of rice flour paste as it is heated and cooled which causes some changes like decrease chalkiness (i.e., white belly), grain cracking, and breakage (Fitzgerald, 2002).

Management of insect and disease pests of rice also affects yield and grain quality. A summary of important disease and insect pests of rice in the United States has been presented elsewhere (Groth & Lee, 2002; Way, 2002), so only a few pests that directly affect grain quality are highlighted here. Nymphs of the rice stink bug, *Oebalus Pugnax* (F.), feed on developing grains and cause the introduction of various pathogens, which results in a discoloration of the kernels called “peck”. Incidence of peck greatly reduces the economic value of the crop. Similarly, the primary concern for controlling rice disease is to prevent loss of grain production. However, even if the rice pathogen does not directly affect the grain, disease like sheath (caused by *Rhizoctonia solani* Kuhn), rice blast (caused by *Pyricularia grisea* Cooke Sacc.), and panicle blight (caused by *Burkholderia glumae*) can cause poorly filled grains and chalky kernels that shatter during milling. The fungus that causes kernel smut, *Tilletia barclayana* (Bref.) Sacc. & Syd., produces black spores on panicle florets that can discolor grain during parboiling. Another disease found on the rice panicle is false smut caused by *Ustilaginoidea virens* (Cooke) disease; this can discolor seed lots. Narrow brown leaf spot caused by *Cercospora janseana* (Racib) O. O. Const. is a disease that can occur on the leaves or panicles. It causes the grain to rapidly lose moisture in the field, making it more susceptible to fissuring, which decreases milling yield (McClung, & Castro, 1994).
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Post-Harvest Factors

Moisture Content

Among the several kinds of storage fungi, each has its own moisture preference, beginning at about 13.5%. However, each grows faster as moisture content rises. Mold growth increases at an accelerating rate during storage because molds improve their growing conditions by their own growth, raising both temperature and moisture content. So in any lot stored grain, certain events can be observed. Mold spore count increases slowly and temperatures rise very slowly. At about 32°C (90°F) odors, some germ discoloration, and small increases in fatty acids become evident. At about 43°C (110°F), strong odors (usually sour), browning of kernels, sharp increases in fatty acids, and some moisture increases are measurable. At about 57°C (135°F) there is a pause in the temperature rise, but kernels are likely to be black, highly rancid and collapsing (Bailey, 1992).

The relative humidity of interseed air is directly related to the moisture content of grain; the grain moisture content moves toward equilibrium. Whenever grain is exposed to air of lower than its equilibrium relative humidity, it gives up moisture to the air. This is the process by which grain dries both naturally and artificially. It is also the method by which a mixture of grain of different moisture contents moves toward uniformity. Unfortunately, this is also the cause of many grain condition problems, usually by translocation of moisture or moisture transfer. Whenever the temperature in any quantity within a mass of grain differs from another part, moisture is carried from warmer to cooler areas by convection and deposited. Most grain storage starts in late summer or fall when grain is warm. As the weather cools, convection currents begin to move upward in the warmer grain. When the currents reach the cooler surface, the air temperature is reduced, and its relative humidity approaches or passes saturation. If the air cools further, it passes the saturation point, and free water will begin to be deposited. In cold weather, water often drips from roof supports back into the grain or runs down inside the bin walls. Conversely, care must be taken not to pass warm, humid air through cold grain because the air cools, its relative humidity increases, and moisture is absorbed by the grain.

It is difficult to measure grain moisture content accurately, partly because the moisture content of any lot is really an approximate average of the moisture content of its individual kernels, and partly because there are variations in any sample. Moisture content of grain in the field can vary 4% points within a few feet and even more between different parts of the field, in addition to variations during a harvesting day. Many truckloads from many fields enter one country elevator or one boxcar during harvest. Since no elevator has been enough to precisely segregate the grain it receives according to moisture content, loads of varying moisture levels go into any one bin. Differences in temperatures cause moisture movements as described earlier. Further, moisture meters are not precise. Repeated tests of the same sample (ignoring sampling errors) with the same or different testing equipment give different results. Any calculations of safe storage life based on reported moisture content are not very dependable, are subject to wide errors, and necessitate constant vigilance.

Temperature

Temperature is as important as moisture content in determining the storage life of grain. Molds grow slowly, and some not at all, below 10 °C (50 °F) but do serious damage at 29 °C (85 °F) if moisture con-
ditions are favorable. Temperatures of grain at harvest and entry into storage range from 39 °C (103 °F) for rice in the southern United States.

Rice is an excellent insulator and changes its own temperature very slowly. Rice in concrete bins without air circulation will change only a few degrees through months of cold weather. Cold rice put into storage in winter remains cold through the summer. A range of about 11 °C (20 °F) may be found in 1.5 m (5 ft) in a rice mass, so that differences persist for a long time if loads of rice of different temperatures are put in storage. Rice next to the steel wall of a bin exposed to the sun may reach 54 °C (130 °F) during the day, but the temperature of rice 1.22 m (4 ft) away remains unchanged. Small lots, such as in small farm bins, follow outside temperatures to some extent, with a time lag, but large lots in large bins may retain essentially the same temperature they had when loaded into the bin for a considerably long duration (Bailey, 1992).

For the same reasons, overheating in a rice mass may proceed undetected for dangerously long periods and completely destroy small amounts of rice. Bins though to be in good condition are often found to contain clusters of badly damaged rice. In fact, temperatures are seldom uniform throughout any bin or lot. When loads of rice of different temperatures are put into storage, rice near walls and surfaces soon acquires a higher or lower temperature. Wherever temperatures differ, convection currents begin to move moisture from warmer to cooler portions.

When cold rice is added to a bin of warm rice, moisture moves up into the cold rice. A bin of cold rice next to a bin of warm rice causes condensation on the wall of the warm bin. Cold rice exposed to warm outside air increases in moisture content. During artificial cooling, alteration of moisture contents must be considered. Temperature and moisture together largely determine the length of safe storage life in addition to many other conditions, such as proportion of kernels infected by fungi and the degree to which they are infected, previous storage conditions, cleanliness and soundness of the grain, insect and mite infestation and age.

Dockage

The presence of “dockage” in grain is not critical for the survival and multiplication of the internally infesting insects. However, for some of the externally infesting species it is quite beneficial and critical at low moisture contents. Cotton, Walkden, White, & Willbur (1960) indicated that the presence of grain dockage or dust was vital for reproduction of flour beetles in dry grain.

The extent of postharvest damage and loss caused by insects to grains and their products is difficult to quantify. The National Academy of Sciences (NAS, 1978) indicated that postharvest loss estimates (unlike production estimates, which are based on the measurable genetics potential of crops) are location- and season-specific to a degree that makes the concept of average levels of loss almost meaningless. Grain losses can be considered in a variety of ways: weight loss, food loss, nutritional loss, quality loss, seed loss, and other specific types of losses. Most of these losses can also be expressed in value terms, as monetary losses. Processed cereal products are also subject to damage and losses. The greatest damage and loss to cereal products is from contamination rather than from consumption by insects. In some societies, the mere presence of a living insect in a processed cereal product is a basis for rejection, whether it is in a 100,000-lb bulk flour shipment or in a single cereal package. The presence of live insects in processed grain products is considered more serious than an equivalent infestation in grains.
Insects destroy about 13% of the crops in spite of all the insecticides used and the biological controls employed. The usage of DDT and other synthetic pesticides has grown in the decades following their introduction in 1946 to over 1.1 billion pounds annually. Although overall crop losses due to insects have increased, important advances have been made in reducing insect losses from certain pests in some crops. According to USDA estimates, rice loss due to insects have also been increasing. Factors contributing to these losses include the planting of insect-susceptible rice types rather than resistant types, thus increasing rice-borer susceptibility (Pimentel, 1975). Damage by stored-product insects is in addition to the direct damage caused by insects to agricultural commodities after harvest and to the products derived from commodities. Stored-product insects increase the cost of goods because of the expenditures required for their prevention and control. These cost affect farmers, warehousemen, millers, bakers, and food processors, those engaged in transportation and marketing, and finally, the consumer.

Dockage, for the most part, has a negative value because of the cost of removing it. In addition, it is a contribution factor to such problems as heating and infestation. Often, in fact, when rice is sold, the buyer deducts the percentage of dockage from the gross weight and makes payment only for the amount of dockage-free grain.

QUALITY ASSURANCE SYSTEMS

Milling

Most rice is milled for direct consumption or for subsequent utilization as an ingredient in end-use products. The primary purpose of milling is to remove the germ and bran layers from the kernel endosperm. The extent to which bran has been removed from the kernel endosperm is referred to as the “degree of milling” (DOM). To a large extent, the milled-rice customer and the intended use of the rice dictate the target bran removal level (e.g., most rice milled for breakfast cereal processing is not milled to the same extent as that used for “table” rice).

Figure 1 indicated four morphological layers surrounding the rice kernel endosperm (the pericarp, seed coat, nucellus, and aleurone layers (Luh, 1980)) and the germ (embryo) which are collectively referred as “bran”. The bran contain approximately 18-20% lipids and 14-15% protein, while milled rice, comprising primarily the kernel endosperm, is generally much lower in lipids (approximately 0.3-0.5%) and protein (approximately 7%). These values can vary greatly due to varietal, environmental, or processing variability. Because of these stark differences in composition between the bran and endosperm, the DOM can affect the functionality of milled rice. In addition to having functional effects, the bran remaining on kernels after milling can affect sensory characteristics. As milling removes the outer protective layers of the rice caryopsis, the endosperm of milled rice becomes relatively more prone to moisture sorption from its surrounding environment. This is particularly true for rice that has just been milled, since rice exiting a mill is typically at higher temperatures than the surrounding air. A situation often experienced in the milling industry that can be very costly in terms of broken rice and mill downtime is the fissuring and subsequent breaking of kernels during post milling operations, often referred to as “residual breakage”.

Milling quality is composed of several factors that directly affect the value of rough rice. It encompasses the total amount of milled rice recovered after milling (total milled-rice yield) and the total amount of whole kernels recovered after milling (head-rice yield or whole-rice yield). The purity of the rough-rice
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Figure 1. Rice kernel structure

samples is also a component of milling quality. Specially, the value of rough rice is negatively affected by the presence of cracked kernels, red rice, discolored kernels, or immature kernels.

Laboratory-sized mills are used to determine milling quality (Figure 2). They serve as important tools used by rice breeders to assess the milling quality of breeding progeny, by scientists to prepare samples for study, by government agencies to determine the grade of rice, and processors to set the price of rice. Differences between rice laboratory mills include the principle behind the milling process, i.e., friction versus abrasion. Also, the mills differ in the sample size required and whether dehulling is first required. The McGill no. 3 miller is used by the USDA to determine the grade designation of milled rice (USDA, 1995). The McGill no. 2 is able to achieve milling yields equivalent to those of no. 3 miller (Andrews, Siebenmorgen, & Mauromonstakos, 1992). McClung and Castro (1994) have demonstrated that a smaller version of the no. 2 miller can be used to mill 50 g of rough rice. The milling yields obtained were reported to be similar to those achieved when starting with brown rice in the no. 2 miller. Other laboratory mills, such as the Test Rice Whitening Machine (Yamamoto Crop.), Rice Miller Tester no. 60 (Grain Machinery Mfg. Crop.), and Rice Test Mill (Satake Crop.), are also available.

Brown rice yield is determined by expressing dehulled rice as a weight percentage of rough rice (Figure 3). This measurement also indicates the amount of hull in a given sample. Total milled-rice yield is determined by expressing combined broken- and whole-kernel yield as a weight percentage of rough rice. Head-rice yield is the yield of milled rice that is three quarters or more of normal kernel length, expressed as a percentage of rough rice or total milled rice. The most common method for determining whole vs. broken kernels is to place a sample on a shaker table (Figure 4), which consists of two inclined indent plates that vibrate. Various types of sieves, indent cylinders, and graders are also in use. Because these are subjective methods, some effort has been made to develop instrumentation able to remove the
subjectivity from the separation of whole kernels from broken. An instrument that is receiving some attention is an automated grain inspection system called the GrainCheck (Lloyd, Cnossen, & Siebenmorgen, 2001). This system utilizes image-analysis technology to measure kernel color, length, and width. Another image-analysis system is the Single-Grain Rice Inspector, developed by Kett Laboratory and in use in Japan. The manufacturers of this instrument advertise that grain color and shape and the percentage of whole grain, immature grain, and discolored kernels can be determined.

Kernel weakness that results in breakage during milling is reported to be related to fissuring (cracking), chalkiness, and kernel dimensions (Bhattacharya, 1980). Both environment and genetics are known to have an impact on fissure resistance (Jodari & Linscombe, 1996). The environmental conditions that promote fissuring are rain and changes in humidity just before harvest (Banaszek & Siebenmorgen, 1990; Lan & Kunze, 1996a, b). Research suggests that grain shape and size, hull and bran diffusivity, and the endosperm chemical makeup may control fissure resistance (Steffe & Singh, 1980; Patil, 1988; Lu & Siebenmorgen, 1992; Juliano, Perez, & Cuevas-Perez, 1993; Sarker, Kunze, & Strouboulis, 1996).

The measurement of rice kernel fissures was reviewed by Bhattacharya (1980). The methods described were of varying levels of sophistication, but all consisted of light being transmitted from below a sample and manual counting of the number of kernels with fissures or particular types of fissures. More recently, high-speed microscopy imaging has been used to study the association of internal stress with kernel fissuring (Jia, Yang, Siebenmorgen, Bautista, & Cnossen, 2002). Also, an image-analysis (machine-vision) system was developed that was able to quantify 94% of the fissures in a medium-grain sample and 100% of the fissures in long-grain rice (Lan, Fang, Kocher, & Hanna, 2002).
Another aspect of milling quality is the degree to which a given sample has been milled. Degree of milling is a quantification of the amount of bran removed from kernels during the milling process. The majority of consumers around the world prefer well-milled rice that has little to no bran remaining on the kernels. This is ironic considering that unmilled (brown), rice compared to milled rice, contain more protein, lipids, vitamins, minerals, and phytochemicals with potential health benefits. While nutritionally inferior, milled rice does have a long shelf life than unmilled rice. Samples milled to different degrees reportedly have varying functionality and sensory properties. For example, Champagne, Marshall, Goynes (1990) and Marshall (1992) reported that a greater degree of milling was associated with decreased onset and peak-gelatinization temperature. Reduced cooking time and higher water-binding capacity, swelling power, and peak viscosity were found for rice milled to a higher degree (Champagne et al, 1990; Kim & Jeon, 1996; Perdon, Siebenmorgen, Mauromoustakos, Griffin, & Johnson, 2001). Sensory panel research revealed that flavor intensities of cooked rice milled to different degrees were dependent on cultivar, growing location, and moisture content (Champagne et al, 1997). Cooked rice with a higher degree of milling was found to have lower corn flavor, raw-rice flavor, wet-cardboard flavor, haylike flavor, and bitterness (Park, Kim, & Kim, 2001). This sensory report also found greater degree of milling to be associated with increased agglomeration, adhesiveness, cohesiveness of mass, inner moisture, and tooth packing, while hardness and chewiness decreased. Therefore, it is important
that only samples that have been milled to the same degree be compared in studies related to end-use quality. This, however, is seldom documented in published research.

The numerous methods developed to determine degree of milling have been reviewed (Barber & Benedito de Barber, 1979). These methods can be categorized into two groups: those that assess the amount of bran remaining on milled rice and those that measure chemical components in the rice kernel’s outer layers. Visual estimation of the bran remaining after milling is performed by comparing milled samples to established rice standards, or by doing so after staining kernels with various bran-specific dyes (Tani, Chikubu, Shikano, 1952; USDA, 1995). Although, these visualization methods are still in use, they rely on person’s subjective judgment and are thus susceptible to a high level of method error. Colorimetric determination of extracted bran left pigments has also been reported to be useful for determining the amount of bran left after milling rice (Bhattacharya & Sowbhagya, 1972a, 1976). Chemical components that decrease with greater degree of milling and have been used to quantify this grain characteristic include lipids, ash, silica, protein, thiamin, and fiber (Barber & Benedito de Barber, 1979). These methods suffer from error because cultivars differ in the concentration gradient of these compounds (Shams-Ud-Din & Bhattacharya, 1978). They also are not practical because most of them are technically demanding and time-consuming. Nevertheless, in the last few decades, extracting the amount of lipid in the outer layers of 10 g of milled rice using a Goldfisch apparatus (i.e., determining surface lipids) has commonly been used to determine degree of milling of rice (Hogan & Deobald, 1961). According to Shams-Ud-Din and Bhattacharya (1978), this technique is suitable only for rice that has been milled beyond the stage of being undermilled. Some have sought to shorten the time of analysis for surface-lipid measurements. For example, a rapid gas-chromatographic measurement of surface lipids

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Figure 4. A laboratory-scale rice sizing device (Model 61, Grain Machinery Manufacturing Corp., Miami, Florida, USA)
that requires only 500 mg of sample has been developed (Bergman, unpublished data). Also, Lam and Proctor (2001) shortened the time of analysis for the standard Goldfisch surface-lipid measurement by changing the extraction solvent from the standard solvent, petroleum ether, to the more polar isopropanol.

Some studies have reported other methods to predict surface-lipid content. For example, Chen, Marks, Siebenmorgen (1997) developed near-infrared (NIR) reflectance calibration equations to predict surface-lipid content of milled rice. Studying three cultivars, they reported the best equation utilizing visible and NIR wavelength, modified partial least squares, and pretreatments of standard normal variate and first derivative. Liu, Tao, Siebenmorgen, & Chen (1998) developed a digital image-analysis system that was able to predict \( R^2=0.95 \) the surface lipid content of one cultivar milled to different degrees of milling. Gangidi, Proctor, & Meullenet (2002) reported the use of diffuse-reflectance Fourier-transformed infrared spectroscopy to predict degree of milling, as measured by solvent extraction of surface lipids. Analysis showed a high degree of correlation \( R^2=0.96 \) between surface-lipid content and the spectra in the 4000-400 cm \(^{-1} \) range for one long- and one medium-grain cultivar. Where most of these predictive method reports fall short is in the very small number of cultivars that each studied. Rice germ plasm is so variable in terms of end-use quality characteristics that, to validate any predictive method, many cultivars with differing genetic backgrounds need to be evaluated.

Other recent developments in the measurement of degree of milling include the use of image analysis to quantify the whiteness of a sample (Yadav & Jindal, 2001). Optical instruments, such as the Satake Milling Meter, quantify the whiteness and translucency of a sample and compute a degree-of-milling value. A whiteness score of 40 is considered by many in the U.S. rice industry to be a well-milled sample. These instruments are very rapid, but their utility is hindered if chalkiness is present.

**Drying**

Rough rice is harvested at 16-28\% (w.b.) moisture content. The drying behavior of a rice kernel, or of a collection of rice kernels in a dryer, depends on the physical characteristics of the rice species. Rice is considered to be hygroscopic capillary-porous products in which the pores are partially filled with liquid water and partially filled with an air/water-vapor mixture. During the drying process, the moisture evaporates at the kernel surface and/or in the pores and leaves the kernel due to the partial vapor pressure difference between the kernel and the surrounding air.

Drying is a process of simultaneous heat and moisture transfer. The heat is required to evaporate the moisture that flows from the product surface into an external drying medium, usually air. Rice, when drying as single particles under constant external conditions, exhibit a constant-rate moisture loss during the initial drying period, followed by a falling-rate drying phase. Rice kernels, however, dry entirely within the falling-rate period. When rice is dried in a batch rather than as individual particles, the batch initially displays a constant-rate drying period (Brooker et al. 1992).

**Conventional Methods**

*Cross Flow Dryer*

The grain flows by gravity from a wet-holding bin into the drying zone consisting of one or several screened grain columns; heated air is forced perpendicularly from the air plenum through the grain in the columns. A similar process occurs in the cooling section where ambient air is employed. The thickness
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of the grain columns in the drying section is 0.25-0.45 m (0.8-1.5 ft); the length of the grain columns in the drying section is 3-30 m (9-100 ft), and in the cooling section about 1-10 m (3-30 ft).

The drying-air temperature depend on the grain to be dried and on the grain quality requirements. Typically for food grains, the temperature ranges between 60 °C and 75 °C (140-165 °F), for feed grains between 80 °C-110 °C (180-230 °F).

Two fans are employed in a conventional cross flow dryer: a heating fan and a cooling fan. The air from both fans passes through the grain and is exhausted directly to the atmosphere. The drying and cooling airflow rates range from 15 m³ to 30 m³ air/min. m² screen area (50-100 cfm/ft²) or 83-140 m³/ min.tonne (75-125 cfm/bu). The static pressures are a relatively low 0.5-1.2 kPa (2-5 in. H₂O).

The grain velocity in the grain columns, and thus retention time of the grain in a cross flow dryer, is controlled by the revolutions per minute (rpm) of the unloading or discharge augers. The grain velocity and the retention time depend on the initial moisture content of the grain, the drying-air temperature and air flow rate, and the dimensions of the dryer. Thus, no definite numbers can be quoted for these quantise for cross flow dryers.

In the cross flow dryers grain is dried non-uniformly; that the grain at the air inlet side of the grain column is over dried and exits from the dryer nearly at the inlet air temperature; and that the grain at the air exhaust side of the column remains well below the inlet air temperature and is under dried. Mixing of the low-temperature and high-temperature grain with the high-moisture low-temperature material in the unloading augers of the dryer produces grain at the desired average moisture content and temperature. Cross flow dried grain always remains non-uniform in moisture content and, thus, in grain quality.

To offset the two major disadvantages of the conventional cross flow design, namely, the large moisture differential across the grain columns and the high specific energy requirement, a number of modified cross flow dryers have been developed.

A very efficient (but expensive) design for decreasing the moisture differential in the dried grain, and simultaneously for improving the energy efficiency of cross flow dryers, is reversal of grain position at a point midway through the drying column. The air that exhausts from the first drying section is exhausted at a high average relative humidity; that from the second drying section is recycled along in the two drying sections. Compared to conventional cross flow dryer, the cross flow model with air reversal and air recycle consumes 42.3% less energy and has a substantially smaller moisture differential (1.3% instead of 5.3%).

Further improvement on the cross flow dryer design is that dryer contains tapered grain columns, dual variable-speed discharge augers, and a tempering hopper separating the first and second drying zones. The exhaust airstreams from the second drying zone and from the cooling zone are mixed and recycled. The hot grain closest to the air inlet moves more rapidly through the drying zones than the colder grain located near to the air exhaust side of the grain columns. The varying grain velocity across the columns is the result of the different rpm of the dual variable-speed discharge augers. With proper control of the ration of the rpm of the two unload augers in each column, the moisture gradient across the columns can theoretically be decreased to zero.

The drying process of the cross flow dryer is interrupted when the partially dried grain reaches the tempering hopper after passing through the first drying zone. During the period of 0.5-1.0 h of tempering (or steeping), the grain is not subjected to an air treatment, and thus the temperature and moisture gradients within the individual grain kernels are diminished before drying is resumed. The tempering process results in limiting the stress cracking and subsequent breakage of the grain. Tempering between consecutive passes through a dryer has been practiced for years in drying rice to prevent fissuring. Also,
tempering between drying zones is a standard feature of multistage concurrent-flow dryers (Brooker et al. 1992).

**Natural Air Dryer**

Rice is in bin-dried in steel bins with full perforated floors or in flat storage houses in which appropriate air distribution systems are placed. The major parameters influencing the operation of an in-bin rice drying system are: (1) initial rice moisture content, (2) average air inlet temperature and humidity, (3) air flow rate and distribution, (4) grain depth, (5) grain quality requirements.

Bin drying of rice is frequently accomplished with natural air. Stirrers are used in some installations. Design requirements in the United States for the natural air in-bin drying of rice are (1) reduction of the moisture in the wettest grain layers to 15-16% within 15-18 days, and (2) final drying to 12.5-13.5%. This combination drying system prevents mold damage and kernel discoloration (USDA, 1959).

For natural air, in-bin drying system, the recommended minimum airflow rate and the maximum grain depth for various initial moisture contents are different location by locations. If the relative humidity of the ambient air is high during the drying season, the natural air in-bin drying of rice to 13% moisture is a technical challenge. Depending on air conditions, wettest layer of rice may only be dried to 16%. Thereafter, the fan is operated intermittently; it should be activated by a humidistatic controller only when the relative humidity of the air drops below 65%, or is appropriate to actual drying.

For proper bin drying of rice to 13.0% moisture, the ambient air may have to be slightly heated to keep the relative humidity below 65%. In California, the highest recommended inlet air temperature for supplemental-heat in-bin rice drying is 29.4 °C (85 °F); in Louisiana, 37.8 °C (100 °F). Recommended maximum moistures and maximum grain depths are the same as for natural air drying.

Stirring devices are frequently used with supplemental-heat in-bin rice dryers. Slightly greater grain depths can be employed due to the decreased static pressure drop of a bed of stirred rice. The annual costs of an in-bin drying and storage system consist of the annual ownership or fixed costs plus the operating or variable costs. For a 1,000-MT (50,000-bu) in-bin system with augers, the fixed costs constitute about 60% of the total annual costs. Depreciation on the bins, dryer fans, heaters, humidistats and thermostats, and stirrers make up half of the fixed costs, and the interest on the investment is about one fourth. The energy costs are about 10% of the total drying expenses.

**Novel Technology**

**Cooling**

The aeration fan of the grain cooler sucks ambient air through a dust filter. Then the air is cooled by an air-conditioner to the desired temperature and dehumidification takes place by condensation of water. However, the relative humidity of the air increases even though the water content is lower because cold air can hold less water compared to warmer air. Afterwards the chilled air goes to the “hygrotherm” process. This process heats up the cold air to reduce the relative humidity to achieve dry air. Since the “hygrotherm” process uses the energy from the refrigeration process no further energy is required. The dry and cold air is supplied through an air distribution system of the storage facility and is forced through the grain bulk. This process can be installed in a warehouse or in a silo. The exhaust air absorb heat and moisture from the grain. The cold and dry air absorbs the energy and humidity from the grain before it leaves the storage area at the top, saturated with humidity and heat. Once cold air exhaust from the top
the cooling process is completed. It is important to finish the cooling process completely before moving the Grain Cooler to the next storage facility. An indicator that completion of the process has been reached is when the grain temperature at the top of the bulk hits 4°C (≈7°F) above the temperature of the air supplied to the storage. Minor temperature difference between the bottom and the top layer may remain due to the pressure drop caused by the bulk. A cooling cycle could temporarily be interrupted only due to unexpected causes. Any interruption should only last for short period of time; the cooling process has to be resumed with prior settings. After the cooling cycle is completed, all openings and connections of the storage should be closed. This protects against the formation of condensation due to the introduction of warmer air and animals like rats. Modern grain cooling devices switch automatically to ventilation mode at lower ambient temperatures. If the ambient temperature rises, the cooling process is automatically switched on again. This improves the profitability of the process. Grain cooling systems work independent of any weather conditions. Once the unit is installed and temperatures are set it runs in automatic mode to deliver air of desired conditions independent of weather conditions i.e. whether foggy or rainy. During rain and/or fog, the water condensation will be higher at the grain cooler. More water will flow out of the condensation hose. However, due to the after-heating of the chilled air by “hygrotherm”, the relative air humidity can be adjusted to the moisture content of the rough rice according to the sorption isotherm diagram. A cooling process creates a drying effect that must be taken into account as well. The drying effect for rough rice for one cooling cycle is approximately 0.75% in average. Wherein the effect depends on the rough rice temperature and its moisture content as well as on the temperature and relative humidity of the supplied cooling air. Since the supplied cooling air warms up at the grain bulk and warmer air can absorb more moisture, the process conditions are continuously changing. If the relative humidity of the supplied cooling air is significantly below the equilibrium moisture content of the rough rice, the drying effect will be higher. The set hygrotherm after-heating for adjusting the relative humidity of the cooling air is therefore crucial. The after-heating should not be set too high to avoid unnecessary energy use. Typically, after-heating of 3 to 7°K (≈ 5 – ≈ 15°F) is used. For higher moisture contents of rough rice, the drying effect is higher (Boser, 1980). However rough rice with moisture contents > 19% should be dried in a mechanical dryer before the cooling cycle.

It is possible to cool the rough rice close to the outlet temperature of the grain cooler. However, its moisture content should not be lower than 14.5% and the static pressure drop of the bulk has to be low (warehouse storage). When the rough rice moisture content is lower and the static pressure drop is high the grain temperature will be approximately 2 to 8°K (≈ 3–14°F) above the supplied cooled air. This is due to the drying effect caused by grain cooling. The evaporation of water from the grain leads to an additional cooling effect.

Rice is typically consumed directly, if the milling process or parboiling is disregard. Rice milling has only a minor influence on decisive quality factors such as taste. For this reason, a particular focus is placed on maintaining the quality of the rough rice after the harvest. In addition to the consumption of rice, the use as seed must not be forgotten, which is no less important, as it ensures the yield and the next harvest. The various quality criteria for rough rice are given in country-specific standards for trade and consumers preference. A subjective parameter of rice quality is taste, which is evaluated differently from region to region. The issue is not the basic taste of the different rice varieties, but rather the purity of this specific quality factor. With grain cooling conservation, the specific taste is maintained as it was after the harvest or achieved by aging. Primarily, this is achieved by reducing unfavourable storage conditions that have an adverse effect on taste. This includes grain respiration, which leads to spontaneous heating and release of water, thus providing favourable conditions for additional negative factors,
such as insects and microbes. These significantly affect taste, so that it can become musty, leading to a significant devaluation of the rice quality (Sontag, 2014).

Damaged and discoloured rice grains are listed in the evaluation systems for rice quality. Damaged grains are caused by insect as well as postharvest processing. Eating by insects and drilling holes to deposit eggs damage rice grains and thus lower the rice quality. Grain cooling slows down the activity of the insects, the quality risk of damaged grains is minimized and the harvest quality is ensured. In addition discoloration of rice is reduced or avoided by storage at low temperatures and higher quality standards are achieved. As previously described, the cooling process also leads to a reduction of moisture content. Due to the duration of the cooling conservation, the drying occurs slowly. Thus the moisture compensation in the rough rice kernel between the dry zone at the outer surface and the core occurs gently. This leads to minimal stress in the grains which do not crack afterwards at the milling. The proportion of broken grains is reduced. The findings from Shafiekhani, Wilson, & Atungulu (2018) demonstrated that cooling of rice may help to maintain the rice color and promote storability of the rice post-harvest. For rice at 12.5% moisture content discoloration was abated across all studied temperatures (10-40°C) and field treatments (fungicide and non-fungicide applications) until 6 weeks of storage duration and increased not in excess of 20% thereafter 16 weeks.

Another important quality criterion of rice is the microbial purity, which is somewhat less important due to the type of rice preparation, but which is becoming ever more important due to the rise in living standards. Not only the burden of fungi and bacteria is relevant, but also the excreta from insects and fungal toxins. It thus becomes apparent that cooling conservation can make a significant contribution toward achieving an improved hygienic standard of rice. In general, as the rice storage moisture content increased from 16% to 21%, the mold counts on rice samples fluctuated based on storage temperature. High growth of mold were not necessarily related to high discoloration, especially at temperature less than 27 °C. However, in the period leading to 10 weeks of storage at moisture content ≥ 19% and temperature 40 °C, discoloration increased with increase mold counts. There was a consistent pattern of discoloration at low moisture contents and low temperatures. However, over the wide range of storage temperature and moisture content, there was no clear direct relationship between discoloration and mold counts (Shafiekhani et al. 2018).

**Infrared Heating**

Infrared-based heating is known to deliver higher heat fluxes compared with conventional convective heated air. The high heat flux causes a rapid temperature rise of heated products; hence has been reported to reduce thermal processing duration of foods significantly. However, for the technology to be successfully developed and commercialized in the food industry, it is vital that relevant processing applications be optimized for energy use efficiency, and improved product quality and safety. In the past two decades, researchers have made significant progress to elucidate the mechanism of infrared (IR) heating of food products and interactions between IR energy and food components. Design and development of new IR emitters have continued to advance processing efficiency. The potential to use selected IR wavelengths and optimize wavelength interaction with biological materials for specialized food processing is gaining attention.

Innovative research at the Food Science Department, University of Arkansas System Division of Agriculture, has led to design and construction of scaled-up IR heating unit with modular processing parameters for food and feed processing. The team led by the principal investigator, Dr. Atungulu at the
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Food Science Department, has developed and built a pilot-scale catalytic IR system consisting of a belt drive, and heating chamber, gas/ fuel supply lines, and control panel. The belt drive conveys the grains from the hopper through the heating chamber and discharges at the outlet. The belt has a dimension of 0.5 m × 0.2 m ×1.2 m, and is made of white butyl, designed for the extremely high temperature of up to 150°C with not more than 1% shrinkage in length. The movement of the belt is controlled by variable speed controller powered by an adjustable frequency AC drive. The belt drive speed can be varied between 0.03 m/s to 0.11 m/s. The belt assembly is equipped with an adjustable frequency drive to vibrate the belt in the case that is desirable. The vibration intensity can be varied using a vibrator controller between 5 Hz to 2000 Hz. The heating zone houses four catalytic IR heaters each with 0.6 m × 1.2 m dimension, inclined at 30° and located above the belt at a predetermined height that is designated as product-to-emitter-gap size. Each of the catalytic IR emitters has heat generation capacity of 57, 600 British thermal unit per hour (BTU/h); the total system energy supply is 230,400 BTU/h. The catalytic IR emitters generate medium and far IR radiant energy with wavelength from 3.3 to 8 μm by catalyzing natural gas or propane gas with a platinum catalyst. The heating chamber is enclosed using heat insulators.

The findings suggested that scaled-up radiant treatment of rice followed by tempering could be optimized to remove significant amounts of moisture from rice with few passes while at the same time maintaining desirable head rice yields and other desirable quality indices such as rice color and paste viscosity. However, results from the treatments are dependent on the rice cultivar. Treatment conditions that gave the highest percentage point moisture removal, maintained head rice yield, and resulted in low energy usage were observed as follows:

- Overall, there is potential to use the IR heating technology for drying rough rice. However, the scale of operation of IR drying could be restricted by the limited penetration depth of IR energy in thick beds of rice which in turn limits expected drying capacity.

Microwave Heating

Microwaves are electromagnetic radiations with wavelengths ranging from 1 mm to 1000 mm in free space with a frequency between 300 GHz to 300 MHz, respectively. In microwave (MW) drying, heat is generated by directly transforming electromagnetic energy into molecular kinetic energy causing heat to be generated from within the material to be dried. The relatively high-energy flux and volumetric heating phenomenon resulting from MW heating hold the potential to dry rough rice with reduced inter-kernel rice temperature, and moisture content gradients are thereby minimizing rice fissuring and maintaining milled rice quality and improved head rice yield. Also, the high and rapid heat flux accorded by MW heating holds the potential to inactivate harmful microorganisms especially aflatoxicogenic mold spores such as *Aspergillus flavus* thus reducing incidences of aflatoxin contamination and spoilage of rice.

Although MW heating has the potential to deliver the energy needed to dry most moist material rapidly, its inherent non-uniformity of the applied electromagnetic field within the heating cavity is a significant drawback. This problem can be partially offset by ensuring that the material to be dried is mixed during drying. Also, the MW field pattern can be modified by incorporating wave-guide that enforce uniform dispersion of the MW energy. In situations where wave-guides were not used, non-uniform drying rate has been linked to excessive temperatures along the edges and corners of products resulting in overheating, irreversible over drying, and occasional burnt product (Nijhuis et al., 1998). Concern has also been raised on the penetration depth of the MW field into the products. This could be partly solved by using MW of 915 MHz which has three times the penetrating depth compared with MW of 2.45 GHz (Kumar,
The 915 MHz MW provides up to 100 kW from a single magnetron at a cost similar to the most massive commercial 2.45 GHz MW with a maximum power of 30 kW (Kumar, 2015). Therefore, for large-scale drying operation, the 915 MHz MW may offer an alternative means to dry freshly harvested rough rice. Moreover, MW drying may offer many other advantages over convective heated air drying; these may include higher thermal efficiency and reduced drying time (Chandrasekaran, Ramanathan, & Basak, 2013; Zhang, Tang, Mujumdar, & Wang, 2006; Jiao, XU, & Jin, 2014) and the potential to inactivate harmful, heat tolerant, mold spore that produce mycotoxin (Atungulu, Smith, Wilson, Zhong, Sadaka, & Rogers, 2016).

Despite the advantages of MW heating technology, there is no commercial use of MW technology for rice drying in the United States. There are a few reports on the use of 2.45 GHz MW driers. Scaling up MW system that operates at 2.45 GHz has been a challenge due to associated low penetration depth, non-uniformity of heating and low energy efficiencies (Vadivambal & Jayas, 2010). In the recent past years, innovative research at the Food Science Department, University of Arkansas Division of Agriculture, in collaboration with Industry Partners (AMTek Inc.), has led to the successful testing of one-pass drying of rough rice with mechanical microwave energy at 915 MHz.

The researcher team at the University Of Arkansas Division Of Agriculture have demonstrated the feasibility of one pass drying of rough rice with microwaves. The resulting moisture content reductions and head rice yield recovery, especially from MW heating followed by tempering treatment, provided a substantial justification to optimize the treatments to achieve commercially viable rough rice drying throughput. The team of researchers has tested continuous drying operation (MW power ranging between 3-24 kW during an 8 minutes of drying run) for rice with initial moisture content of 25% (wet basis) at multiple rice bed thicknesses of up to 0.05 m; supplied specific energy was maintained at 450, 600 and 750 kJ/kg of rough rice. Moisture removed varied between 6%-15% points, depending on rice bed thickness and applied specific energy. Increasing rice bed thickness and specific energy reduced milling and head rice yields, increased the final viscosity of milled rice, but marginally affected rice peak viscosity and surface lipid and protein contents (p<0.05). To achieve the desired percentage point moisture content reduction (~12% points) at specific energy of 600 kJ/kg1 and 750 kJ/kg of rough rice, 4574 kJ and 5986 kJ were required per kg of water removed, respectively; this translated to 13 and 16 USD per metric ton of dried rice, respectively. The study demonstrated the feasibility of one pass MW drying of rough rice; 450-600 kJ/ kg of rough rice was recommended to preserve rice quality and achieved better energy use efficiency. These studies combined led to a conclusion that the MW heating technology using 915 MHz, may have the potential for drying in the rice industry, especially in rice parboiling operations which typically require rapid drying of rice at high initial moisture contents – often higher than harvest moisture content.

Parboiling

Parboiled rice is the major staple throughout South Asia (the Indian subcontinent), where over 90% of the world parboiled rice is produced and consumed. It is estimated that as much as a fifth of the world’s rice is parboiled (Kik & Williams, 1945; Tata, 1962; Gariboldi, 1974). Use of parboiled rice seems to have been increasing in recent times.

Parboiled rice is “par”-tially “boiled” (i.e., partially cooked) rice. In other words, parboiling means precooking of rice within the husk without disturbing its size and shape. To avoid over imbibition and
deformation of the grain, water and heat must be kept separate. Paddy first is hydrated, then heated to cook the rice, and finally dried.

The first step in parboiling is to hydrate the paddy sufficiently by soaking it in water to enable it to be gelatinized on subsequent heating. Pillaiyar, Sabarathinam, & Sulochana (1998) recently have shown that grains from different tillers or at different positions within a panicle hydrate at slightly different rates; younger grains are slow to hydrate. Therefore, grain-to-grain variation is a definite hazard during soaking of a paddy lot. Appreciable variation in the initial grain moisture is said not to affect its hydration significantly (Ali & Ojha, 1976).

The second step in parboiling is steaming or heating. The purpose of steaming the soaked paddy is to gelatinize the starch. If the grain has been hydrated adequately and evenly, steaming for just 2 min at atmospheric pressure is enough to gelatinize it (Bhattacharya & Subba Rao, 1966a). However, the heat input has an effect on the milling quality. The ability of the parboiled grain to withstand adverse conditions of drying without giving rise to cracks increases with increasing severity of heat treatment. In fact, Mecham, Kester, & Pence (1961), who dried paddy after parboiling it in a cross-flow dryer, needed steaming under high pressures to get a good yield of head rice. This may be one reason why all high-technology processes from the United States and Europe traditionally used steaming under elevated pressure.

Steaming, although used almost exclusively in practice, is by no means essential for parboiling. Other systems of heating, such as mild heating at 80°C in a closed box immersed in a bath (Pillaiyar & Mohandoss, 1981a,b) or heating in a closed rotating drum by flue gases in the jacket (Pillaiyar, Venkatesan, & Narayanasamy, 1977), by thermic fluid (Pillaiyar, Sabarathinam, Subramaniyan, & Sulochana, 1996), by electrical resistance (Vasan & Ganesan, 1981), by ohmic heating (LSU, 1998), by microwave (Velupillai, 1994), and even by hot sand or air, can be used.

After regular parboiling, paddy contains ~35-38% moisture. The drying protocol exerts a profound influence on the milling quality of the product. If properly processed parboiled paddy yields nearly 100% whole grains after milling; but if it is dried in the sun or with heated air, breakage can be very high. The method of drying is the kingpin of the parboiling process insofar as the milling quality of rice is concerned. When wet parboiled paddy is dried in the sun or with hot air, no damage occurs until the moisture content drops to ~16% (Craufurd, 1962, 1963; Sluyters, 1963; Bhattacharya & Indudhara Swamy, 1967), after which the amount of breakage rises steeply. Increasingly, cracks appear in the grain not during but after drying, when the rice has cooled, and over some period of time. In fact, if the grain is tempered hot immediately following drying, no damage occurs, not even upon subsequent cooling. The conclusion is that a steep moisture gradient and cooling are both necessary for cracking to occur following drying; neither condition alone is sufficient. This phenomenon may be related to the effect of glass transition temperature (Cnossen & Siebenmorgen, 2000; Perdon, Siebenmorgen, & Mauromoustakos, 2000).

Parboiling greatly changes the properties of the rice grain. These changes must have their roots in the changes brought about in the grain constituents during the parboiling process. Since rice is a seed and soaking for parboiling is akin to the initial phase of germination, a large amount of enzymatic activity is to be expected. Ali and Bhattacharya (1980b) noted appreciable enzymatic conversion of sucrose into reducing sugars and de novo production of sugars and amino acids. The well-known discoloration of parboiled rice is no doubt partly related to these reactions. Other reports of increase in reducing sugars (Anthoni Raj & Singaravadel, 1980) and in phenolic compounds (Singaravadel & Antoni Raj, 1979), of activities of diverse enzymes (Xavier & Anthoni Raj, 1996), and of excretion of chloride during soaking (Anthoni Raj, Singaravadel, & Subramaniyan, 1996) have appeared. In view of natural
contamination, much microbial action during soaking may be expected. However, what part it plays, if any, in the process or the product is not known. Only the undesirable fermentation during the traditional parboiling has been noted. The fermented odor is eliminated if the soaking occurs in hot water. Whether any residual microbial activity persists and what effect it has are not known. Ramalingam and Anthoni Raj (1996) have studied the microbial population and concentration of various organic compounds in the soak-water effluent.

After vitamin content, the remarkable milling quality of parboiled rice is its second most widely observed property. Considerable “reduction” in grain breakage during milling after parboiling has been repeatedly mentioned by countless authors. However, what caused the improvement and why had been little understood. However, this has been clarified by Bhattacharya (1969, 1980). After rice is parboiled and air dried in the shade, grain breakage during milling of any sample is close to zero, irrespective of its breakage before processing. In fact, even paddy deliberately damaged to give nearly 100% breakage, and separated immature grains that shatter almost completely during milling, all yield nearly 100% whole grains after parboiling. Examination in transmitted light shows no trace of cracks, chalkiness, or cloudiness (characteristic of immature grains) after parboiling, no matter what their content was before treatment. Clearly, the swelling of the starchy endosperm during gelatinization completely heals the preexisting defects. As a result, grain breakage is not reduced but virtually eliminated.

Some additional changes occur in the milling behavior of parboiled rice. The husk slightly splits after parboiling; shelling therefore becomes easier, consuming less energy. This is an advantage. However, the following changes are disadvantageous: Parboiled rice, being harder, required greater time or force and, therefore, more energy, for whitening; in addition, bran from parboiled rice contains more oil and is flakier than raw-rice bran. Hence, the mill screen tends to get clogged. Also, the milled rice appears oily and sticky, especially if under milled. Usually overcome these problems by adding a little husk or chalk to the brown rice during whitening or by maintaining a high pressure in the cone (Gariboldi, 1984).

The better nutritive value of milled parboiled compared with milled raw rice has been reported. Parboiled rice after milling contains more B vitamins than raw rice (Yang and Cho, 1995). The loss of vitamins during storage of rice (Cailleau, Kidder, & Morgan, 1945; Vinacke, Hartzler, & Tanada, 1950; Narayana Rao, Vsiwanatha, Mathur, Swaminathan, & Subrahmanyan, 1954) and also during its washing (Subrahmanyan, Sreenivasan, & Das Gupta, 1938; Vinacke et al, 1950; Swaminathan, 1941, 1942) also are present in greater amounts.

Storage and Value Addition Systems

Rice is produced in a number of processed forms for different value-added applications; some cook quickly, others sustain harsh processing techniques. Some provide texture or flavor for finished products, like crisped rice in breakfast cereals (Deis, 1997; Burrington, 2001).

Parboiling rice gelatinizes the starch in the grain and ensures a firmer, more separate grain when it is milled to white rice and cooked. This form takes longer to cook because the gelatinized starch is more resistant to absorbing water. The cooked kernels are firmer in texture than cooked raw-milled rice and appear wider.

Quick-cooking processes reduce the cooking time to within 5 min for white rice and 10-15 min for brown rice. Many quick-cooking processes have been developed and patented; these are reviewed by Roberts (1972), Roberts et al. (1980), Juliano and Sakurai (1985), and Luh (1991b). Other methods use dry heat treatments and abrading of the kernel, in which the starch is not gelatinized.
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Another recent addition to quick-cooking products is individually quick-frozen (IQF) rice. IQF rice is fully cooked to about 64% moisture and then quickly frozen. The process provides a free-flowing ingredient for use in frozen and prepared food products, as well as in foodservice operations to decrease preparation time and equipment needs (Pehanich, 2002). The rice can be heated in a microwave oven in 2-4 min for consumption. Unlike some products for quick cooking, IQF kernels do not crack or fissure.

Rice kernels can be processed in several ways to create desired textures for cereals, candy bars, and energy/sports bars. These include processes for making puffed and crisped rice. There are several methods for making puffed rice: oven-puffed, gun-puffed, and extruder-puffed methods. Crisped rice can be manufactured by oven puffing or high-pressure extrusion puffing (Hsieh & Luh, 1991).

Whole or broken kernels of rice can be ground into flour. Since each variety has unique viscosity, gelatinization temperatures and other characteristics, applications vary depending on the type of rice used (Hegenbart, 1995). The milling method employed and the type of mill used also influence functional properties. Rice flour is often the preferred choice of manufacturers creating products targeted to consumers who require a hypoallergenic alternative to gluten and wheat-flour products (Deis, 1997).

Rice syrup can be made from white or brown rice by enzymatic or chemical hydrolysis, using processes similar to those used in making corn syrup. Rice syrup on the market in the United States is mainly a natural- or health-food item with limited distribution (Deis, 2001). The demand for it has expanded as the demand for soy milk products has grown; rice syrup is often used as a sweetener in soy milk to mask beany flavors (Klahorst, 2000). Syrups range from 26 dextrose equivalent (DE) to 70 DE and a minimum 78 ° Brix (Knehr, 1998).

Enrichment

The most significant change in the enrichment of rice in the past several years is the addition of folic acid to the U.S. standard of identity for rice and other cereal grains. As research reveals new insights into the treatment and prevention of disease with nutrients, traditional suppliers of cereal grains have responded accordingly, with various kinds of enrichment and fortification in terms such as breakfast cereals, food bars, and snack foods. The market for functional foods using cereal grains as an ingredient has also increased in the last decade. Before adding folic acid to the standard of identity for cereal grains to prevent neural tube defects (NTDs), the Food and Drug Administration (FDA) conducted an extensive three-year study on the feasibility of adding folic acid to grain products. The evidence of the positive benefits of folic acid enrichment proved overwhelming. This is just one of many cases in which enrichment and fortification of cereal and other foods made a significant impact on the prevention of disease. Enrichment generally refers to the restoration of vitamins and minerals lost during processing. Fortification generally means adding vitamins and minerals to foods in higher amounts than were present before processing. Before the standards of identity were adopted to define enriched foods, the term fortification was used when any vitamins and minerals were added to foods (Hoffpauer & Wright, 1994).

Currently two forms of enrichment are used commercially in the United States. The first form is a preblended powder mixture of thiamin, riboflavin (if requested), niacin or nicinamid, folic acid, and either ferric orthophosphate (white iron), ferrous sulfate (yellow iron), or reduced iron. Riboflavin and ferrous sulfate give the powder and the rice a slight off-white to yellow color, which is undesirable to some consumers. Reduced iron has the potential to turn the rice gray to black. Ferric orthophosphate is the most requested form of iron used in the industry due to its white color and ability to blend with the white rice. However, when ferric orthophosphate is oxidized or contains excessively moisture, it can turn
tan, yellow, purple, and/or black. When powder enrichment is used in the packaged product, the statement, “To retain vitamins do not rinse before or drain after cooking” is required according to 21 CFR 137.350 4©. One of the disadvantages of powder enrichment in rice is that 20-100% of the enrichment washes off the rice, depending on the amount of water used in rinsing and the application time. Other disadvantages of powder enrichment are that the vitamins and minerals are less stable during storage and after application; the uniformity of application can be a problem and may cause assay problems; and the vitamins and minerals can react easily with other food components. The principal advantage of powder enrichment is that the blend is less expensive than other forms of enrichment.

The second form of enrichment available commercially is a premixed and treated kernel-type enrichment. The “premix”, as it is known in the rice industry, is a powder-blended enrichment that is applied to the milled rice grains and coated with a water-insoluble surface to retain the vitamins and minerals during rising. The enrichment of the rice grains is concentrated so that, when added to the milled rice at 50%, all of the enrichment required per pound of rice is provided according to the standard of identity. One unique aspect of kernel-type enrichment is that the rice can be rinsed without losing the enrichment before cooking. The insoluble food-grade coating is broken down when it reaches the acid environment of the stomach, thereby releasing the vitamins and minerals. In addition, the vitamins and minerals are stable and do not react with other food components, and the kernels are easy to detect and assay in the final product (Hoffpauer & Wright, 1994). Kernel-type enrichment is slightly more expensive than powder-type enrichment because it is not as concentrated as powder enrichment. Many of the suppliers of instant white rice package the rice in “boil-in-the-bag” containers. This rice must be enriched with a rinse-resistant premix such as the coated kernel-type enrichment currently available.

**Fortification**

Rice in a potentially excellent product for delivering micronutrients to a very large number of people and has the potential to significantly alleviate micronutrient deficiencies. However, this will only achieve the desired result as long as the sensory characteristics of the end product are not discernibly changed and people do not object to incorporating fortified rice into their daily diet. In addition, using rice to deliver micronutrients will work only as long as fortified rice is economically accessible to people at the bottom of the income pyramid. Unpolished rice is a rich source of vitamins B1, B6, E, and niacin (USDA, 2012). During polishing, the majority (75–90%) of these vitamins are removed. Only when parboiled does more than 50% of the water-soluble vitamin levels of brown rice remain, and this is due to their migration from the outer layers to the endosperm (USDA, 2012). It is important to stress that the selection of micronutrients depends not only on their legal status, price, expected bioavailability, stability, and sensory acceptability but also on the product forms fitting the applied fortification technology. In some applications, water-soluble forms might be suitable, and in others water insoluble or even oily forms might be preferred. The size difference between rice kernels and micronutrients is much greater than that between flour and micronutrients. Simply mixing rice kernels with a micronutrient blend will lead to micronutrient separation, inhomogeneity, and losses during production, transport, and further rice preparation, especially rice washing. One form of intrinsic micronutrient improvement in rice, rather than fortification, was the introduction of parboiling. Before removing the bran, rice kernels are soaked, steamed, and dried again. During these steps, the content of vitamins B1, B6, and niacin in the endosperm increases three fold due to their migration from the bran into the endosperm. In the case of high rice consumption, the total daily need of these vitamins might be covered. However, other
micronutrients, such as iron and zinc, are not elevated in white rice after parboiling; this is why other means of micronutrient fortification are advisable. During dusting, micronutrients in the form of fine particles are blended with the bulk rice. This method makes use of the electrostatic forces between the rice surface and the micronutrients. Nevertheless, there is a segregation risk (Alavi et al. 2008). In addition, washing and/or cooking in excess water that is then drained leads to significant losses. These losses are such that, in the United States, a warning has to be printed on the label not to rinse the rice before cooking or not to cook in excessive water. In developing countries where intensive rice washing is practiced, dusting is not recommended.

One of the oldest ways to prevent micronutrient losses through washing is to add high concentrations of micronutrients to a fraction of the rice and to subsequently coat the rice kernels with water resistant edible coatings, and then mix the coated kernels with normal rice in ratios ranging from 1:50 to 1:200. Most methods have in common the addition of a solution or suspension of micronutrients. Several coating layers, usually alternated with layers of coating material alone, are added by spraying the suspension through nozzles into a rotating drum containing the rice kernels to be fortified. The same drum is generally used during drying of the kernels by means of a hot air current. Many different coatings have been tried, including waxes, acids, gums (e.g., agar), starches, and cellulosic polymers (e.g., hydroxypropyl methylcellulose, ethyl cellulose, and methylcellulose (Peil, Barrett, Rha, & Langer, 1982; Shrestha, Arcot, Paterson, 2003). The major problems encountered with coating technologies are related to color, taste, and a loss of micronutrients during washing, as well as during cooking. High variability is reported among technologies (Alavi et al. 2008), and in many of them, consumers are easily able to distinguish the fortified kernels, which will most likely be discarded during rice cleaning. As opposed to extrusion technologies, where micronutrients are dispersed throughout the extruded kernel body, in coating the micronutrients are concentrated on the surface. The coating layer of the kernel makes them highly visible, particularly if the micronutrient forms are colored. In addition, the taste effects of the superficially present product will be high, and the resistance against mechanical separation and removal during washing low. If the coating is not resistant to cooking, it is likely that the micronutrient layer will come off leaving the vitamins more exposed to heat and moisture. Some commercially available coated rice fortification premixes claim to be stable during washing and cooking. It is advisable to stress-test these materials before incorporation into national fortification programs. Coating technologies generally imply a lower initial financial investment than extrusion technologies, but the cost per metric ton of fortified rice is relatively comparable.

Extruded rice kernels that carry vitamins and minerals are added in a ratio of 1:50 to 1:200 to intact rice kernels similar to vitamin/mineral–coated rice kernels. However, these kernels differ in their performance. In the food industry, extrusion is often applied where biopolymers, such as carbohydrates, are processed (Schuchmann, 2008). Extrusion is a versatile, continuous process and uniquely combines different processing steps, such as mixing of different components, degassing, thermal and mechanical heating, forming, and expanding (Kokini, Ho, & Karwe Marcel Dekker, 1992; O’Connor, 1987). The process is commonly classified into cold and hot extrusion, also called shape-forming and cooking extrusion, respectively. Cold extrusion takes place at temperatures above glass transition but below starch melting temperatures, while the melting temperature of starch is exceeded in hot extrusion (Mercier, Deschamps, & Mathey, 1989; Colonna, Della Valle, & Areas, 1994; Pinkaew, Wegmuller, & Hurrell, 2012).
SAFETY ASSURANCE

Arsenic and Other Metals

Arsenic is problematic in rice due to the fact that rice is the only major crop grown anaerobically (i.e. under flooded conditions), and that rice is particularly efficient at assimilating some forms of arsenic, particularly those generated under anaerobic conditions, and exporting them to grain (Williams, Villada, Deacon, Raab, & Figuerola, 2007; Xu, McGrath, Meharg, & Zhao, 2008). With respect to plant uptake and transport, protonated arsenic species (arsenite, MMA and DMA) can behave like silicic acid analogues and arsenate, and potentially deprotonated DMA, as phosphate analogues (Karim, Raab, Feldmann, Ghaderian, & Meharg, 2009). These species have varying affinities for minerals present in the soil. Under oxidized conditions arsenate has a high affinity for iron oxyhydroxides (FeOOH) and manganese oxides (Chen, Zhu, Liu, & Meharg, 2005), which makes it relatively immobile in soils, while arsenite has a lower affinity for these solid phases, making it more mobile. Under strongly reduced conditions arsenic can be precipitated as sulphide minerals such as arsenopyrite (Smedley & Kinniburgh 2002). The humic and fulvic acids that constitute dissolved organic matter in soil pore waters compete with arsenate for anion exchange sites. Arsenic speciation is highly dynamic over the range of redox potential found in paddy fields, and those redox conditions vary spatially and temporally throughout the growing season (Dittmar et al. 2007; Takahashi et al. 2004). The flooding regimen is an obvious driver for redox, as is the vertical gradient with atmospheric oxygen perfusing down the soil profile. Rice roots aerate their rhizosphere to enable roots to survive in reduced conditions, creating redox gradients from the root surface to the bulk soil, leading to the formation of iron plaque on the root surface and in the rhizosphere (Chen et al. 2005; Liu, Zhu, Hu, Williams, & Gault, 2006).

The development of inductively-coupled plasma mass spectrometry (ICP-MS) as an ultra-sensitive arsenic detector, combined with High Performance Liquid Chromatography (HPLC), enabled the robust, low level quantification and qualification required to survey arsenic speciation in rice grain (Williams et al. 2005). As the relative cost has decreased, along with increased reliability, HPLC-ICP-MS has become the “gold-standard” for arsenic speciation in foods, including rice (Meharg & Raab 2010). The first comprehensive survey of inorganic arsenic in foodstuffs, using HPLC Atomic Fluorescence Spectroscopy (AFS), Schoof, Yost, Eickhoff, Crecelius, & Cragin (1999) stated “that rice has higher inorganic arsenic concentrations than most other foods, and consequently, diets that rely heavily on rice may contain the most inorganic arsenic.” A range of detection systems can be used to quantify arsenic, and a range of separation techniques to aid in species qualification and quantification. The lack of Certified Reference Materials (CRM) for arsenic speciation has been an issue for setting inorganic arsenic standards in rice (EFSA 2009; Meharg & Raab, 2010).

Mycotoxin

Mycotoxin can have adverse effects on human and animal health, productivity, economics and trade. Efficient and cost-effective sampling protocols and analytical tools and methods are needed for the detection and control of mycotoxins worldwide. Effective testing schemes depend on sound analytical methods and on sampling plans that generate results that reflect the actual concentrations present in consignments or lots of produce. Test results can be used to implement regulatory decisions on the suitability of lots of food for consumption or trade. Several studies have been conducted to gain knowledge on the variability
of mycotoxins and enabling the establishment of sampling plans for the control of mycotoxins in several commodities. Even when using accepted methods or protocols, there are uncertainties associated with the mycotoxin test procedure. Producing safe and good quality food is a prerequisite to ensuring consumer health and successful domestic and international trade, and a key to the sustainable development of national agricultural resources. Therefore, a holistic approach for the control of mycotoxins, which includes the adoption of the best agricultural practices in the field and throughout the whole farm-to-fork chain, the best sampling practices, the use of validated and fit-for-purpose methods, trained professionals, and participation in integrated food control systems is important (Maestroni & Cannavan, 2011).

Besides aflatoxin, other mycotoxins including, citrinin, cyclopizonic acid, fumonisins, fusarins, gliotoxin, moniliformin, ochratoxin A, patulin, sterigmatocystin, tricothecenes, zearalenone have been reported to have contaminated rice in different studies all over the world (Lee, Choi, Lee, & Park, 2001). Most mycotoxins are heat-stable and very resistant. During processing they are typically not broken down chemically nor rendered harmless. For this reason, the formation of toxins must be prevented by preventing harmful fungi from forming and proliferating on rice during storage.

### Adulteration

Adulteration in rice either adventitiously or deliberately is feasible right from crop harvest to till the grain reaches to the hands of the consumers. The common forms of rice prone to adulteration are brown rice, polished rice, rice flour, rice cake and rice bran oil. Many methods based on criteria such as morphological parameters, physico-chemical properties, DNA, protein, and metabolites have been developed to detect the genuineness of the agricultural food products (Arvanitoyannis 2008; Findlay, Quirke, Frazier, & Urquhart, 1997; Li & Rutger 2000; Third & Sogi 2005; Vaingankar & Kulkarni 1989; Zhang, Maroof, Lu, & Shen, 1992), yet there is an ambiguity in choosing one of them for commercial scale detection and quantification of adulteration. However, a few methods have proven fit to unravel the menace of adulteration (Vemireddy, Archak, & Nagaraju, 2007).

With the availability of whole genome sequence of rice including *indica* (9311) and *japonica* (*Nipponbare*) cultivars, thereby resulted discovery of molecular markers have provided unprecedented avenues in the quality control of food products. Currently, DNA-based methods proved handy and robust enough for unambiguous detection and quantification of adulteration (Primrose, Woolfe, & Rollinson, 2010; Woolfe & Primrose 2004). However, these methods are unsuitable to detect the geographical area of the product from where the product has been produced/cultivated. Geographical area of cultivation can be determined by isotopic and multi element analyses of rice varietal samples (Kelly et al. 2002).

Adulteration is rife in almost all agricultural food products where distinguishing the adulterant with look-alike food products is difficult with naked eye/visual observation. Many of the food products targeted for adulteration are of high commercial value products and/or produced in high tonnage around the world. In any food product, adulteration may be due to 1) substitution with look-alike material of low cost, 2) substitution with low quality material, 3) dilution of the original product, and, 4) mislabeling of age and origin of the material. These are the four major criteria being followed by most of the unscrupulous traders for illegal adulteration to obtain profits out of their products. However, rice has largely been sold either as a brown rice form (exporting purpose) or polished rice form (available in domestic markets). Hence, high quality rice are being adulterated with low quality and low price rice by the traders. There are many sophisticated methods or protocols being employed over the past decades for unambiguous detection and precise quantification of the adulterant using DNA or protein or metabolites or chemical composition of
the material being marketed. However, no one method detects the adulterants in all agricultural products. Different combination of methods/protocols are necessary to curb this menace effectively. Broadly, the methods employed for detection and quantification of adulteration are classified as non-DNA based and DNA based methods depending on the source material used (Vemireddy et al. 2014).

In the past, morphology based methods were the criterion for differentiating various rice groups (Thind & Sogi 2005; Vaingankar & Kulkarni 1989). Significant variation in price within similar kind of kernel morphology, made this criterion unsuccessful for differentiating the cultivars. To determine the morphology of kernel traits, techniques such as electron microscopy (Beerh & Srinivas 1991) and image analysis (Carter, Yan, & Tomlins, 2006; Kim, Jo, Kim, & Sung, 1997) were used.

Physico-chemical properties of starch such as water uptake, loss of solids in cooking water (Vaingankar & Kulkarni 1989), protein characteristics (Thind & Sogi 2005), and grain length after cooking (Siddiq, 1982) were also used for cultivar identification and quantification of adulteration. Osborne, Mertens, Thompson, Fearn, (1993) reported that it was feasible to use near infrared transmission (NIR) spectroscopy to classify 9 Basmati or other rice samples on 200 g bulk samples. However, NIR spectra of individual grains misclassified 8% of basmati and 14% of the other rice. Subsequently, a number of analytical techniques such as Gas Chromatography (Rao & Muralikrishna 2004), Gas chromatography in conjunction with Mass Spectrometry (Suzuki et al. 1999), High Pressure Liquid Chromatography (Huebner, Bietz, Webb, & Juliano, 1990; Hamada 1996), Calorimetry (Ahmed, Ramaswamy, Ayad, & Alli, 2008), Mid or Near-Infrared (NIR) Spectroscopy (Largo-Gosens et al. 2014; Osborne et al. 1993), Fourier Transform NIR Spectroscopy (Attaviroj, Kasemsumran, & Noomhorm, 2011), Fluorescence and UV spectroscopy (Gangidi et al. 2002), Flame Atomic Absorption Spectroscopy (Srikumar, 1993), have been used for cultivar discrimination either alone or in conjunction with the application of chemometric or multivariate analysis methods like Principal Component Analysis, Discriminant Analysis, and Cluster Analysis, and Partial Least Squares (Singhal, Kulkarni, & Rege, 1997; Vlachos & Arvanitoyannis, 2008). Among non-DNA based methods, protein-based methods also played important role in detection of the adulterants. Important protein-based methods includes isozymes based gel electrophoresis, immunoassays (Vlachos & Arvanitoyannis 2008), Sodium dodecyl sulfate polyacrylamide gels (SDS-PAGE) (Montalvan, Ando, & Echeverrizaray, 1998), Western blotting (Li et al., 2011; Singh et al., 2004) and Kjeldahl method and Soxhlet apparatus (Storck, Picolli da Silva, & Fagundes, 2005).

The availability of thousands of DNA markers and cheaper sequencing methods offer unprecedented applications of DNA based methods to unravel the authentication crisis in food industry in general and rice market in particular (Arvanitoyannis, 2008; Blair, Hedetale, McCouch, 2002; Lockley & Bardsley, 2008; Dhanya & Sasikumar, 2010; Saini, Jain, N, Jain, S, & Jain, R, 2004; Voorhuijzen et al., 2012). Wide array of DNA-based markers are available for cultivar identification which includes random amplified polymorphic DNA (RAPD) Choudhury, Kohli, Srinivasan, Mohapatra, & Sharma (2001), restriction fragment length polymorphism (RFLP) (Zhang et al., 1992), amplified fragment length polymorphisms (AFLP) (Mackill, Zhang, Redona, & Colowit, 1996), fluorescent labelled inter simple sequence repeat (F-ISSR) Nagaraju, Kathirvel, Kumar, Siddiq, & Hasnain (2002), insertion and deletions (Steele, Ogden, McEwing, Briggs, & Gorham, 2008), single nucleotide polymorphism (SNP) (Shirasawa, Shiokai, Yamaguchi, Kishitani, & Nishio, 2006) and microsatellites (Bligh, 2000; Archak, Lakshminarayanareddy, & Nagaraju, 2007; Vemireddy et al. 2007). Recently, evenly-distributed hypervariable microsatellite markers were reported to be showed more polymorphism than non-hypervariable SSRs (Narshimulu, Jamaloddin, Vemireddy, Anuradha, & Siddiq, 2011) and also used for estimating the temporal trends of the genetic diversity over decadal periods (Choudhury et al. 2013).
The quantitative competitive PCR (QC-PCR) and real-time PCR allows simultaneous detection and conformation of fragments using specific probes or fluorescently labelled primers by PCR. The Real-time PCR analysis used in the genetically modified (GM) crops, relies on the continuous measurement of increments in the fluorescence during cycles and the PCR cycle number required to generate a signal that is significantly above noise level (cycle threshold). As of today, real time PCR assay is regarded as the most sought after method for accurate quantification of the nucleic acids. It is a reliable as well as commonly used method to detect foreign DNA in genetically modified (GM) food samples (Baeumler, Wulff, Tagliani, & Song, 2006; Leimanis et al., 2006). In a study by Ganopoulos, Argiriou, & Tsaftaris (2011) high resolution melting (HRM) analysis has been used for detection and quantification of adulteration. The HRM analysis was reported as a rapid, cost effective DNA based method with efficiency comparable to capillary electrophoresis. With this analysis it is possible to discriminate PCR products of the same allele size with different melting profiles due to their difference in nucleotide base composition.

FUTURE PERSPECTIVE RICE QUALITY AND SAFETY

Organic Farming

Organic farming is an ecologically-based farming method that avoids or largely excludes the use of synthetic fertilizers and pesticides. As much as possible, organic farmers rely on crop rotation, cover crops, compost, and mechanical cultivation to maintain soil productivity and fertility, to supply plant nutrients, and to control weeds, insects, and other pests. The United States Department of Agriculture (USDA) National Organic Program standards established in 2000 prohibit the use of GE seed or other GE inputs. Currently, organic farming is practiced by less than 2% of U.S. farmers.

Clearly, genetic modification through plant breeding has been critical to increased land sparing in the past and will continue to be so in the future. But production practices are also important for the ecology of the land. For example, much of the high yield achieved in North America is dependent on synthetic inputs such as pesticides and fertilizers, which are costly and can degrade the environment, reducing biodiversity. It is estimated that the pesticides used in the United States kills seventy million birds each year as well as billions of insects, both beneficial and harmful. Such environmental losses cost the public about $1 billion each year (Pimentel & Raven 2000). Herbicides, used to kill weeds, also have negative impacts. Atrazine, the most commonly used herbicide in the United States and probably the world, causes male demasculinization and hermaphroditism of African clawed frogs. Overuse is speculated to be responsible for the drastic reduction in frogs worldwide over the last fifty years. The Global Amphibian Assessment found that nearly one-third of the world’s 6,000 or so species of frogs, toads, and salamanders face extinction—a figure far greater than that for any other group of animals (GAA, 2004). These examples illustrate one of the global challenges for the next century: the need to develop high-yielding varieties that require minimal inputs, so that impacts on biodiversity can be minimized. An alternative to the “high-input” approach is to expand the number of organic farms. Because organic farmers do not use synthetic pesticides, their farms support higher levels of biodiversity than conventional farms. Furthermore, there is accumulating evidence that organic farming can yield as much, for some crops, as conventional agriculture (Reganold, Glover, Andrews, & Hinman, 2001). Unfortunately, because the biodiversity value of farmland generally declines with increasing yield on a given piece of land, even organic farms usually host far fewer species than do original pristine ecosystems (Green, Cornell,
Scharlemann, & Balmford, 2005; Pain & Pienkowski, 1997; Krebs, Wilson, Bradbury, & Siriwardena, 1999; Donald, Green, & Heath, 2001). What this means is that even if we convert all of agriculture to organic farms (now only 2% in the United States), we still need to increase yield if we want to spare land and protect wildlife.

**Transgenic Rice/ Genetically Modified Organism (GMO)**

Fundamental to the success of rice-improvement programs is access to germ plasm that is genetically diverse for traits of interest. The USDA-ARS National Plant Germplasm System maintains more than 17,000 germplasm sources, which are available for use by breeders and researchers. However, most breeders have been unsuccessful in incorporating foreign germ plasm into their breeding programs because of negative effect it has on milling and cooking quality. Exceptions to this have occurred for incorporating semi dwarf plant height, parboiling and canning stability, disease resistance, and specially grain traits (Rutger & Bollich, 1991; Mackill & McKenzie, 2003). More recently, researchers have begun to explore wild species of rice as a resource for identifying useful genes that can improve cultivated rice (Xiao et al., 1998; Moncada et al., 2001; Eizenga, Rutger, & Lee, 2002) With these populations, molecular marker technology has facilitated the introgression of alleles for desirable traits into breeding materials that can be used for the development of new commercial cultivars. In some cases, tissue culture techniques have been employed to rescue embryos that would have otherwise aborted due to large difference in the genetic makeup of the two mated species (Eizenga et al., 2002).

Mutation breeding has been utilized in the rice research community for decades. Chemicals or radiation are used to induce genetic changes in one or few genes. Because many genetic mutations are lethal, thousands of seeds are mutagenized so that the number of survivors is sufficient for evaluation. Mutation breeding has been commonly used in rice to induce short-saturated cultivars (semi dwarfs), early maturity, and waxy endosperm. More recently, rice mutagenesis has been used to induce herbicide resistance (Johnson et al. 2002; Sandhu et al. 2002), influence cooking properties (Bao, Shu, Xia, Bergman, & McClung, 2001), and improve nutritional aspects (Larson, Rutger, Young, & Raboy, 2000).

In the 1970s, tissue culture techniques were developed as a means to modify or propagate plants. Genetic changes (called somaclonal variation) that occur during tissue culture are due to aberrant segregation of chromosomes or induced mutations and are frequently lethal or genetically unstable. However, examples of heritable somaclonal variation in height and plant color (Xie, Rush, & Linscombe, 1996) and sheath blight resistance (Xie, Linscombe, Rush, & Jodari-Karimi, 1992) have been reported.

Genetically modified plants are those that have genes integrated from unrelated plants or organisms using particle bombardment or bacteria-mediated transformation techniques. This technology has been used to improve traits commonly found in rice as well as to introduce traits that are rare or unknown in rice. Zhang et al (1998) used particle bombardment to successfully introduce a bacterial leaf-blight-resistance gene from a wild species of rice into two rice cultivars that are widely grown through Asia. The bacterium, *Agrobacterium tumefaciens*, has been used to introduce a modified (antisense) form of the gene that controls glutenin A in rice (Maruta, Ueli, Saito, Nitta, & Imaseki, 2001). The presence of the antisense gene resulted in decreased levels of glutenin is the grain. In brewing test, the transgenic rice produced Japanese rice wine (sake) with improved quality because of reduced amount of amino acids, which can give undesirable flavors. Tinjuanjun, Loe, Gatehouse, Gatehouse, & Christou, (2000) used particle bombardment to introduce a gene from an herb, snowdrop, into two commercial rice varieties, which produced resistance to the brown plant hopper, a common yield-limiting insect in Asia. Rice has
also been transformed with a gene that produces a protein that inactivates a fungal toxin in corn. Transformation of rice with this gene was found to confer resistance to rice blast disease (Uchimiya et al., 2002). Genes from a bacterium and daffodil were used to transform rice, resulting in increased levels of vitamin A precursors (Potrykus, 2001). Other genes have been used to confer resistance to nonselective herbicides (Oard et al., 1996).

Climatic Changes

International Rice Research Institute (IRRI) report by far most of environmental change impacts and the general effect of environmental change on rice creation are probably going to be negative. Overpowering logical research and confirmation have demonstrated that the atmosphere is evolving. While there is as yet progressing logical investigation into environmental change, IRRI perceives two general patterns anticipated by all environmental change models: Temperatures will increment, bringing about more warmth stress and rising ocean levels. There will be more regular and serious atmosphere extremes.

The International Food Policy Research Institute (IFPRI) report Environmental Change: Effect on Agribusiness and Expenses of Adjustment gauges that by 2050 rice costs will increment in the vicinity of 32 and 37% because of environmental change. They additionally demonstrate that yield misfortunes in rice could be in the vicinity of 10 and 15%. Specialists have anticipated that, as a result of liquefying polar ice tops and ice sheets because of rising temperatures, seawater levels may ascend by and large by around 1 m before the finish of the 21st century. Rice is developed in immense low-lying deltas and seaside zones in Asia; ocean level ascent would along these lines make rice creation extremely helpless against environmental change. The greater part of Vietnam’s rice deliver, for example, is developed in the Mekong Stream delta which would all be influenced via ocean level ascent. Foreseeing the exact impact of ocean level ascent on rice creation in helpless zones is confounded on the grounds that the impact goes past ocean level ascent itself. The whole hydrology of the delta will be influenced; residue release and shoreline slopes will change. Rice is one of a kind in that it can flourish in wet conditions where different harvests fizzle. Uncontrolled flooding is an issue, be that as it may, in light of the fact that rice can’t survive if submerged for significant lots of time. Flooding caused via ocean level ascents in beach front zones and the anticipated expanded power of hurricanes with environmental change will probably prevent rice generation. At present, around 20 million hectares of the world’s rice-developing territory is in danger of periodically being overflowed to submergence level, especially in real rice-delivering nations, for example, India and Bangladesh. Significant flooding occasions are probably going to increment in recurrence with the assault of environmental change and rice-developing zones, presently not presented to flooding, will encounter surges. Saltiness is additionally connected with higher ocean levels as this will bring saline water advance inland and uncover more rice-developing zones to salty conditions. Rice is just respectably tolerant of salt and yields can be lessened when saltiness is available. Likewise with ocean level ascents, the impacts of saltiness can penetrate all through deltas and in a general sense change hydrological frameworks. Increments in both carbon dioxide levels and temperature will likewise influence rice generation. Higher carbon dioxide levels normally increment biomass creation, yet not really yield. Higher temperatures can diminish rice yields as they can make rice blooms clean, which means no grain is created. Higher breath misfortunes connected to higher temperatures likewise make rice less beneficial. The diverse expectations for hoisted temperature, carbon dioxide levels, changes in moistness, and the associations of these components make guaging future rice yields under these conditions testing. IRRI look into shows that an ascent in evening time temperature by 1 degree Celsius may
decrease rice yields by around 10%. Rice requires adequate water to develop. Rainless days for seven days in upland rice-developing territories and for around two weeks in shallow swamp rice-developing regions can altogether lessen rice yields. Normal yield diminishment in rainfed, dry season inclined regions has run from 17 to 40% in serious dry spell years, prompting creation misfortunes and sustenance shortage. With the beginning of environmental change, the force and recurrence of dry seasons are anticipated to increment in rainfed rice-developing territories and dry spills could broaden encourage into water-short flooded zones. Water shortage influences in excess of 23 million hectares of rainfed rice creation regions in South and Southeast Asia. In Africa, repeating dry spell influences about 80% of the potential 20 million hectares of rainfed marsh rice. Dry season likewise influences rice generation in Australia, China, USA, and different nations. Reviews in several ranchers’ fields in the course of the most recent 10 years demonstrate that rice illnesses and irritations are firmly affected by environmental change. Water deficiencies, sporadic precipitation designs, and related water stresses increment the force of a few maladies, including dark colored spot and impact. Then again, new ecological conditions and moves underway practices that ranchers may receive to adapt to environmental change could prompt decreases of maladies, for example, sheath curse or creepy crawlies, for example, whorl slinky parasites or cutworms. Accordingly, new harvest wellbeing progression are rising. Weed invasion and rice-weed rivalry are anticipated to increment and will speak to a noteworthy test for maintainable rice creation. Additionally, extraordinary climate occasions have as of late prompted sensational rat populace episodes in Asia due to unseasonal and offbeat trimming.

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REFERENCES


Reference on Rice Quality and Safety


Reference on Rice Quality and Safety


Reference on Rice Quality and Safety


Kelly, S., Baxter, M., Chapman, S., Rhodes, C., Dennis, J., & Brereton, P. (2002). The application of isotopic and elemental analysis to determine the geographical origin of premium long grain rice. European Food Research and Technology, 214, 72–78.


Reference on Rice Quality and Safety


Reference on Rice Quality and Safety


Reference on Rice Quality and Safety


Reference on Rice Quality and Safety


Reference on Rice Quality and Safety


Reference on Rice Quality and Safety


Chapter 11

Food Quality and Safety Regulation Systems at a Glance

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ABSTRACT

The quality and safety of all food products are the essential parameter for both ends manufactures and end consumers. This parameter of the food products we cannot overlook or liberalize in any situation. More than two-thirds of diseases are spread through the contaminated or spoiled food source. Looking at the importance of quality and safety management issue, the various governments made a series of rules and regulations for the assessment of food products. This chapter explains the role of various assessment agencies and their rights and workflows.

INTRODUCTION

With the correct ventures and assets, agribusiness can give satisfactory, moderate, protected and nutritious nourishment to everybody, all over the place, each day. However, notwithstanding critical advance, the world keeps on bearing a triple weight of lack of healthy sustenance. As indicated by 2016 information, around 800 million individuals around the world one of every four individuals in Sub-Saharan Africa and one out of six individuals in South Asia - still did not expend their base dietary vitality needs. Less advance has been accomplished in handling different types of ailing health. More than 2 billion individuals do not have the micronutrients required for development, improvement and malady anticipation. More than 2 billion individuals experience the ill effects of the antagonistic wellbeing impacts of being overweight or fat. Tainted sustenance is likewise a broad issue, affecting the wellbeing of 1 out of 10 individuals internationally every year and contrarily influencing the livelihoods of agriculturists, nour-
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Hunger and nourishment borne ailments force huge present and future human, financial, social and monetary expenses on nations. Lessening these expenses requires multi-sectoral approaches: There is extraordinary potential for powerful mediations through horticulture and the sustenance framework generally speaking.

Regardless of the enormous endeavours paid by the nourishment security experts, masters and industry, sustenance wellbeing still stays basic and frequently is coming into spotlights pulling in media's consideration with flare-ups that can bring a pile of different negative outcomes. Such real occasions like BSE in 2000, dioxin or PCB (polychlorinated biphenyls) emergency in 1999 and others doubted the viability of the sustenance quality confirmation frameworks and nourishment security administration connected and exhibited that new device is expected to supplement the genuine frameworks set up. While assessing the negative outcomes one need to consider the restorative expenses brought about, the practical misfortunes that can gravely shake nearby little enterprises, and minimum yet not last consumers’ trust. The worldview food security is that in spite of the fact that nourishment is more secure, consumers’ demeanour is commanded by elevated amounts of vulnerability. In this changing atmosphere, we are that as it may, require perceiving the exertion EU experts make to re-establish consumers’ trust and authorize new directions and better impart nourishment wellbeing related issues. An imperative highlight of sustenance industry is that makers, to adapt to showcase needs and lawful prerequisites, need to fulfil both wellbeing and quality criteria for their items. Having various choices as various quality as well as administration frameworks, nourishment makers ought to choose the most proper one for its particular movement and should build up, archive and execute powerful frameworks for overseeing quality also, security (van der Speigel et al., 2003).

Among the accessible Quality Assurance (QA) frameworks there are within reach today frameworks, for example, GMPs (Good Manufacturing Practices), GHPs (Good Cleanliness Practices), GAPs (Good Agricultural Practices) or other essential frameworks and HACCP (Hazard Analysis. Basic Control Points) (van der Speigel et al., 2003; Rotaru et al., 2015). This chapter also covers the following point mainly:

- Recommended international code of practice - general principles of food hygiene.
- Good Manufacturing Practices (GMPs)
- Good Hygiene Practices GHPs
- The hazard analysis and critical control point (HACCP) System.
- International Organization for Standardization

RECOMMENDED INTERNATIONAL CODE OF PRACTICE: GENERAL PRINCIPLES OF FOOD HYGIENE

Codes of Practice

Codes of practice are a group of guidelines, or one can be described as process specifications. These guidelines and specifications are generally helpful in providing constructive advice to manufacturers who have the same production facilities and manufacturing similar kind of products. These guidelines involve endorsements for the operational method, the design of construction facility, plant cleaning.
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procedures, personal hygiene, quality and type of equipment, standard packaging procedures, and the handling of various raw materials at various stages of production. Codes of practice were prepared by the Codex Alimentarius Commission. For example, the international codes for various fish products were also prepared by the commission, it contains numerous commendations for each product, and starting from its raw material, vessel design and ends up to goods retail practices. It details the codes of practice includes regulations for the processing facility, sanitation procedures, growing areas and harvesting techniques. Some the codes of practice are made compulsory by governments. Such as, the Code of Federal Regulations concerning to human food production in the United States of America, which is imposed by the USFDA (Royce et al., 1996; Rosentrater et al., 2017).

Codes of practice and government authorities are in interference with free trade, and it is needed some practical attitude to the questions, such as what can be done and how costly it will be. Consumers can only be protected by eliminating the doubtful products from the market via strong rules and regulations. There are numbers of products in the market, so it was very difficult to command it uniformly. Codes and standards should full proof, fair, widely acceptable, easy to understand, and can be easily managed. It can be effectively applied by the good collaboration between government authorities and industry (Royce et al., 1996).

Codex Alimentarius

The Codex Alimentarius Commission was formed by the Food and Agriculture Organization (FAO) of UN (United Nations) in November 1961, and in June 1962 it was further joined by WHO (World health organization). In October 1963, the first meeting of Codex Alimentarius Commission was held in Rome. The contents are established and maintained by commission (Ottaway et al., 2003).

The commission had narrated Codex Alimentarius. It is mainly providing information regarding the HACCP system and also defines its lacking. FAO/WHO commission had accepted the HACCP system in early 1990 and comprises it into the Codex Alimentarius. It provides the details about the need for hygiene rules in the supply chain, regarding the HACCP, phases of implementation and also discuss the definitions. In general, the Codex Alimentarius is a set of internationally accepted guidelines, standards, codes of practice, and some other recommendations concerning to food safety, foods, and food production (Sorreaux et al., 2015; Sikora et al., 2005).

The Codex Alimentarius includes every food products, raw, processed, or semi-processed. It includes specific standards for specific foods as well as some general standards for other. General standards provide details about additives, labelling, hygiene, pesticide residue, and methods for evaluating food quality. The Codex Alimentarius also provides guidelines about the official management, such as import and export examination by government and food certification systems. The Codex Alimentarius is available in the six certified languages of the United Nations (UN): French, Arabic, Russian Chinese, Spanish, and English (CODEX Alimentarius: Understanding Codex”. FAO and WHO. 1999. Retrieved 6 September 2012).

The aim of the commission was shielding the public health by implementing standard practices in manufacturing and international trading of products. The World Trade Organization renowned the Codex Alimentarius as an international reference for resolving clashes related to consumer protection and food safety (Winickoff et al., 2010; Agreement on the Application of Sanitary and Phytosanitary Measures. World Trade Organization. Accessed 3 September 2008).
Food Quality and Safety Regulation Systems at a Glance

The Codex Organizations

In Codex organization the detailed work is alienated within several committees. Numbers of committees were structured separately for focusing on ‘horizontal’ concerns like food labelling, whereas some others were focusing on ‘vertical’ concerns like specific needs for foods for its particular dietary uses. In the developing stage of the standards, it will be accepted by both kinds of the committee. In addition these committees, there are other five regional committees including Europe, Africa, Latin America, Asia, Caribbean, South-West Pacific and North America. The Codex Alimentarius Commission and their committees can take guidance from WHO and FAO expert Committees. Three other intergovernmental bodies are also there which deals with some particular commodities groups. They are also reporting to the commission. These are united committee of WHO and FAO of Government Experts officials on the Code of Principles regarding to the Milk and related products, a united Codex group of experts/ UNECE (United Nations Economic Commission for Europe) on fruit juices, and a combined UNECE and Codex Group of Experts on quick frozen foods (Ottaway et al., 2003).

As we mentioned earlier, the Codex committees are differentiated in two parts: specific and general subject committees. There are nine committees currently working on horizontal subjects (Labelling, pesticide residue and food additives). The rest of 15 Codex Commodity Committees are dealing with specific commodity groups (vegetable proteins, oils, and fats).

As per the Codex policy, every Codex committee has a host country. The host countries and their governments are responsible for their allotted committee’s meeting arrangement and the administrative infrastructural facilities for meetings should also be provided by those countries. The country is also liable for the financial support for meeting arrangements, most of the currently hosting countries are in Western Europe and North America. The Meat Hygiene Committee was hosted by New Zealand from 1972 until its suspension 1983, and in 1972, the Methods of Analysis and Sampling Committee was taken by Hungary from Germany, and Mexico hosting the Committee on Tropical Fresh Fruits and Vegetables, which was made in 1988. Codex has prepared a task force on biotechnology, because of the fast growth in biotechnology, specifically genetic engineering. In March 2000 in their first meeting, they were agreed for the development principles regarding the risk assessment of foods prepared from modern biotechnology and also agreed for preparing guidelines for the safety analysis of food products made by those types of processes. The Codex Alimentarius Commission has 186 members of 186 member countries and one additional, the European Union as a member organization in 2012. It had 16 United Nations (UN) organizations, 215 codex observers, 150 non-governmental organizations and 49 intergovernmental groups (Randell et al., 1997; Sikes et al., 1998; Codex Alimentarius Commission: procedural manual. Food & Agriculture Org. 2007).

The Codex General Principles of Food Hygiene

1. Primary production
2. Establishment: Design and Facilities
3. Control of operation
4. Establishment: Maintenance and sanitation
5. Transportation
6. Product information and consumer awareness
7. Training
Food Quality and Safety Regulation Systems at a Glance


<table>
<thead>
<tr>
<th>General Standards</th>
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<tbody>
<tr>
<td><strong>Food Hygiene</strong></td>
</tr>
<tr>
<td>It includes codes and general principle of hygienic practice in particular industries or guidelines for the implementation of the HACCP system, and food handling establishments. These guidelines were represented in broad spectrum. Its primary objective is to ensure that whether the food products are safe for the intended purpose or not.</td>
</tr>
<tr>
<td><strong>Food Labelling</strong></td>
</tr>
<tr>
<td>It includes guidelines regarding labelling claims and some general guidelines and standards on nutrition (Cheftel et al., 2005).</td>
</tr>
<tr>
<td><strong>Risk Assessment</strong></td>
</tr>
<tr>
<td>Methods for evaluating safety of food which were prepared through biotechnology such as DNA-modified micro-organisms, DNA-modified plants, and allergens (Poli et al., 2004).</td>
</tr>
<tr>
<td><strong>Food Additives</strong></td>
</tr>
<tr>
<td>It includes general standard regarding quality specification of food grade chemicals, and its approved utilization (Alimentarius, C., 2009).</td>
</tr>
<tr>
<td><strong>Methods</strong></td>
</tr>
<tr>
<td>Process and techniques for sampling and analysis.</td>
</tr>
<tr>
<td><strong>Food Contaminants</strong></td>
</tr>
<tr>
<td>It includes standards and tolerance limits for particular contaminants such as aflatoxins, mycotoxins and radionuclides (Henry et al., 1999; D’Mello et al., 2003; WHO., 1999).</td>
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<tr>
<th>Specific Standards for Specific Products</th>
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<tr>
<td><strong>Special Dietary Foods</strong></td>
</tr>
<tr>
<td>It includes baby formula foods, infant formula and specially manufactured foods for particular purposes (Joint FAO/WHO Codex Alimentarius Commission. 1994).</td>
</tr>
<tr>
<td><strong>Meat</strong></td>
</tr>
<tr>
<td>It provides guidelines about frozen meat, fresh meat, processed meat and also about poultry (Mead et al., 2006).</td>
</tr>
<tr>
<td><strong>Oils and Fats</strong></td>
</tr>
<tr>
<td>It includes information about the oil-fats products and their derivatives (Alimentarius, C., 1999; Alimentarius, C., 2012).</td>
</tr>
<tr>
<td><strong>Fish and Fishery</strong></td>
</tr>
<tr>
<td>It involves fish and fishery products from aquaculture, marine water, and fresh water (Ababouch et al., 2006; Tacon and Metian et al., 2008).</td>
</tr>
<tr>
<td><strong>Dairy Products</strong></td>
</tr>
<tr>
<td>It includes guidelines related to milk processing and other dairy product (Koletzko et al., 2005; Rastogi et al., 2004; Wiles et al., 1998).</td>
</tr>
<tr>
<td><strong>Miscellaneous Food Products</strong></td>
</tr>
<tr>
<td>It includes standards for sugar, mineral water, chocolate, and honey products (Kugonza et al., 2008; Rizelio et al., 2012; Baba et al., 2008; Semerjian et al., 2011; Man et al., 2015; Copetti et al., 2014; Chopra et al., 2002).</td>
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**Principle 1: Primary Production**

The primary food production should be managed in such a way that, it can ensure the food safety and can also confirm its suitability for intended utilization (Cerf et al., 2011). Primary production involves:
Food Quality and Safety Regulation Systems at a Glance

- The plants and animals should be kept in proper atmosphere so that they are free from diseases and contaminants. This ultimately eliminates threats to food safety.
- The use environmental threaten areas is evaded.
- For the hygienic atmosphere and conditions, the standard practices and measures should be considered and this will ensure food safety (Joint FAO/WHO Codex Alimentarius Commission, Joint FAO/WHO Food Standards Programme, & World Health Organization. (2003). Codex Alimentarius: Food hygiene, basic texts. Food & Agriculture Org).

Principle 2: Establishment: Design and Facilities

Construction and designing of equipment, premises, and facilities should be done with consideration of associated risks and the nature of the operation. The appropriate hygienic construction and design, suitable location, availability of facilities are required for controlling hazards effectively. The design and facilities should such that:

- Contamination is diminished;
- Layout and designing are suitable to easy cleaning, sanitation, disinfections, maintenance, and reduce air-borne contamination (Cramer et al., 2013).
- Materials and surfaces which come in contact with food should be inert, non-toxic, durable, and should be easy to clean and maintain.
- Required facilities should be available for controlled conditions such as humidity, temperature, and other necessary controls.

Principle 3: Control of Operation

The food products consumed by human should be suitable and safe. This can be only achieved by operational control. So the food safety can be achieved by designing appropriate control and monitoring systems for raw materials, raw material composition, processing practices, distribution and handling.

Figure 1. Important factors involved in primary production
Food Quality and Safety Regulation Systems at a Glance

Figure 2. Schematic representation shows the parameters involved in design and facility establishment (Joint FAO/WHO Codex Alimentarius Commission, Joint FAO/WHO Food Standards Programme, & World Health Organization. (2003). Codex Alimentarius: Food hygiene, basic texts. Food & Agriculture Org; Cramer et al., 2013)

Proper designing, implementation, process monitoring and documents reviewing and verification are the effective control systems. The corrective and preventive actions should be taken at every stage of operation; this will be helpful in minimizing the food hazards. The business operators should implement HACCP type of systems. It should be implemented in whole food chain to control hygiene. The shelf-life of food can be protected by appropriate designing of process and product. Proper monitoring methods and analytical techniques for analysing physical, chemical, and microbial contamination. For prevention of contamination and cross-contamination, the personal entry in the controlled area is monitored by implementing area wise accessing protocols. Portable water should be used food processing. In case of threat to any food product, the product recall channel should be very effective.

Principle 4: Establishment - Maintenance and Sanitation

For the development of efficient food processing system, the following steps are the most necessary.

- The periodically pest control in the facility (Troller et al., 2012).
- Corrective and preventive maintenance after some fixed time intervals.
- Cleaning and cleaning records.
- Waste management systems should be implemented.
- Sanitation and maintenance should be effectively observed and maintained (Troller et al., 2012).
Food Quality and Safety Regulation Systems at a Glance


| Control of Food Hazards | • Identification of critical steps.  
|• Implementation of control procedures.  
• Monitoring for assurance of effectiveness.  
• Reviewing. |
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<tr>
<td>Incoming Material Requirements</td>
<td>• Specifications for the raw materials should be prepared and employed. And incoming material should be properly inspected.</td>
</tr>
</tbody>
</table>
| Important Aspects of Hygiene Control Systems | • Controlling time and temperature.  
• Specific Process Steps.  
• Physical and chemical contamination.  
• Microbiological and other specifications.  
• Microbiological cross contamination (Van Schothorst et al., 1998). |
| Management and supervision | • Supervisors and managers should be highly knowledgeable, effective and able to take proper corrective and preventive actions. |
| Packaging | • It should provide satisfactory protection.  
• Packaging material should be inert and non-toxic. |
| Documentations and Records | • Proper record keeping of manufacturing, processing and distribution up to the shelf life of the food product.  
• It will increase the effectiveness and credibility of food safety control system. |
| Water | • In processing and handling of food only portable water should be used.  
• Water is used as ingredient, steam and in ice from in food processing. |
| Recall | • For the prevention of food safety hazard, the recall procedure should be rapid.  
• The recall products are kept in supervision and then destroyed. |

Principle 5: Establishment - Personal Hygiene

The establishment of personal hygiene is necessary because those who are in direct contact of food may be contaminating the food. By maintaining appropriate personal cleanliness and hygiene, the contamination can be minimized. And also by following the standard operating and working procedures, the chances of contaminations can be reduced. Personal hygiene is helpful in preventing the food contamination due to the personal illness (Lelieveld et al., 2014).

Principle 6: Transportation

Food transportation should be done under control measures. Transportation is comes under food supply chain and distribution. The food should be provided to end user in suitable form without any contamination. During food transportation following measures should be taken:

- The food products should be protected from damaging, so that its not became unsuitable for the end user.
- The food must be protected from its effective source of contamination.
- The transportation environment must be suitable to the quality sustenance of the product. Appropriate environmental conditions will protect the food from micro-organism and pathogenic growth.
**Food Quality and Safety Regulation Systems at a Glance**


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<tr>
<th>Maintenance and Cleaning</th>
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<tbody>
<tr>
<td>• General maintenance.</td>
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<td>• Cleaning procedures and techniques.</td>
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<tr>
<th>Pest Control Systems</th>
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<tr>
<td>• General pest control.</td>
</tr>
<tr>
<td>• Harbourage and infestation.</td>
</tr>
<tr>
<td>• Preventing access.</td>
</tr>
<tr>
<td>• Eradication.</td>
</tr>
<tr>
<td>• Monitoring and detection.</td>
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<tr>
<th>Cleaning Programmes</th>
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<tbody>
<tr>
<td>• Disinfection and cleaning should guarantee that each parts of facility are clean.</td>
</tr>
<tr>
<td>• These programmes should be continuously monitored and documented.</td>
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<tr>
<td>• The cleaning and sanitation programme should be designed by consulting with relevant experts.</td>
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<th>Monitoring Effectiveness</th>
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<tr>
<td>• Verification for the effectiveness of sanitation systems.</td>
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<tr>
<td>• Microbiological assessment of working environment, and contact surfaces should be inspected and reviewed regularly.</td>
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<tr>
<th>Waste Management</th>
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<tr>
<td>• The waste accumulation in working and storage areas must be prevented.</td>
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<tr>
<td>• Some regulatory protocols should be followed for the storage and elimination of waste.</td>
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</tbody>
</table>

*Table 4. Factors to be considered for the establishment of personal hygiene (Joint FAO/WHO Codex Alimentarius Commission, Joint FAO/WHO Food Standards Programme, & World Health Organization. (2003). Codex Alimentarius: Food hygiene, basic texts. Food & Agriculture Org)*

<table>
<thead>
<tr>
<th>Health Status</th>
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<tbody>
<tr>
<td>• If any personal is suffering illness or disease, then he should not be allowed to enter in food processing area.</td>
</tr>
<tr>
<td>• Any kind of illness or symptoms of personal should be informed to the management.</td>
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<tr>
<th>Personal Cleanliness</th>
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<tbody>
<tr>
<td>• The food handling personal should maintain personal hygiene and cleanliness by using personal protective equipments such as apron, shoe cover, head cap, and hand gloves.</td>
</tr>
<tr>
<td>• The workers should always wash their hand before and after food handling activities.</td>
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<tr>
<th>Illness and Injuries</th>
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<tr>
<td>• If any working personal is suffering from jaundice, fever, vomiting, diarrhoea and sore throat with fever. Then the situations should be informed to management, so that further medical examination can be done.</td>
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<tr>
<th>Visitors</th>
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<tr>
<td>• The visitors coming to the manufacturing facilities should were personal protective cloths for avoiding threat to food contamination.</td>
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<tr>
<th>Personal Behaviour</th>
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<tr>
<td>• During food handling activities spitting, smoking, eating, chewing, sneezing, and coughing will contaminate foods. So that it should be avoided.</td>
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<tr>
<td>• Watches, jewellery, pins and other items should avoid to worn during food handling.</td>
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</table>
The type food containers and packaging form will depend on the nature of foods. The food products should be transported in their suitable conditions. The designing and construction of bulky food containers should be according to following requirements:

- The food containers should not contaminate foods.
  - There should be an appropriate separation of foods and food from non-food materials.
  - They should be easy to clean and easy to be disinfected.
  - The containers have to maintain humidity, temperature, atmosphere and other required conditions to protect food from deterioration and microbial growth.
  - The container should design in such a way that the food products are free from fumes and dust.
  - The design should be such that the humidity, temperature and other conditions can be easily checked and operated.


**Principle 7: Product Information and Consumer Awareness**

The food products should contain proper details. The sufficient and manageable should be available to the food chain personal so that they can be easily stored, handle, prepare and display products correctly and safely. With the help of product information, it can be rapidly identified and recalled. The consumers should be aware of food hygiene so that they can easily understand the significance of product information. The end user should have appropriate information and awareness so that they can eliminate contamination and microbiological and pathogens growth. The end user information and trade information can be easily distinguishable (Ababio et al., 2012; Gendel., 2012; Caswell et al., 1996).

**Principle 8: Training**

Personals who are working in food processing or who are in direct or indirect contact of food should be well instructed and trained for food hygiene and safety. They should be trained for following standard codes of practice so that the level of food hygiene can be maintained in the processing facility (Ehiri et al., 1996; da Cunha et al., 2014). The Components of training are mentioned below:

*Awareness and Responsibilities:* The training is one of the most necessary thing to maintain food hygiene. All the workers should be aware of their working responsibility for personnel should be aware of their role and responsibility in guarding foods against deterioration and contamination.

*Instruction and Supervision:* There should be regular supervision of instruction and training programmes. The efficiency of training should also monitor. Supervisors should be knowledgeable about food hygiene safety principles and practices. And they should be able to identify the risk and take corrective actions.

*Training Programmes:* Workers should be frequently trained for the procedures to be followed during the handling, packaging, and storing.
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Refresher Training: The personal training should be frequently observed, modified and updated as per the norms and necessity.


GOOD MANUFACTURING PRACTICE (GMPs)

Good Manufacturing Practices (GMP) is a collection of detailed information and guidelines for the act and standard operating procedures to be followed, and their requirements should be fulfilled. GMP is implemented for the ensurement of food safety. GMP covers the basic activity of the facility. The activities should be as per the standard procedures and norms so that the quality food products can be prepared (Sikora and Strada, 2003; Rotaru et al., 2005; Sikora 2005).

GOOD HYGIENE PRACTICE (GHPs)

Good Hygienic Practices (GHP) contains a collection of guidelines focusing on the hygienic conditions which should be at a satisfactory level and monitored at every stage of the food chain for the assurance of safety of food. Following the GHP rules and regulations is generally making all the activities in the preparation process and in the profit of foods with ensuring appropriate conditions to foods and their decent health quality. In the case of the Health Conditions of Foods and Nutrition, the GMP and GHP are explained differently, both are intimately connected, and both are implemented for hygienic require-
ments in the facility. Both the GMP and GHP are employed and properly maintained and documented (Sikora and Strada, 2003; Rotaru et al., 2005; Sikora 2005).

HAZARD ANALYSIS AND CRITICAL CONTROL POINT (HACCP)

The HACCP was constructed for the assurance of food health and safety. It is composed of two main stakes: Health hazard analysis and critical control points which were settled after the completion of hazard analysis. An improper following of guidelines and conditions leads to health hazards. The health hazards cannot be controlled by conventional tools.

In accordance with the HACCP system, each deviation and potential hazards in the manufacturing method will be identified at a time of production or before that. The main objective of the HACCP is to eliminate any hazards before its establishment. In the early time of system establishment, primarily it was just designed to prevent every microbiological hazard. Secondly, it was employed to physical, chemical and biological hazards.

Basic steps of implementation of HACCP system: the 1st is hazard analysis for identifying the possible danger related to food processing at each stage up to the consumption. In the next step, monitoring methods should be developed, and observations should be mentioned in registers.

The proper employment of HACCP system needs:

- Appropriate designing of the documentation process.
- Carrying out detailed hazard analysis.
- Designing of control points and critical control points.
- Structuring of monitoring methods.

The HACCP system should be systematic. The manufacturing processes and practices should be performed according to the seven basic rules. The HACCP system should be specifically designed ac-

Figure 4. The schematic representation shows the characteristics of HACCP systems
Food Quality and Safety Regulation Systems at a Glance

cording to every enterprise. The system should be capable of the prevention of all possible hazards. For defeating the problems and issues, the system should be creative and innovative in the finding of new solutions. Teamwork is most necessary for proper implementation of the system because personals with diverse specialization are involved.

Advantages of the HACCP system:

- By the implementation running the HACCP system, there is no needs of permanent control on the end product.
- Preventive and corrective features of system will defeat the problem before tis arising.
- Working according to the HACCP system will ensures the quality food production without any health hazards.

(Sikora, 2005; Kijowski et al., 2003; Sun and Ockerman, 2005; Motarjemi et al., 1996)

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION

On 23 February 1947, the International Organization for Standardization (ISO) is an international standard-setting body was created that’s representatives from various national standards organizations. The ISO 22000 addresses the food safety standard management issue, the significances of unhygienic and unsafe food can be harmful to the health, The ISO’s food safety management standards service organizations categorise and regulator the food safety standard and hazards (Arvanitoyannis, 2009).

Nowadays many food products frequently cross national boundaries, so the international standards are required to certify the safety of the worldwide food supply chain. The ISO 22000:2018 fixed the necessities for a food safety management system and can be certified the food products. It recognizes which organization needs to do validate its ability to regulate food safety and standards and hazards to certify that food is safe or not. More than two hundred diseases are speeds only because of contaminated or spoiled food stuff so that it is very clear the hygienic, safe, sustainable food production is one of our extreme challenges. The food trade globalization is further complicated because of maintaining the food safety standards. The food safety is about the elimination, avoidance, and regulates the food products from the foodborne hazards factors, from the production site to the utilization site.

Meanwhile, food safety standards and hazards may be introduced at any stage of the food processing. Each food supply chain company must implement adequate hazard controls. Food safety can be secured only by the united efforts of all parties: producers, governments, retailers and end customers.

The new edition of ISO 22000 improved the clarity of understanding for the many of companies globally that already used this standard. Its latest following improvements comprise:

- Implementation of the High-Level Structure common to all ISO management system standards, creating it easier for organizations to combine ISO 22000 with other management systems (such as ISO 14001 or ISO 9001) at any given time
- A different approach to risk as an important concept in the food product business – which differentiates between risk at the working level and the corporate level of the management system
- Strong links to the Codex Alimentarius, a United Nations food group that develops food safety guidelines for government authorities.
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The new ISO 22000 standard offers a forceful control of food safety hazards coalescing the following generally recognized key elements: systems management, interactive communication, Prerequisite Programmes (PRPs), and Critical Control Points (HACCP), and the principles of Hazard Analysis (Arvanitoyannis, 2009; Surak, 2005)

FOOD SAFETY LEGISLATION

Legislative regulations which people need to be aware of are:

- Food Safety Act 1990
- Food Hygiene Regulations (Northern Ireland) 2006
- Food Hygiene (Scotland) Regulations 2006
- Food Safety and Hygiene (England) Regulations 2013
- Food Hygiene (Wales) Regulations 2006

These regulations make compulsory implementation of HACCP based food safety management procedures for all food businesses.

- **Food Safety Acts in Europe and the United Kingdom**: The European Union established the European Food Safety Authority in the year 2002 which is an independent source of scientific advice. The independent Food Standards Agency (FSA) was established in 2001 by the government of UK. FSA was made by merging various prevailing agencies under one body. The aim behind FSA is to promote standards and to advise the government.

- **India's Food Safety Act**: India implemented the Food Safety and Standards Act in 2006, which merged various existing organisations to establish the Food Safety and Standards Authority of India (FSSAI).

- **Food Safety Modernization Act (FSMA)**: On 4 Jan 2011, the FSMA was signed into law by US President Obama. FSMA gives major importance on food safety and public health assurance by using preventive action, rather than countering after cases of contamination. It will modify the role of the USFDA. FSMA gives the FDA legal authority.

CONCLUSION

The quality and safety assessment of all food products are the very essential step for the entire food chain from the manufacturer to end consumers. Because of the causes of the maximum disease are reported from the contaminated or unhygienic food source so that the food safety and quality standard assessment is very crucial before selling or consuming the food products. This chapter summarises, in brief, the analysis of the specific and integrated/advanced food quality and safety management system, along with the identification and analysis of the factors that can influence the employment process. The various investigating and assessment agencies and their role in the whole process of quality and safety assessment
Food Quality and Safety Regulation Systems at a Glance

for the food products. The efficiency of the ISO systems is based on the association between external and internal organizational factors. In addition to that, these factors act into the food industry have to balance the food quality and safety assurance management systems, select the appropriate ones permitting to its resources and requirements and implement tolerable outfits for continuously evaluating and measuring the quality safety and performance of the individual or advanced/integrated management systems.

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REFERENCES


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Chapter 12
Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems

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University of Arkansas, USA

Zeinab Mohammadi-Shad
University of Arkansas, USA

ABSTRACT
Mycotoxins are a group of naturally occurring toxins that are produced by different filamentous fungi genera such as Aspergillus, Penicillium, Fusarium, etc. The word mycotoxin literally is derived from Greek word “myke” meaning fungus and “toxicum” meaning toxin. These contaminants can develop on different food and feed commodities during different stages including pre-harvest, harvest, and storage. Mycotoxins are of concern because their outbreak result in animal and human diseases and economic losses. It has been estimated that global post-harvest losses are approximately at 50%. Human exposure to mycotoxins is typically through consumption of contaminated agricultural products or indirectly by consumption of animal products containing mycotoxins or their metabolites. The chapter provides the latest information on mycotoxin issues and challenges related to food and feed safety.

INTRODUCTION
Mycotoxins and Their Significance

Mycotoxins are a group of natural occurring toxins that are produced by different filamentous fungi genera such as Aspergillus, Penicillium, Fusarium, etc. (Binder et al., 2007). The word mycotoxin literally is derived from Greek word “myke” meaning fungus and word “toxicum” meaning toxin. These contaminants can develop on different food and feed commodities during different stages including

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Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems

pre-harvest, harvest and storage. In fact, mycotoxins are a large group of secondary metabolites which are in center of concerns because of their outbreaks in animal and human diseases and economic losses due to their pathologic disorders in plants and animals. It has been estimated that post-harvest losses is globally 50% because of fungal and bacterial infections (Piotrowska, 2014). Mycotoxins consist from various types of toxins that represent numerous and diverse chemical and physical properties. Human are in exposure to mycotoxins directly through consumption of contaminated agricultural products or indirectly by consumption of animal products product containing mycotoxins or their metabolites. When animals consumed contaminated feedstuffs, mycotoxins will be transferred into milk, meat, egg and other products (Bhat et al., 2010).

In addition, mycotoxins generally have a potential resistance against most processes, so the toxins remain in processed food and feed. Ingestion of mycotoxins in high quantities or over a long period of time poses a health threat to consumers. The most affecting mycotoxins in animal feed and food are aflatoxins, ochratoxins, trichothecens, fumonisins and Zearalenone (Armando et al., 2012; Richard, 2007).

The first discovery of aflatoxin was in 1960s when they recognized as toxic substances produced by fungi. Aflatoxins (AFs) can be produced both before and after harvest depending on the environmental conditions. AFs are mostly produced by Aspergillus flavus and A. parasiticus. A. flavus only produce type B of AFs, however, A. parasiticus produce types B and G (Pitt, Taniwaki, and Cole, 2013). Aflatoxin is classified as class 1 carcinogenic and mutagenic mycotoxin affecting 25% of global crops (Williams et al., 2004; Marin et al., 2013).

Some agricultural products such as peanuts, maize and cottonseed (in the USA) are the most affected products by the Aspergillus species compared to tree nuts, rice, and spices. Aspergillus fungi contaminate peanuts due to insect damage, drought stress and high soil temperature in field (Pitt, Taniwaki and Cole, 2013; Atungulu, Mohammadi-Shad and Wilson, 2018). AFs are commonly found in food crops, particularly maize, groundnuts, oilseeds, and tree nuts, depending on drought stress, rainfall, crop adaptability to weather, pest damage, and agricultural practice (Khlangwiset, Shephard, and Wu, 2011). Aflatoxin can be produced during food storage, transportation, and processing. Humans are mainly exposed to aflatoxin by maize and groundnuts consumption due to susceptibility and high consumption rates of these products (Khlangwiset, Shephard, and Wu, 2011). A. flavus and A. parasiticus contaminate maize and groundnuts by dispersing from soil, organic matter, and alternative hosts to developing commodities. Fungal infection and aflatoxin concentration raise up during crop development when the weather is hot and dry and during maturation/harvesting when the conditions are warm and humid (Kachapulula et al., 2017). One of the most safety hazards in the world is A. flavus and subsequent aflatoxins contamination in peanuts.

Aflatoxin B1 (AFB1) can be formed in a wide variety of water activity and temperature. However, when temperature and water activity are lower than 20 °C and 0.85, respectively, the growth of A. flavus is slow down. The optimum temperatures and water activities for A. flavus growth and subsequent AFB1 production in peanuts are 37 °C and 0.98, 28 °C and 0.96, respectively (Liu et al., 2017). If dairy animals ingested contaminated feed AFB1, after 12-24 hours, AFM1 (the metabolite of AFB1) will be appeared in milk (Sadia et al., 2012; Bilandžić et al., 2016). Different percentage of AFM1 contamination has been found in raw and processed milk in different countries (Li et al., 2017; Sadia et al., 2012; Michlig et al., 2016; Kos et al., 2014; Elzupir and Elhussein, 2010; Mohammadi Shad and Atungulu, 2017). Feeding cows and buffalos with less contaminated feed with AFB1 leads to good quality of milk. AFM1 incidence also depends on weather conditions. It was seen higher incidence of AFM1 in milk collected during cold weather (fall) than warm weather (spring) (De Roma et al., 2017). As it is mentioned, the mold growth on dairy products is a serious problem. The most mycotoxigenic mold grown on cheese is Penicillium
species. Penicillium can enter into cheese naturally (through contaminated milk) or deliberately inoculated using commercial ripening cultures. Penicillium is capable to produce some types of mycotoxins such as ochratoxin A, penicillic acid, citrinin, and patulin (Bullerman, 1981). In the case of ripened cheese, mold species are intentionally added for development of appearance, texture, and flavor (Sengun, Yaman, and Gonul, 2008). However, these types of cheese can be at risk. Camembert and gourmet cheese can be contaminated with cyclopiazonic acid produced by ripening culture of P. camemberti (Le Bars, 1979; Bennett and Klich, 2003). P. roqueforti which is mostly used in the fermentation of blue-veined cheese produces some secondary metabolites like PR-toxin which is a risk to human health (Martín and Coton, 2016). Although cheese is a good medium for mold growth, the mycotoxin formation rarely happens compared to other dairy products (Bullerman, 1981). However, the possibility of using high-quality ripening strains of molds unable to produce mycotoxins in cheese is of great interest.

Fumonisins are produced by Fusarium fungi mainly by Fusarium verticillioides and lesser amount by F. proliferatum. However, there are some reports alarming fumonisins production by A. niger strains. Fumonisins are produced during pre-harvest and harvesting than storage; because Fusarium species require water activities more than 0.9 aw to grow. The most susceptible product to fumonisin production by Fusarium is maize and maize products. (Pitt, Taniwaki, and Cole, 2013). High incidence of fumonisins was found in maize grain (Van Der Westhuizen et al., 2003; Abbas et al., 2015). The high level of contamination with fumonisins was found in maize and maize products which significantly increased by sun drying for one week followed by one month storage (Nguegwouo et al; 2017; Latorre et al., 2015).

There is negligible impact of thermal processing below 150°C on fumonisin levels in food products (Pitt, Taniwaki, and Cole, 2013). The fumonisin group consists of different types of toxins. However, fumonisin B1 and B2 are the most toxic ones among all identified fumonisins (Bordin et al., 2014).

Deoxynivalenol (DON) and nivalenol (NIV) are the main trichothecene mycotoxins produced in foods principally by Fusarium species such as F. graminearum, F. culmorum. These compounds are mostly found in small grains like wheat and barley. Unlike the fumonisins, DON is formed as the result of rainfall. The disease caused by Fusarium, Fusarium head blight, in small grains are promoted by heavy rainfall. After harvest, if water activity in grains drops below 0.9, F. graminearum growth and these toxins will cease. Therefore, due to high required water activity for F. graminearum growth, DON and NIV levels will not increase during storage (Pitt, Taniwaki, and Cole, 2013).

The ochratoxins group incorporates more than seven structurally related metabolites. Among ochratoxins, Ochratoxin (OTA) is known for the most toxic one. OTA is produced by different groups of storage fungi such as A. ochraceus, A. alliaceus, A. ostianus, A. melleus, P. viridicatum, P. cyclopium, P. variable, and others (Jay, Loessner, and Golden, 2005). Also, it was reported that OTA can be produced by other fungi depending on target product divide it into three groups: firstly, A. ochraceus in long stored grains, secondly, A. carbonarius and A. niger in in fresh fruits, vegetables and grains, and lastly by P. verrucosum and P. nordicum in cooled stored grains and meat, respectively (Pitt, Taniwaki, and Cole, 2013). Additionally, this toxin has been found in maize, dried beans, soybeans, barely, oats, cocoa beans, citrus fruits, peanuts, coffee beans, spices, wine and other products (Nakajima et al., 1997; Truckssess et al., 1999). OTA, like other mycotoxins, is heat tolerated. In one study, the rate of 0-12% reduction of OTA achieved by roasting green coffee beans at 200 °C for 10-20 min, and the investigators concluded that OTA could not be destroyed by roasting under these conditions (Tsubouchi et al., 1987).

Another mycotoxin produced by Fusarium fungi particularly by F. graminearum and also by F. culmorum, F. cerealis, F. equiseti, F. verticillioides, and F. incarnatum in food and feed is zearalenone (ZEA) (Marin et al., 2013). These estrogenic compounds are produced particularly in moist and cool
field conditions and in poor storage condition. ZEA is often found as a co-occurrence of other mycotoxins (Tanaka et al., 2000). ZEA is soluble in aqueous alkali such as ether, benzene, and alcohols, but it is insoluble in water (Urry et al., 1966).

ZEA can contaminate a variety of food products most importantly wheat and maize (Giménez et al., 2013; Iqbal et al., 2014; Pleadin et al., 2012). These ZEA producing fungi invade field maize at the silking stage, mostly during rainy season. The fungi grow and produce toxin if the product kept at high moisture content following harvesting (Jay, Loessner and Golden, 2005). The toxin has been found in other products including wheat, barley, oats (Tanaka et al., 1990; Tanaka et al., 2000). ZEA may tolerate thermal processes depending on the process condition. It was found that the reduction rate of ZEA can be increased by elevating temperature above 175 °C. More than 92% of ZEA was destroyed after heating at ≥175 °C for 60 min and complete reduction was achieved at 225 °C for 30min (Ryu et al., 2003).

Effective Factors on Fungal Growth and Mycotoxin Production in Food and Feed

There are several factors that contribute to fungal growth and also favor mycotoxin production during pre-harvest, harvesting and storage. The required conditions for mold growth is different during pre-harvest and postharvest (Didwania and Joshi, 2013). Among various conditions, the most affecting parameters are temperature, water activity (aw), pH, moisture and oxygen content. Generally, it has been reported that high temperature, high moisture content and high water activity will facilitate fungal growth and toxin production. Furthermore, interactions of several factors such as temperature, water activity, moisture, time, substrate, etc. are effective in mycotoxin formation. Therefore, prediction of fungal growth and mycotoxin production will be more complicated. It is crucial to know marginal and critical conditions for mold germination and mycotoxin production in order to set up critical control points for applying preventative strategies. It should be noted that fungal growth does not necessarily mean mycotoxin production since the required conditions are different. For example, growth of Fusarium genera remarkably occur at temperatures between 25 to 30°C but production of their mycotoxins significantly happen if temperatures are near freezing (Bhat et al., 2010).

Temperature

Depending on the fungal genera and substrates nature, fungi usually grow and produce toxins at temperatures between 10 to 40°C and -5 to 60°C, respectively (Didwania and Joshi, 2013; Klich, 2007; Juric et al., 2007). For example, A. flavus can produce aflatoxin in range of 12 to 42°C and the optimum required temperatures are in range of 24-30°C ; however, the aflatoxin production will be decreased at temperatures near 30°C (Klich, 2007; Gallo et al., 2016; Bhat et al., 2010). It is essential to know that fungal growth and mycotoxin production result from interaction of temperature with other factors like water activity. In one case study, the effect of temperatures in range of 5-30°C, water activity in range of 0.900-0.995 and incubation time (7-49 days) and their interactions on F. graminearum and DON was investigated on irradiated wheat grains. The results indicated that at a constant temperature, the fungal growth was increased with increasing aw amounts until it became maximum at 0.995 aw. On the other hand, at a constant aw, the fungal growth increased and reached a maximum growth rate at 25°C but afterwards followed by descending pattern. Results of interaction between aw and temperature showed that the maximum growth happened at 0.995 aw and 25°C. Also, no fungal growth was seen at 5°C at
all examined aw levels and also at lowest aw (0.90) and highest temperature (30°C). Furthermore, in-
teraction of aw, temperature and incubation time also demonstrated that maximum DON was detected
at 0.995 aw, 30°C and after 42 days of incubation (Ramirez et al., 2006).

Water Activity (aw) and Moisture

There are different water activity and moisture requirements for fungal growth and optimum mycotoxin
production among various fungi which also depends on the type of substrates. Generally, water activity
more than 0.70 and moisture content more than 12% can stimulate fungal growth (Juric et al., 2007). The
optimum moisture content in grains for growth of A. flavus and aflatoxin generation is 18%. The critical
moisture content and water activity for OTA production and the fungal growth on grains are 17-18% and
0.80-0.83 aw, respectively. Therefore, maintaining moisture content lower than 14% and water activity
lower than 0.7 is crucial to inhibit fungal contamination (Magan and Aldred, 2007).

Depending on the fungi types, the required aw for growth is different. As an illustration, A. flavus,
P. chrysogenum and Fusarium spp optimally grow at aw between 0.78 to 0.80, 0.78 to 0.81 and 0.85 to
0.87, respectively (Bhat et al., 2010). However, Aflatoxin producing fungi are hindered from growth
and germination by low aw amounts in range from 0.70 to 0.75 aw (Gallo et al., 2016).

As it was mentioned above, mycotoxins production occurred at different aw levels. Aflatoxins
generally are produced highly in the substrates with relatively high amount of water activities. It was
found that aflatoxin formation was maximum at water activities ranging from 0.95 to 0.96 in cowpeas
substrate (Klich, 2007). In an investigation on paddy rice, it has been reported that aflatoxin formation
was positively dependent on levels of water activity. So that decreasing water activities from 0.98 to
0.92 aw, the growth of A. flavus followed by aflatoxin production decreased and the lag phase of fungal
growth increased in paddy rice. But this reduction was more due to interaction with other parameters
such as level of CO2 and temperature (Mousa et al., 2016).

In another survey, it was illustrated that P. citrinum was able to grow in conditions with a low avail-
ability of water. As reported by Comerio et al., (1998), P. citrinum could grow at water activities lower
than 0.81; however, it was accelerated by higher water activities. Regarding citrinin accumulation, the
toxin was not detected at 0.800 aw and it reached to high level of 20 mg/kg at 0.885 aw. The minimum
required aw for citrinin production was 0.810 aw (Comerio et al., 1998).

Interaction of water activity and temperature on A. flavus growth and aflatoxin production on almond
enriched medium was investigated. The results showed that at lower temperature (20°C) the fungal growth
was seen only at higher aw values (0.96 and 0.99 aw) and it was suppressed at lower water activities (0.90
and 0.93 aw). Although the fungal growth was accelerated at higher temperature (37°C) but the aflatoxin
production decreased. Higher and lower temperatures were not favorable for aflatoxin production, so
the best condition in this analyzed medium was concluded to be 28°C and 0.96 aw (Gallo et al., 2016).

To provide proper conditions for preventing growth of ochratoxigenic fungi and OTA production,
it is important to know that OTA production occurs at limited ranges of aw and temperature compared
to the fungal growth. In a survey, the effects of water activity (0.80-0.99 aw) and temperature (10, 20,
30°C) and their interaction on growth of A. ochraceus and OTA production were investigated in irradiated
barley grain. The results showed that both fungal growth and OTA production were minimum at lowest
temperature and water activity. So the lowest required aw for fungal growth and OTA production were
0.85 and 0.90, respectively. At 30°C, the effect of water activity on growth was more evident; so that
decreasing aw from 0.99 to 0.95 led to sharp reduction in the growth rate. Also, at 30°C, OTA produc-
tion had a decreased level at 0.95 aw and no detectable level at remaining other aw amounts. It was also concluded that the optimum conditions for fungal growth and OTA production were 0.99 aw and 30°C on examined barley grains (Pardo et al., 2004).

pH

The impact of pH is very important on fungal growth and mycotoxin production. There are different pH requirements regarding mold growth and mycotoxin production. By and large, pH amounts ranging from 4 to 8 and 5 to 7 are needed for fungal growth and mycotoxin production, respectively (Juric et al., 2007; Didwania and Joshi, 2013). The maximum production of aflatoxin can occur at pH of 4-6. It has been reported that with reducing pH from 8 to (4-5), aflatoxin production became five to ten times higher. In addition, AFB1 is produced mainly at lower pH than aflatoxin G1 (Klich, 2007). It was reported that aflatoxin production could occur in anaerobic rumen environment which has low pH (<4) and temperatures between 15-35 °C (Nidhina et al., 2017).

Oxygen

Another determining factor for mold growth and subsequently mycotoxin production is the presence of Oxygen (O2). It is important to reduce O2 content to levels lower than 0.14% to prevent growth of mycotoxigenic fungi (Magan and Aldred, 2007). During some processes like feed ensiling it is important to keep the conditions anaerobic. If ensiled materials exposed to atmospheric Oxygen, the preventative balance pH would be broken and so fungal and mycotoxin contamination spread quickly (Zachariasova et al., 2014). In contrast, there is one report related to the probability of aflatoxin production in anaerobic condition of cow rumen environment. It was reported that the isolates form cow rumen liquor inoculated on both aerobic and anaerobic have the capability to produce AFB1 and B2 in both conditions. However, the produced level of AFB2 was more in aerobic condition than anaerobic. Meanwhile, AFB1 generation was not significantly different in both conditions (Nidhina et al., 2017).

GEOGRAPHIC DISTRIBUTION AND THE EFFECT OF CLIMATE CHANGE ON MYCOTOXINS LEVEL

Nowadays global climate change is considered as main concern of the world. It includes several changes including changes in atmospheric air composition, global warming, increasing sea water level, and desertification, etc. Reports by United States Environmental Protection Agency (USEPA) show 2000-2009 as the warmest years (EPA, 2010). It is matter of discussion between scientists how these changes will affect different aspects of human life. As reported by Intergovernmental Panel on Climate Change (IPCC), an increase in average global air temperatures, due to evaporation of water from land and ocean and hold of more moisture by the air, beyond 3°C can lead to decreased global agricultural production (Ongoma, 2013). Therefore, one of the main concerns is food security which deals with availability of sufficient nutritious food for human consumption. Food safety is also relevant to food security because it defines if the available foods have the quality to be edible. Food safety issues affected by climate change could be several items like pesticides residues, heavy metals, pathogenic microorganism, molds and their toxins (Tirado et al., 2010). Climate change and variability would have a significant impact on
the agricultural food safety, with prevalence of specific mycotoxin-producing fungi as one of the most crucial threats (Miraglia et al., 2009). Fungal occurrence and plant susceptibility would be affected by weather condition and may lead to mycotoxin contamination of the crops (Tirado et al., 2010). Extreme meteorological events such as droughts and precipitation pattern, floods, and heat waves development may lead to contamination of agricultural lands, water, food and feed, which very likely become more frequent, stronger and of longer duration. It is expected as one of the highest challenges of the 21st century in production loss and economic impact (Farkas, 2011). For example, the occurrence of a heat wave in Italy in 2003 led to growth and production of aflatoxin in maize crops which were consumed by cows, resulting in AFM1-contaminated dairy products (Giorni, 2007).

Some of the Forecasted Environmental Changes in the Future are Mentioned as Below

Temperature Increase

Global warming is one of the changes forecasted in weather conditions. It is anticipated that global temperature will increase between +2 to +5°C (Medina et al., 2014). Every year it is expected that global temperature will increase 0.03°C (Magan et al., 2011). This temperature increase will happen in different rates based on geographical locations. For example, coastal areas will have less temperature changes compared to the areas in the lands. Also, more severe changes are expected in already dry areas compared to moist areas. Generally, areas located in higher geographical latitudes would be more prone to temperature increase (Miraglia et al., 2009). It is also forecasted that due to temperature increase the length of freezing season decreases and consequently the length of growing season increases. This leads to longer production season and can lead to increase of pest population.

Precipitation Change

Precipitation rate change due to climate change is dependent on the latitude as in the higher latitude there will be more rain. Meanwhile, in the subtropical areas less rain would be expected (Miraglia et al., 2009).

CO2 Elevation

Since industrial time, CO2 level has increased in the atmosphere and this will further increase because of less absorption capacity of land and ocean related to global warming (Miraglia et al., 2009). In the next 10-20 years, it is forecasted that CO2 will increase 1.5 µmol per year (Magan et al., 2011).

Correlation Between Environment and Mycotoxin Contamination

Incidence of mycotoxin contamination in the crops is dependent on the correlation of the fungi and plant and environment. A particular climate change will not necessarily influence the pattern and populations of all types of mycotoxigenic fungi in the same way. Temperature and humidity were recognized as the effective direct climate factors on fungal growth and toxin production (Shah et al., 2013; Nazari et al., 2014). The prevalence of aflatoxin contamination in maize products has been observed in Europe since 2000s which was increased during the hot summer (Medina et al., 2014b; Rijk et al., 2015). In a study
sponsored by the European Food Safety Authority (EFSA), the probability of occurrence of AFB1 in maize for a +2°C temperature elevation is expected to increase with a high risk in the southern European countries and low and medium risks in Romania, France, Hungary, and Northeast Italy, as the main countries for maize production (Farkas et al., 2011). OTA has been reported in different areas of the world in the current temperature, due to the ability of a wide range of fungi to produce this type of mycotoxins in products including cereals, grape, and onion (Gil-Serna et al., 2015), with optimal temperatures between 15-30°C. However, the maximum growth of OTA occurs around 30oC. High temperature has been recognized as a crucial factor for the contamination OTA in grapes and grape products (Visconti et al., 2008). In an investigation on wine contamination with OTA in Europe, the occurrence of OTA in grapes was observed to be higher in the Southern European regions than those in the northern regions (Zimmerli and Dick, 1996). Fumonisins, and in particular the B group being as the dominant one in food and feed, are mainly produced with temperature around 30oC depending on the water dynamics. Maize is the only crop that contains a high amount of fumonisins with a relatively high resistance to thermal degradation (Sundheim et al., 2015). The amount of fumonisin however, can be reduced during food processing. Zambia being the major source for producing Maize in Africa has proper weather for maize cultivation enhancement. However, maize is contaminated with a high amount of fumonisin, which can affect the health of domestic animals by consuming the contaminated feed. Based on available data on the fumonisin condition in Zambian maize, effect of climate change on the risk of fumonisin contamination of maize in Zambia as well as, other South and East African countries in future is not possible to predict (Sundheim et al., 2015).

Climate change affects selection of the fungi and mycotoxin contamination. For example, F. graminearum and F. culmorum both prefer to grow in cool environments. But optimal temperature for the first one is a little higher than the second one (Kos et al., 2017). Consequently, F. graminearum becomes dominant in maize when temperature is higher. In Serbia, more F. graminearum and F. culmorum contamination was reported in maize during the years which temperature was low and rain fall was more (Kos et al., 2017). Also, it is expected that in Europe when the weather gets hot it will lead to more Aspergillus infection and less Penicillium infection. Temperatures around 30°C are favorable for A. flavus contamination (Paterson and Lima, 2010). For instance, increasing of average global temperatures leads to change of altitude ranges, under which aflatoxin contamination is more probable to occur. As reported by Payne, this high temperature along with drought leads to aflatoxin contamination in crops such as nuts, maize, peanuts, and cotton seeds (Payne, 1998), especially in tropical and subtropical regions (Lewis et al., 2005).

Another climatic change is elevation of the CO2 which may lead to more fungal diseases. For example, sheath blight in rice farms will distribute faster when level of atmospheric CO2 is higher (Paterson and Lima, 2010).

It is expected that, as the results of climate change, the areas where used to not to be infected become infected by fungi in more quantity and variety; so that this defines which types of fungi can grow in plants (Paterson and Lima, 2010). Drought stress may lead to make xerophilic fungi become dominant in plants because they can tolerate 0.65-0.75 water activity. In Italy, it was reported that due to drought stress F. verticillioides was replaced with A. flavus. Consequently, maize grains became contaminated with aflatoxins instead of fumonisins and at the end of the food chain AFM1 was exerted into the dairy products (Medina et al., 2014).

Any stress or damage to the plant may lead to susceptibility of the crop to fungal growth and mycotoxin contamination. In Kerman province (Iran), It was reported that temperature increase and reduction in regular raining led to early split of pistachio hull which contributed to aflatoxin contamination (Tirado et
Another example is cracks on the peanut due to drought stress which led to A. flavus growth and aflatoxin contamination (Magan et al., 2011). In general, any drought stress or damage to the crops may lead to increased crop contamination.

Also, soil erosion may lead to further susceptibility of the crops to fungi contamination (Paterson and Lima, 2011).

Environmental changes may also affect mycotoxin contamination of the crops indirectly. For example, population and type of insects may change due to climate change which can cause mold growth on the host plants (Miraglia et al., 2009). Also, climate change will tend to influence survival of insects between the seasons and their distribution (Cotty and Jaime-Garcia, 2007). It is stated that pests and diseases are moving to the poles with the rate of 3-5 km/h (Medina et al., 2014). Another indirect effect of climate change is the increase of feeding rate of the insects as the result of temperature increase. Additionally, increase in night temperature is an important factor for feeding of the insects because many of them are active at night. So increase in their feeding rate will lead to more fungal infection (Paterson and Lima, 2010). Insects can contaminate the crops in two ways: 1) through the physical damage of the crops 2) by increasing moisture content in the environment via their aspiration. In addition, increase in pest infestation will lead to increase in bird’s population. Subsequently, they will cause further damage to the crops and mycotoxin contamination (Nesic et al., 2015).

It is noteworthy to know that mycotoxin contamination during different stages of plant growth has different environmental requirements. For example, during development stage of the crop, hot and dry environments can lead to further mycotoxin contamination. Meanwhile, moist and hot environments can cause further mycotoxin contamination when the crops are matured (Cotty and Jaime-Garcia, 2007). Plants during their sensitive physiological steps are more susceptible to fungal growth. For example, rain fall when cotton ball are open or during flowering of the wheat can lead to more mold infection (Paterson, and Lima, 2010). Weather condition during flowering of the wheat seems to be an important factor for Fusarium Head Blight (FHB) disease. Heavy rainfall during this period causes further FHB contamination (Paterson and Lima, 2010).

Climate change may also affect storage of the grains after harvest. Water availability below 0.70 aw is the limit which inhibits mold growth. Environmental moisture that cause moisture content in the grain exceeds this limit will contribute to fungal growth in the crops (Paterson and Lima, 2010). Physiological changes caused by environmental changes are another reasons lead to mold and mycotoxin contamination of the crops. For example, change in stomatal pattern on the leaf lead to further susceptibility of the plants to molds and insects (Nesic et al., 2015).

Finally, it should be noticed that the combined effects of different environmental factors like CO2, temperature and moisture might be different from the effect of each item individually (Magan et al., 2011). In a survey, it was reported that these interacting factors did not have any effect on the growth of fungi but they had positive impact on the ability of fungi in order to generate mycotoxins (Medina et al., 2014).

**HEALTH CONCERNS OF MYCOTOXINS**

Mycotoxins have devastating effects on both human and animal health. They can result in several illnesses and this is a matter of worldwide concern. The mycotoxigenic molds can produce more than one mycotoxin. Additionally, more than one mycotoxin has been reported in most contaminated food and feed products which worsen its health concern. The term used to describe the illness caused by mycotoxins
is mycotoxicoses (Richard and Thurston, 1986). An interesting fact regarding the mycotoxicoses is that unless the number of affected individuals is high, the detection by medical doctors is not an easy task and most of the time they remain unrecognized. As described in Section one, the environmental parameters that control the fungal growth and mycotoxins production are temperature, water activity, pH, moisture, and oxygen. While these parameters can be controlled during food and feed storage, some other factors (e.g., fungal strain) may not be manipulated effortlessly.

Acute and long-lasting effects of different types of mycotoxins on human and animals are dependent on mycotoxin type and vulnerability of affected animal. Fortunately, the micro-organisms in ruminant’s body (cattle, sheep, and their relatives) are capable of decomposing mycotoxins and these animals show better resistant to mycotoxins’ disastrous effects.

Aflatoxins

The aflatoxin detection and its health concern were unclear up until the death of nearly 100,000 turkey poultries near London, UK in 1962 (Bennett and Klich, 2003). The contaminated feed ingested by turkey poultries was peanuts carrying aflatoxins. The contaminated animal feed with aflatoxins, not only deteriorates their quality but also impacts their exporting industry. Dairy products such as milk can play an indirect source of aflatoxin. As it was mentioned before, when dairy cows digest feeds contaminated with AFB1, it is converted to AFM1 in their milk due to their body metabolism (Kang’ethe and Lang’a, 2008).

The most severe cases of aflatoxin contamination ends in death while the long-lasting illnesses ranges from cancer to malfunctioning of immune system (Eaton and Groopman, 1994; Kensler et al., 2010). The main organ target in case of AFB1 contamination is liver both in animals (poultry and fish) and humans (Liu et al., 2012; Groopman et al., 2008). The adverse effects of aflatoxins on a same species depend on sex, age, weight, mycotoxin concurrence, and the extent of exposure to aflatoxin. Affected farm animals such as turkey, chicken, and pig with aflatoxin contaminated feed have shown a substantial decrease in their immune system (Smith et al., 1995). With more than 4 billion people in danger of liver cancer (hepatocellular carcinoma, HCC) due to exposure to dietary aflatoxins across the globe, the health impact of aflatoxins on humans is a serious issue as well (Liu et al., 2012). They can lead to hepatocellular cancer in Africa and Asia (Scholl and Groopman, 2008).

Trichothecene Mycotoxins

The DON and T-2 toxin belong to a specific group (A) of trichothecene mycotoxins (Rocha et al., 2005). The fundamental damage of trichothecene mycotoxins inside the body is intervention of the protein synthesis which causes imbalance in cellular protein level. The dividing cells in digestive tract, skin, lymphoid cells, and erythroid cells are under adverse influence of trichothecene mycotoxins (Zain, 2011). In a study conducted by Schwarzer, unpleasant effects of trichothecene mycotoxins were observed in necrosis of the mucous membrane lining inside of the mouth and trichothecene-exposed skin. Additionally, severe effects on gastrointestinal tract, reduction of bone marrow, and malfunctioning of immune system were reported as well (Schwarz, 2009). The outbreak of idiopathic pulmonary hemorrhage among infants in the city of Cleveland located at Ohio state has been linked to inhalation of trichothecene which resulted in 12 death cases from 1993 to 1998 (Dearborn et al., 1999). Diseases, threatening farmers in contact with trichothecene-contaminated hay, have been reported as nasal and tracheal bleeding (Żukiewicz-Sobczak
et al., 2012). A class of trichothecene mycotoxins interrupts protein synthesis in eukaryotic cells and may lead to eye irritation, throat irritation, cephalea, nose bleeding, and dizziness (Lourenço, 2011).

**Zearalenone**

This mycotoxin promotes estrogen-like activity in farm animals such as cattle, pigs, and sheep. It can introduce into natural waters thorough contaminated cereals and can create a serious threat to animals and humans. A negative impact on heat and eye early development as well as upward curvature of the body axis in larvae exposed to ZEA has been reported (Bakos et al., 2013). It is also responsible for reproduction problems in cows and ovine species (Nezami et al., 2002). If the percentage of ZEA is high in pig feed, it may cause issues in its conception and abortion.

**Fumonisin**

These types of mycotoxins have structural resemblance to sphinganine. It was reported that the maize grains contaminated with fumonisins has been resulted to several incidents of esophageal cancer in different regions of world. In animals, fumonisin mycotoxins are accountable for different kind of diseases. Some important ones are Leukoencephalomalacia in horses (Christley et al., 1993), rat’s liver cells destruction (Voss et al., 2002), Leukoencephalomalacia, pulmonary edema and hydrothorax in swine and hemorrhage in the brain of rabbits (Bucci et al., 1996).

**Ochratoxin A**

These mycotoxins exhibit similar chemical structure to aflatoxins and have nephrotoxic effect on almost all contaminated animals (Duarte et al., 2011). OTA reveals immunosuppressive, hepatoxic, teratogenic and carcinogenic behavior as well.

**ECONOMIC LOSSES RELATED TO MYCOTOXINS IN FOOD AND FEED**

Mycotoxins on the food grain and livestock industry have considerable economic impacts. There are several factors and uncertainties that affect production loss due to mycotoxin contamination. These factors include: diminished crop value, reduced productivity due to infections developed by toxigenic fungi, reduction of animal productivity resulted from health issues associated with mycotoxin contamination, and human health cost. Considering the first two factors, the cost attributed to mycotoxin infection losses in the United States was estimated about 0.5 to 1.5 billion dollars per year. The most significant factor impacting the production losses is the decreased value of production, which also affects the crops that are entered in domestic trade, as well as those that are exported.

While it is really difficult to estimate the economic impact of mycotoxins, major losses was reported for crops, including wheat, maize, peanuts and other nut crops, cottonseed and coffee. Approximately, 25% of the crops are contaminated by mycotoxins each year in the world, with annual losses of around 1 billion metric tons of foods and food products, as was estimated by Food and Agriculture Organization (FAO).
Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems

Few reports based on the increased levels of aflatoxins in developing countries are available, showing a higher level of losses compared to those happening in the United States. For instance, according to FAO, the mycotoxins have considerable effect in food grains in Southeast Asia. The annual losses of food grains such as peanuts, maize, cashew and walnut, wheat and barley, rice, and soybean were estimated of around 1849, 16042, 769, 123, 12010, and 2296, respectively, in metric tons (Lubulwa and Davis, 1994). In another study, it was reported the 900 million dollars of maize and groundnut losses due to aflatoxins in Indonesia, Philippines, and Thailand per year. The impact of export losses in developing countries is even worsened since the food grains with the highest quality are mostly exported and the grains with poorer quality are retained for local use.

In addition, in the case of farm animals, the majority of outbreaks are caused by aflatoxin, fumonisins and ZEA. Poultry, dairy cattle, horses and swine are the most affected farm animals by mycotoxins. Even a small amount of exposure of feed to mycotoxins can cause a great production loss, resulted in field outbreaks. It was presented that the economic losses could also be associated with mycotoxin residues in milk, eggs, meat, etc. In an investigation conducted in India, the poultry exposure to the feed contaminated by aflatoxins caused a loss of about 10% of the initial investment (Prathapkumar et al., 1997). It was also revealed that the majority of the loss was because of mortality in birds followed by a reduction in egg productions, as well as extra expenses on the protein source. The occurrence of fumonisin mycotoxins were reported as an outbreak in India, in which 10% bird mortality and 20% drop in egg production were reported (Prathapkumar et al., 1997).

The contamination of six mycotoxins for several feed samples throughout the world was studied by Williams (2008). The most common contaminant occurring frequently in maize grains and finished feed was found to be fumonisin (58%). Therefore, apart from aflatoxin, considerable attention has been focused on fumonisin. It was reported that the aflatoxins in US maize was estimated to cause $163 million impact per year. It was also observed that rejecting the maize for food caused market loss of about $31 million per year, whereas the annual loss of rejected corn for feed and livestock was reported about $132 million.

SAFETY EVALUATION AND REGULATION LOSSES

As it has been mentioned mycotoxins have adverse effect on animals and human health as well as economic losses. As per report provided by FAO 25% of world grain commodities are contaminated with mycotoxins (Sherif et al., 2009). Therefore, local and international authorities have established maximum residue limits regarding mycotoxins. Non-compliance to these limits will lead to trade rejection of agricultural products which would be costly. More stringent European Union (EU) regulation for mycotoxins costs Africa 670 million dollars losses every year. To set up international regulations, there should be always a balance between safety and economy (Wu, 2004). So an accurate risk analysis is required to optimize safety regulations versus economic losses.

Risk Analysis Definition

Systematic approach for food safety management is called risk analysis and consists of three parts: risk assessment, risk management and communication (Sherif et al., 2009). Risk assessment is to evaluate risk of an identified hazardous material. Hazard is any physical, chemical and microbial contaminant
which can cause health problem for consumer. Risk is combination of probability of occurrence and severity of the disease. So risk is exposure defined as probable daily intake (PDI) versus severity of health problem or estimated tolerable daily intake (TDI) (Goodman, 1995). According to World Health Organization (WHO) definition, exposure assessment is to determine surveillance of a contaminant in human population (Sherif et al., 2009). This is country specific because it is affected by various climate conditions and different dietary intake in each country (Goodman, 1995).

**Risk Analysis and International Regulations**

Concept of risk analysis is used by authorities to set up international regulation for mycotoxins. Codex Alimentarius Commission (CAC) is an organization established by Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO). Main objective of CAC is to make international legislations for food and feed to facilitate international trade and protect public health (Worldwide regulation for mycotoxins in food and feed, 2003). There are two other committees in FAO and WHO which collaborate with codex to adopt these standards. Risk analysis is conducted by FAO/WHO Joint Expert Committee on Food Additives (JECFA). Result of this assessment is presented as TDI. Then, the Codex Committee on Food Additives and Contaminants (CCFAC) uses these data to define risk management of mycotoxins. This is to decide about the maximum limits (MLs) and required actions to provide public health in specific condition. At the end, CAC establish codex standards (Table 1). EU also with the same approach has legislation organization which their regulations are most of the time similar to Codex standards (Berg, 2003).

JECFA define total daily intake for each mycotoxin using available data related to consumption and contamination in five regional diets in Africa, Europe, Far East, Latin America and Middle East (Serrano et al., 2012). Contamination data are provided through scientific researches and consumption data provided in national dietary surveys. European Food Safety Authority (EFSA) has provided large information related to food consumption during last 5 years (Marin et al., 2013). In scientific studies one approach is to assess exposure to mycotoxins through usage of biomarkers. They are used to determine mycotoxin excretion into blood or urine following exposure to contamination (Marin et al., 2013).

Another approach is available through national investigation reports available in some countries. For example, mycotoxin exposure data are provided by Norwegian scientific committee of food safety. IARC is another source of information for JECFA to define toxicity rate of mycotoxins. According to the report provided by IARC, AFB1 is classified as group1 carcinogen for human and AFM1 is classified as group 2B carcinogen. For mycotoxins which no carcinogenic evidence are available, they are reported as ‘‘not classifiable as to its carcinogenicity to humans’’ and categorized in group 3. They consist of

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**Table 1. Different stages in preparation of international standards**

<table>
<thead>
<tr>
<th>Step</th>
<th>Responsible</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk assessment</td>
<td>FAO/WHO Joint Expert Committee on Food Additives, JECFA</td>
<td>Acceptable Daily Intake (ADI) Or Tolerable Daily Intake (TDI)</td>
</tr>
<tr>
<td>Risk management</td>
<td>The Codex Committee on Food Additives (CCFAC)</td>
<td>Acceptable limit in particular situation and required actions to protect against mycotoxins</td>
</tr>
<tr>
<td>Execution</td>
<td>Codex Alimentarius Commission</td>
<td>Establishment of the standards</td>
</tr>
</tbody>
</table>

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some mycotoxins in different groups including patulin, some metabolites of ZEA, some trichothecenes (T-2 toxin, NIV and DON) (Sirot et al., 2013).

As it was mentioned above, risk management is to define controls and regulations based on results of risk assessment (Sherif et al., 2009). After a comprehensive risk assessment, management strategies are identified. Risk management need to be defined only for significant risk factors (Goodman, 1995). Meanwhile, to define risk management strategies and regulatory norms, technological feasibility, cost impact, international trade requirements and availability of analytical methods should be considered (Goodman, 1995). Mycotoxin exposure should be controlled as Low as Reasonably Achievable (ALARA) as it is recommended by JECFA (Serrano et al., 2012). Also According to CAC, higher TDI is recommended in the countries that prevalence of hepatitis B infection is low (Bhat and Vasanthi, 2003).

A review was provided on exposure, toxicity, legislation and intake of ZEA all over the world. In this review, it was reported that Provisional Maximum Tolerable Daily Intake (PMTDI) of ZEA and its metabolites is 0.5 µg/kg of body weight (Zinedine et al., 2007). Based on new evidence more restrict norm was proposed by JECFA at the same year which was 0.2 µg/kg bw/week. It later was increased to 0.25 µg/kg bw/week. The PMTDI provided by JEFCA for OTA is 2 µg/kg bw/week (Sirot et al., 2013).

**Risk Analysis as a Preventative Approach**

Guideline based on risk analysis concept is provided to control food safety risks. This approach can be implemented to provide more alignment on mycotoxin contamination prevention. In this regard, according to Hazard Analysis Critical Control Point (HACCP) concept outlined by FAO (2001) seven steps are required (Table 2) (Binder et al., 2007).

Consequently, following increasing awareness worldwide related to mycotoxins contamination nowadays more countries in the world are adopting local regulations for mycotoxins. International survey was conducted by the National Institute for Public Health and the Environment to investigate availability of local regulation for mycotoxins. The result indicated that 87% of the world population are living in the countries which they have regulation for mycotoxins (FAO, 2003). This indicates the importance of availability of global organizations like CAC to align all legislation of all these countries.

**Table 2. Recommended steps for mycotoxin management preventative approach**

<table>
<thead>
<tr>
<th>No.</th>
<th>Step</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Risk analysis</td>
<td>Make list of mycotoxins and define if their risk is significant or not</td>
</tr>
<tr>
<td>2</td>
<td>Define critical control points</td>
<td>If the risk is significant based on process flow diagram points should be identified to control contamination</td>
</tr>
<tr>
<td>3</td>
<td>Critical limits</td>
<td>Maximum limit should be identified</td>
</tr>
<tr>
<td>4</td>
<td>Monitoring plans</td>
<td>Plans for mycotoxin monitoring in control points should be provided</td>
</tr>
<tr>
<td>5</td>
<td>Corrective actions</td>
<td>In case of noncompliance corrective actions should be available</td>
</tr>
<tr>
<td>6</td>
<td>Verification</td>
<td>Effectiveness of mycotoxin management plan should be verified</td>
</tr>
<tr>
<td>7</td>
<td>Documentation</td>
<td>All the data related to monitoring, corrective actions and verifications should be documented</td>
</tr>
</tbody>
</table>
MYCOTOXINS DETECTION METHODS

There are several established regulations regarding mycotoxin limits to ameliorate their adverse effects on humans and animals health. To check compliance to these regulations, analytical instructions have been developed. In general, these instructions include three steps: sampling, sample preparation and measurement. One analytical protocol cannot be implemented for all mycotoxin determinations because of structural difference of mycotoxins and also different food and feed matrixes which might be available (Turner et al., 2009).

Preparatory steps: Many analytical methods have been developed to be able to analyze mycotoxins at trace levels. All these analytical methods generally include extraction from the feed or food matrix using a solvent, clean up step to purify the extract and finally detection or measurement of mycotoxins using analytical instruments (Leslie et al., 2008). Preparatory steps are very important for successful analysis. Due to their importance, they affect selection of quantification method. Sometimes they are very time consuming and two third of time of analysis is for these steps.

Sample collection: First step of doing any analysis is sampling, so applying accurate sampling is very important to take a representative sample. There is no homogenous distribution of mycotoxin contamination in one batch of consignment, so incorrect sample selection may lead to error (Bailly and Oswald, 2013; Atungulu, Mohammadi-Shad and Wilson, 2018). Generally, 90% of the error in mycotoxins analysis is linked to collection of the samples. Grab sampling for mycotoxins analysis is not generally recommended because it leads to very low accuracy of mycotoxins results (Turner et al., 2009; Atungulu, Mohammadi-Shad and Wilson, 2018). There are two types of mistakes in sampling: false positive and false negative (Magan and Olsen, 2004). Without accurate sample taking, correct decision about acceptance or rejection of one batch of consignment would not be possible. If the batch is misclassified, there would be negative financial or health consequences. Development of sampling plan for mycotoxins analysis has always been an international concern. Effective sampling plan should specify the size of sample, collection method and the way it must be divided and analyzed (Bailly and Oswald, 2013; Atungulu and Shad, 2017).

Sample preparation: Quantification of mycotoxins usually is required at trace amounts in complex food and feed matrix (Malachová et al., 2014). So the first step for mycotoxin analysis is to separate them from these matrixes. Several methods are available depending on mycotoxin structure and the matrix that toxin from which should be extracted (Turner et al., 2009).

Then, in the cleaning step extract is purified to eliminate interfering materials which may affect accuracy of the assay. As it is shown in table 3, there are three major methods applicable in extraction step including liquid-liquid extraction (LLE), supercritical fluid extraction (SFE), and solid phase extraction (SPE) (Turner et al., 2009). Nowadays, the most common cleaning method is SPE and the most popular bounding agent used in this method is silica gel (Turner et al., 2009; Atungulu, Mohammadi-Shad and Wilson, 2018).

Based on physical and chemical properties different analytical methods have been developed to provide sufficient flexibility for different compounds and environments (Turner et al., 2009).
**Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems**

**Table 3. Different types of cleaning methods**

<table>
<thead>
<tr>
<th>Method</th>
<th>Basic principle</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| LLE    | Use of Solvents like Hexane and cyclohexane to extract non-polar contaminants | - Applicable for several toxins  
- Small scale preparation | - Time consuming  
- Type of food matrix is important  
- Type of analyte is important  
- Losses due to adherence to the glass wall |
| SFE    | Use of supercritical fluid like CO2 to extract the compound | Work well due to high solvating power | - Not good for routine analysis  
- High cost  
- Need for specialized equipment |
| SPE    | Small disposable cartridge filed with silica gel or bonded phase as stationary phase rinsed with sample loaded in one solvent | - High capacity for binding  
- Depend on type of bonding agent can be used for different toxins | - No single cartridge available for all mycotoxins  
- Each column work at certain conditions (pH, Solvent and ion concentration) of the sample |

**Conventional Techniques**

For quantitative determination of mycotoxin classical methods used for analysis includes: High Performance Liquid Chromatography (HPLC) coupled with ultraviolet (UV), Fluorescence (F) or Mass Spectrometry (MS) detection, Gas Chromatography (GC) coupled with electron capture detection, flame ionization detection or mass detection and Thin Layer Chromatography (TLC). Conventional mycotoxin detection methods need very skilled operators. Also, sample preparation is very complicated and instruments are sophisticated (Chauhan et al., 2016). They have very high accuracy but they are instrumental and not portable, so they are not suitable for onsite sampling (Lu et al., 2016). Conventional analyses are usually used for qualitative and quantitative analysis (Chen et al., 2016).

**Thin Layer Chromatography (TLC)**

Concept of chromatographic approach is separation of every compound from its surrounding matrix before identification. Then, highly sensitive detectors are used such as fluorescence and mass spectrometry (Turner et al., 2015). Thin layer chromatography (TLC) is very common method for mycotoxins analysis which can economically screen the large number of samples (Turner et al., 2009). It is simple method which is often used when low detection limit is not required (Leslie et al., 2008). This method is still very popular because of low operation cost and easy identification of the targeted compound (Turner et al., 2009). Sample preparation is required in this method and clean up protocol depends on the targeted toxin in the study. Several cleanup methods had been used in this test which silica gel column is one of the most common methods. Meanwhile, other techniques have also been reported including ELISA, PH bond phase, PH bond cartridge (Turner et al., 2009). It was reported that fumonisin B1 and B2 were detected in corn using a rapid TLC (Rottinghaus et al., 1992)

**Liquid Chromatography (LC)**

Liquid Chromatography combined with mass spectroscopy (LC/MS) has become a popular method in mycotoxins analysis in feed materials (Turner et al., 2009). To improve accuracy of LC/MS, extracts

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**Note:** The text continues with more detailed information on mycotoxins occurrence, prevalence, and risk assessment in food systems.
should be purified using Mycosep or immunoaffinity columns before detection (eds Leslie et al., 2008). In few last years, new improvements in the LC-MS technology have been created. The method of LC is combined with tandem mass spectroscopy (LC-MS/MS) in order to determine multiple classes of mycotoxins in different feed matrices (Tsiplakou et al., 2014).

In a study, Core-shell poly (dopamine) magnetic nanoparticles were used as dispersive solid-phase extraction (dspe) sorbent to extract six mycotoxins in complex matrices such as milk and yogurt before their LC-MS analysis (González-Sálamo et al., 2017). In another investigation, Aflatoxins (M1, B1, B2, G1, G2), ochratoxins (A and B), HT-2, T-2 toxins, deoxy-deoxynvalenol, sterigmatocystin, fumonisins (B1, B2 and B3) and ZEA were quantified simultaneously in cow milk using liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS). Extraction was conducted using acidified acetonitrile and for clean-up stage sodium acetate was used. Moreover, simultaneously presence of different mycotoxins in coffee was investigated by using LC-MS/MS (Moraleja et al., 2015). In compression Electrospray Ionisation Mass Spectrometry (ESI-MS) technique is useful to detect different species in solution (Wang, et al., 2018).

**High Performance Liquid Chromatography (HPLC)**

TLC has been reported to have more accuracy compared to HPLC method but more versatile HPLC has been more popular for mycotoxins detection in different reports (Turner et al., 2009). Depending on physical and chemical properties of mycotoxins, HPLC have the capability to select different adsorbents which provide more flexibility for this method to be used in modern mycotoxins analysis. HPLC is standard method for industry to determine mycotoxins. It is coupled with different detectors including Ultraviolet (UV), Diode Array Detector (DAD), Fluorescence Detector (FD), Mass Spectrometry (MS).

HPLC-FD had been used to determine OTA in wine, rice and green and roasted coffee (Turner et al., 2009). Only mycotoxins such as OTA, aflatoxins and citrinin which have chromophore can be detected in HPLC-FD method. For the mycotoxins which do not have natural florescence to be detected they need derivatisation. For example, fumonisins need to be derivatised using agents such as phthaldialdehyde and 9-(fluorenylmethyl) chloroformate (Turner et al., 2009). Usage of HPLC-FD for detection of Fusarium mycotoxins including ZEA, NIV and DON has been reported.

Mass spectroscopy has become standard detection method for mycotoxins in industries due to its high accuracy which can be linked to HPLC and GC methods in order to increase identification power of these two systems. Negative points related to this system are high cost and complex laboratory requirements and also the limit in extraction and separation phase to select type of solvents (Turner et al., 2009). Usage of HPLC-MS with an Atmospheric Pressure Chemical Ionization (APCI) was reported for detection ZEA in food and feed (Turner et al., 2009). Another reported detection method in HPLC was Diode Array Detector (DAD) used to determine beauvericin (BEA) in maize (Turner et al., 2009).

Electrospray Ionization (ESI) in negative mode is another detection system which had been used in HPLC. Also, for better selectivity, sensitivity and accuracy of liquid chromatographies (HPLC and UPLC), it had been coupled to tandem mass spectrometry (LC-MS/MS) (Malachová et al., 2014). The most important advantage using LC-MS/MS method is the simultaneous detection of several mycotoxins. In an investigation, LC-MS/MS method was used to investigate multi mycotoxins co-occurrence in maize base porridge (Geary et al., 2016). It was also used in another study to determine T-2 toxin, HT-2 toxin in the tissues of broilers (Yang et al., 2013). In addition, a LC-MS/MS method was developed to determine DON, deoxyDON, T-2 toxin and HT-2 toxin in plasma and bile of animals (Baere et al., 2011).
Having high quality separation and low limit of detection, it would be possible to combine different detection systems including fluorescent, UV, diode array to allow multiple compounds from one sample to be detected (Turner et al., 2009).

**Gas Chromatography (GC)**

Gas chromatography is based on Flame Ionization Detection (FID), Electron Capture Detection (ECD) and mass detection (Leslie et al., 2008). In these methods, first stage is clean up to get a purified extract using charcoal-alumina, florisil, silica gel or Mycosep. Furthermore, volatile and sensitive pre-column derivatization steps is conducted to make purified extract of toxins because mycotoxins are nonvolatile (Leslie et al., 2008). Gas chromatography coupled with mass detector (GC/MS) is used to quantify trichothecenes, ochratoxins, zearalenon, Patulin and fumonisins (Zöllner et al., 2006).

**Enzyme Linked Immunosorbent Assay (ELISA)**

Several rapid methods are developed to detect mycotoxins in food and feed ingredients. Rapid immunometric assays including Enzyme Linked Immunosorbent Assay (ELISA) or membrane base immunoassay are developed for mycotoxins determination in commercial uses (Leslie et al., 2008). These methods are mainly screening methods which mean positive samples will still need to be verified using classical methods. Despite the fact that majority of analytical methods require extraction and clean up steps but ELISA method can be consider as an exception because it does not need any clean up (Turner et al., 2009). ELISA is appropriate method for commercial application because it involves few steps and simple extraction method (Stachowiak et al., 2016). In this system specific antibodies are used for detection of the mycotoxins through competitive incubation in one or two hours (Juan et al., 2013). Antibodies used in this method need to have high sensitivity and cross reactivities. High sensitivity makes high sample dilution possible and eliminates effects of food or feed matrix. Meanwhile, for total aflatoxin determination 100% cross reactivity is required to have accurate results. Due to availability of immortal cell line producing antibodies with sustainable quality, monoclonal antibodies are always preferred for this purpose. In one study a fast and simple ELISA method was developed using monoclonal antibodies for detection of AFB1 and total aflatoxin (Stachowiak et al., 2016).

**Evolutionary Mycotoxins Detection Methods**

**Biosensors**

Biosensors are user-friendly devices developed for mycotoxins detection to replace conventional methods (Leslie et al., 2008). These instruments should have simple work instruction and be easily portable. They include one part for recognition and another part which transduce recognition event to a signal which might be acoustic, electrical or optical. Electrochemical biosensors are major biosensors used for mycotoxins detection. Their technology is based on antibody and antigen affinity interaction which lead to an electrical analytical signal. This can be based on several electrical techniques including amperometric, potentiometric, conductimetric and impedimetric. The best electrochemical transducer is amperometric (voltametric) due to high sensitivity in different mycotoxins concentration. It is based on measurement of the current under fixed (potensiostatic control) or variable (Voltametry) potential (Juan et al., 2013).
Inert metals like Pt, Au or carbon (graphite or glassy carbon) are very common electrodes used to make transducers (Juan et al., 2013). In this regard, use of nano-structured metal oxides has been reported in several studies and Bi2O3 is one of the latest that is reported to make an efficient immunosensor for aflatoxin detection (Pratima et al., 2016).

Sensors used in immunosensors can be Natural and artificial. Natural receptors include antibody, DNA, Enzyme and artificial receptors include engineered antibodies, antibody fragments, aptamers and molecularly imprinted polymers. Mycotoxins molecules can be more detectable if sensors be labeled by enzymes, nanoparticles, redoxmolecules and fluorophores, etc. Therefore, two types of sensors are available as labeled and label free. Colloidal semiconductor nanocrystals and quantum dots (QDs) were used to label antigens of three mycotoxins (DON, ZEA and AFB1) in tripled analyte multiplex (TAM) imunosensor. This system is used for simultaneous detection of different analytes using immobilization of antibodies related to the same analytes in the same well of microtiter plate.

Immuno-Chips

Immuno-based mycotoxins detection methods are expensive and have unsatisfactory detection limits. So microfluidic devices (lab on chip) look promising alternatives for modern analytical techniques. It is based on Total Analysis System (TAS) concept which means to incorporate all the necessary steps of analysis into a chip in micrometer size (Guo et al., 2015). This leads to less consumption of reagents and samples and also shorter time for analysis (Li et al., 2016). In this system nanoliter of fluids pass through microsclae channels (Guo et al., 2015). Liquid flow in micro channels follows different rules compared to macro flow channels. Microfluid devices are composed of two parts including actuators and sensors. Actuators consist of micro valves, micro pumps, and micro mixers, while sensors are mainly cellular and molecular detectors. Micro valves are used for flow control for separation and timing. There are two valves available named active and passive. Active micro valves are driven with active pressure but passive micro valves open when the pressure outside the flap is more than pressure inside the channel. Then the valve would be forced to open and chemical reaction would happen. Critical function of micro flow pumps also is providing transportation flow and controlling flow rate. Micro mixers are also used to increase mixing efficiency and increase molecule transmission. Major part of fluidic devices is detectors. They also need to be small in size and be ultra-sensitive since they are dealing with very small quantity of reagents (Guo et al., 2015).

Lateral Flow Devices (LFDS)

This method is also called immunochromatographic test which is based on a strip with a control line. In the controlled line there is a colored receptor (latex or colloidal gold) coated with an antibody which have the capability to bind the analyte. If analyte is present the control line loose color or disappear but if analyte is not available the control line shows strong color. This method is commercially available and has several benefits including being user-friendly, rapid response and economical price (eds Leslie et al., 2008).
Other Rapid Technologies

For rapid quality assessment of agricultural products, hyperspectral imaging (HSI) had been used. This is a rapid, nondestructive and accurate method which doesn’t need several sample preparations (Selvaraj et al., 2015). Another rapid method is short-wave infrared (SWIR) hyperspectral imaging technique which was used to detect Aflatoxins in corn kernels (Selvaraj et al., 2015). Electrochemical biosensors have several advantages including simplicity, sensitivity, low cost and portability (Lu et al., 2016).

MASKED MYCOTOXINS

In recent decades masked mycotoxins have become more challengeable issue in food safety despite their identification from 1990. Live organisms like microorganisms and plants and also food processing can modified and alter the forms of mycotoxins (Dall’Asta and Berthiller, 2015).

Masked Mycotoxins Generated by Plants and Microorganisms

When plants infected by mycotoxins, they can alter the structure of mycotoxins to more polar substances which are not detectable by routine techniques. This transformation of mycotoxins occurs mostly for mycotoxins that are more predominant in the field like mycotoxins produced by Fusarium (e.g. ZEA, DON, fumonisins, T-2 toxin and NIV) because they are more in contact with plant active substances than mycotoxins produced by Aspergillus or Penicillium fungi (Dall’Asta and Berthiller, 2015). The mycotoxins would be biotransformed by glucuronidation, glucosylation (Glc), sulfation (S) and conjugation with glutathione (GSH) or amino acids reactions that occur in plant Phase II (Dall’Asta, and Berthiller, 2015). These chemical transformations are part of plant defense against toxins that is facilitated by plant enzymes in phase-II metabolism reactions (Berthiller et al., 2012). Then, the formed metabolites in phase-II can be stored in vacuole or conjugated to cell wall materials during phase III in plants (Berthiller et al., 2007). For example, conjugation of mycotoxins with glutathione (GSH) catalyzed by glutathione S-transferase (GSTs) is one detoxification mechanism by plants which results in the masked mycotoxin formation. The levels of masked mycotoxin can even exceed their parent toxins (Berthiller et al., 2013). As it was mentioned above, plants defend against toxic effects of xenobiotics such as mycotoxins through changing the structure of mycotoxins into masked mycotoxins. For example, conjugation of DON into DON-3-β-D-glucopyranoside (D3G) in wheat plants would make the plants more resistant to bleaching which is common symptom of Fusarium Head Blight (FHB) disease but its stability in digestive system of animals is not approved yet (Berthiller et al., 2007).

Also, the assessment of adverse effect of D3G was conducted on human intestinal cells and porcine jejunal explants. The results indicated that although DON was cytotoxic and inflammatory inductive, the D3G-treated cells did not show such a toxic effect on mammalian cells. As in silico study showed the higher molecular weight and polarity of D3G due to glucoside group inhibited it from binding to site A of ribosome 60S. Thus, it could not activate inflammatory biomarkers. Also, in treated cells with D3G was not seen any alteration in histological, morphological and functional properties (Pierron et al., 2015). However, it should be considered that the masked D3G may be re converted to its parent DON and this reactivation of the parent molecule would lead to the expression of toxic effects again (Pierron et al., 2015).
There are some debates about the sound risk of masked mycotoxins since they may become unmasked by in vivo mechanisms and then turn to their parent precursors. As an example, conjugation of mycotoxins with lactones, epoxides or aldehyde groups is stable; however the conjugation with glucose is reversible by enzymes available in plants or in digestive tract. Human breast cancer cell culture incubated by zearalenone-14-glucoside (ZEN-14-Glc) for 2 and 6 hours showed that ZEA and its isomers, α-zearalenol and β-zearalenol, was present in cultured mediums (the cell lysate and growth medium) except β-zearalenol in the growth medium after 2 hours of incubation. As it was reported, the ZEN-14-Glc was converted to the toxic and xenoestrogens metabolites by culture of human breast cancer cell (Dellafiora et al., 2016).

New form of masked ZEA was identified in zearalenone-treated barely root, wheat and Brachypodium distachyon suspension. After administration of ZEN into these cultures a new compound which is zearalenone-16-O-Glucoside was found after different time of incubation besides the ZEN and known zearalnon-14-O-Glucoside. The zearalenone-16-O-Glucoside was 16-18 times more than zearalnon-14-O-Glucoside in the barely roots. The main advantage of this conversion is the non-estrogenic activity of this masked mycotoxin. However, it might be hydrolyzed to its original parents by intestinal bacteria and again reactive the toxic and estrogenic ZEA (Kovalsky Paris et al., 2014). Screening of food and feed commodities for masked mycotoxins is also important since the toxicity of masked mycotoxins due to reactivation of parent mycotoxin in digestive tract of animals and humans is possible (Berthiller et al., 2007).

Several fungi most notably Fusarium spp. are capable to excrete conjugated mycotoxins (Berthiller et al., 2007). The co-occurrence of masked mycotoxins with their precursor mycotoxins is important to be considered in assessment of food and feed safety. It was reported that DON-3-glucoside was simultaneously present with DON in artificially DON-treated and Fusariums-inoculated wheat samples. And they had a same average of distribution in the wheat samples. Also, about 42% of wheat samples had higher concentrations of DON-3-glucoside than DON concentrations. Further, there was 87.5% natural occurrence of DON-3-glucoside in all samples (maize and wheat) ranging from 0.05 to 0.20 mg/kg. Although the acetylated forms of DON were also detectable in the Fusarium-inoculated wheat samples, generally the concentration of DON-3-glucoside was higher than the concentration of these derivatives. So it is very important to measure DON-3-glucoside along with DON in evaluation of cereal safety and to include it in the risk assessment of DON contamination (Berthiller et al., 2005).

The improper extraction of masked mycotoxin by usual solvents due to its high polarity and also absence of commercial standards make these metabolites undetectable by conventional methods. Therefore, the detective method for masked mycotoxins is different depending on the type of masked mycotoxins. Generally, high performance liquid chromatography coupled with tandem mass spectrometry (HPLC-MS/MS) is a powerful technique for determination of masked metabolites, as it was used for DON-3-glucoside measurement. Likewise, masked fumonisins were determined by HPLC coupled with fluorescence or mass detector after alkaline release treatment (Berthiller et al., 2005). In another study in China, it was reported that corn kernels and corn-based products were contaminated with DON, DON-3-glucoside, 3-acetyl-DON and 15-acetyl-DON. The most frequent toxin was DON toxin; however, DON-3-glucoside was available along with DON in 619 out of 969 total corn samples. Meanwhile, the lowest detected mycotoxin was 3-acetyl-DON. It was pointed out that the presence of DON-3-glucoside was positively linked to DON occurrence in all tested samples that led to 25%±5% and 34%±4% relative proportion of DON-3-glucoside to DON in corn kernels and corn based products, respectively (Wei et al., 2012).
Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems

It is importantly suggested that hidden fumonisins should be considered in risk assessment of fumonisins occurrence in corn silage. Latorre et al., (2015) have confirmed that hidden fumonisins were present in corn silage even in amounts higher than free forms of fumonisins. These hidden forms could be formed through binding to macro molecules in food products such as proteins and carbohydrates. The hidden fumonisins were increased when exposed to aerobic conditions. Generally, the hidden forms were higher than their free forms. Moreover, the highest concentrations of mycotoxins were related to fumonisin B1 and its hidden form.

Masked Mycotoxins Generated by Processes

One the other side, food processing mostly heating at elevated temperatures and fermentation can also contribute to the formation of masked or hidden mycotoxins by chemically changing the structure of mycotoxins. As reported by Bryła et al., (2016) hidden fumonisins were higher in processed maize-based products compared to the unprocessed products. The highest levels of mean concentrations of free fumonisins and total fumonisins (free+hidden) were seen in maize snack. The reason is that high temperatures may contribute to the formation of masked mycotoxins.

Another important finding was the comparable or even higher level of DON-3-Glc incidence in beer and malt made from barely. The highest level of DON-3-Glc was 37 μg/l in the examined samples. It could be due to contaminated barely grains or malting and brewing process that can release the conjugate. Higher amount of alcohol was correlated to higher amount of DON and its conjugate because of relatively larger usage of wort extract in the process (Kostelanska et al., 2009). Enzymatically release of conjugated mycotoxin from cell wall and/or production of mycotoxin conjugates by Fusarium spp. in infected barely may account for the increase of the conjugates of mycotoxin during malting process (Berthiller et al., 2009).

Finally, with development in analytical methods, masked mycotoxins were identified as an emerging issue in food and feed safety. Since the masked forms can be hydrolyzed back to their free form, they should be considered in risk assessment.

MYCOTOXINS CONCURRENCE AND INTERACTIONS

Different mycotoxins can be found simultaneously in the same grain or feed products during preharvest, harvest or storage. Combined intake of multi mycotoxins consumption will occur depending on the adsorption rate of mycotoxins; which can alter the individual toxic effects of mycotoxins (Speijers and Speijers, 2004). There are several scenarios about how feed ingredients are contained multi mycotoxins:

- **First**: Contamination with one fungus capable producing divergent mycotoxins
- **Second**: Using of feed ingredients with different mycotoxin types in feed final product
- **Third**: Feasibility of multi fungi contamination in specific feed ingredient

Indeed, the co-occurrence of various mycotoxins in feed final product is more common than individual occurrence, since different ingredients are mixed together and each of them can contribute to concurrent presence of diverse mycotoxins (Binder et al., 2007). There are several reports of multiple mycotoxins that frequently occurred in a combination (Table 4).
Multi mycotoxins produced by Fusarium spp. in a specific matrix has become an important issue in risk assessment (Speijers and Speijers, 2004). Binomial and tertiary co-presences of Fusarium produced mycotoxins were seen most frequently in wheat flour and unprocessed wheat samples, respectively. Furthermore, the tertiary combination of ENA1 + ENB + ENB1 was most detectable co-occurrence in contaminated samples. Then, followed by binomial combination of ENB + ENB1 (Stanciu et al., 2017). The co-contamination of OTA and AFB1 was also reported in maize flours with 37.5% frequency due to concomitant contamination with various fungi (Kara et al., 2015). Co-incidence of various mycotoxins found to be more common in animal feedstuffs because feed materials can be contaminated with various fungi subsequently a broad spectrum of mycotoxins. So the coincidence occurrence of mycotoxins should be evaluated in feedstuffs since the harmful health effect would be worsened. The mycotoxin DON was one predominant that occurred with other mycotoxins like its acetylated and glycosylated derivatives, OTA, ZEA, AFB1, FB1, T-2 toxin, HT-2 toxin, enniatins and beauvericin. These co-occurring mycotoxins mostly occurred in maize-based dried distiller’s grains with solubles (Zachariasova et al., 2014). Kosicki and others indicated that the combined occurrences of DON + ZEN, DON+T2+HT2, ZEN +T2+HT2 and DON+T2+HT2 +ZEN were mostly available in feedstuffs. In Poland, Kosicki et al., (2016) examined corn samples (295), corn silage samples (143), small grain cereal samples (466) and complete feed samples for swine, poultry and cattle (480). They reported ZEA and DON were most frequent mycotoxins occurred in maize, maize silage samples and small grain cereals. More than 90% of complete feed samples were contaminated with trichothecenes and ZEA. Interestingly, a weak to strong correlation was found between DON and ZEA, T-2 and HT-2 toxins for all examined samples. The most common co-present combination of mycotoxins was related to DON plus ZEA due to their high incidence in analyzed feed samples. This co-occurring combination had a strong positive correlation in maize and maize silage and a moderate positive correlation in cereal grains and complete feed samples. Also, a strong positive correlation was recorded for T-2 and HT-2 in examined feed samples except maize silage. The most and least occurrence of multiple mycotoxins found in complete feed and maize silage, respectively.

Most of studies have focused on the effects of individual mycotoxins. It is worth to know that co-incidence of mycotoxins exert combined effect which is complex. The possible interactions occurred between multiple mycotoxins can be defined as: additive, synergistic and antagonistic. The combined effects of multi mycotoxins depend on several factors including the animal species, the type of mycotoxins and used endpoint. For instance, the interaction between citrinin and OTA could be synergistic, additive or antagonistic. Generally, knowing the mode of actions of each mycotoxin at cellular level would be helpful to understand the type of interactions (Speijers and Speijers, 2004).

Additive Interaction

The additive effects are mostly probable between mycotoxins which are structurally similar or of similar species and families (Speijers and Speijers, 2004). Thus, the interaction between most trichothecenes combination are usually additivism which group tolerable daily intake (TDI) should be considered for their risk assessment (Speijers and Speijers, 2004). However, the additive interaction was reported between aflatoxin and OTA in swine. The toxin combined effects on swine are severe (Huff et al., 1987).
Synergistic Interaction

One of the main concerns in risk assessment is related to synergistic interactions between concurrent mycotoxins. It is possible that a feedstuff with lower contamination of one type of mycotoxin cause severe symptoms because of synergistic interaction due to naturally concurrent of other mycotoxins contamination (Binder et al., 2007). For example, the co-concomitant occurrence of aflatoxin and OTA result in synergistic toxicity on kidney along with the absence of toxic effect of aflatoxin on fatty liver (Huff et al., 1987). The simultaneous incidence of fumonisin B1 along with AFB1 has synergistic toxic effect on liver tumor and the more suppression of antibodies would be seen (Kamala et al., 2015). Indeed, fumonisin B1 enhance hepatocarcinogenesis initiated by AFB1 (Gelderblom et al., 2002). According to Jia and et al., (2016), co-presence of aflatoxin plus ZEA led to synergistic effects on laying chicken performance. Combination of AF + ZEN synergistically reduced egg production, feed intake, feed conversion ratio and eggshell strength. Moreover, eggs from hens fed combined AF + ZEA diet had higher residue of AF than group with only AF in diet. Interestingly, it was reported that Bacillus subtilis showed to be effective in amelioration of these synergistic effects on layers.

Antagonistic Interaction

citrinin as a nephrotoxin substance results in much more water consumption followed by an increase in excretion when poultry consumed contaminated feed with citrinin. However, concurrent exposure to citrinin plus OTA in poultry could alter and ameliorate these toxin effects of citrinin (Huff et al., 1987). In general, since most combined effects due to multiple mycotoxins are synergistic or additive, the exposure limits should be revised (Šegvić Klarić, 2012).

Table 4. Some reported co-occurring mycotoxins

<table>
<thead>
<tr>
<th>Reference</th>
<th>Co-occurring mycotoxins</th>
<th>Food matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kara et al., 2015</td>
<td>AFB1 + OTA</td>
<td>Maize flour</td>
</tr>
<tr>
<td>Kamala et al., 2015</td>
<td>Aflatoxins + Fumonisins Aflatoxins + OTA Aflatoxins + Fumonisins + OTA</td>
<td>Maize kernels</td>
</tr>
<tr>
<td>Alkadri et al., 2014</td>
<td>AFB2 + AFG2 Emerging mycotoxins (enniatins and beauvericin)</td>
<td>Wheat grains</td>
</tr>
<tr>
<td>Ibáñez-Vea et al., 2012</td>
<td>AFB1 + DON + OTA AFB1 + DON + OTA + Zearalenone</td>
<td>Barley</td>
</tr>
<tr>
<td>Kosicki et al., 2016</td>
<td>DON + Fumonisins</td>
<td>Maize, maize silage and complete feed</td>
</tr>
<tr>
<td>Kosicki et al., 2016</td>
<td>DON + HT-2 + T-2 + ZEA DON + HT-2 + T-2 ZEA + HT-2 + T-2 OTA + DON OTA + T-2 + HT-2</td>
<td>Complete feed samples for swine, poultry and cattle</td>
</tr>
</tbody>
</table>
MYCOTOXINS CONCURRENCE AND INTERACTIONS

Major problem of mycotoxins contaminated animal feed are not acute diseases but are metabolite disordersthat lead to low productivity of the animals (Bryden, 2012). This becomes more important when you face with cases that mold growth is not visually detectable but they can cause illness in animals. Meanwhile, considering that there are many sources for fungal infection and subsequent mycotoxins generation in the food and feed, so it is inevitable that prevention strategies in different stages of food chain should be integrated to intervene contamination (Jouany, 2007).

There are two major approaches to combat mycotoxins contamination in agricultural products including:

- Pre-harvest prevention which is the time that product is cultivated in the farm
- Post-harvest prevention which includes steps of harvesting, transportation, storage and consumption

Pre-Harvest Prevention

Logically, first step to control mold growth and mycotoxins contamination in the crops should be started in the Field; because contamination of crops before harvest may lead to more fungal growth during storage after harvest (Udomkun et al., 2016). There are several methods to avoid fungal growth in the farm as mentioned below.

Selection of the Breeds

Theoretically, the best approach to control mycotoxins concentration in feed and food ingredients is selection of the breeds which are resistance to fungal growth. It was reported that selection of varieties is linked to susceptibility of the silage to Penicillium and Aspergillus species and it is related to kernel wax composition difference.

Crop Rotation

Several Fusarium species can lead to Fusarium head blight disease (FHB) in wheat and Ear rot in Maize. These plant diseases leave mycotoxins in the crops which may cause significant health problems in humans and animals (Logrieco et al., 2002). Considering susceptibility of these crops to fungal diseases they should not be cultivated following each other. These grains should be rotated with crops like Potato, vegetables and dry beans to reduce inoculums of the molds in the field (Alberts et al., 2017). These are the crops naturally more resistance to mold infestation. Another resistant crops to mold infestation which are recommended for crop rotation are beans. Phenolic compounds in the beans are the reason that they are relatively resistant to mycotoxins contamination.

Tillage

Mold’s spores are spread by wind and then settled in soil and inoculated on derbies and plants residues left on the ground. Then wind or rain droplets can transfer molds conidiophores or ascospores and infect next year crops (Jouany, 2007). Deep ploughing berries derbies, weeds and residues of last year crops
under the soil. This takes away inoculums of the molds and breaks the chain of infection (Magan and Olsen, 2004).

**Soil Fertilizers**

Use of soil fertilizers helps growing vigorous crops which are resistant to contamination by fungi (Magan & Olsen, 2004). It also changes the structure and microbial activity of the soil which may affect mold incidence in the crops (Jouany, 2007). Fertilizers should be used based on soil tests to maintain soil pH and Nutrition in order to avoid plant stress (Alberts *et al.*, 2017).

**Pest Management**

Insect damage in maize can lead to mycotoxins contamination especially fumonisin, aflatoxin, DON and other mycotoxins (Miller *et al.*, 2014). There are two mechanisms that pest can cause plants infestation to molds. First, they remove natural barrier of the seeds and let mold penetrate to the seeds and get access to nutrients and second, they can carry fungal spores to the plants (Jouany, 2007). Pest management is through usage of pesticides, fungicides and integrated pest management practices (Alberts *et al.*, 2017). Usage of fungicides is recommended before sowing and in the field to prevent fungal contamination of maize. To control trichothecenes contamination, sufficient dose of fungicides should be applied because sub-lethal dosage of fungicides can increase mycotoxins concentration without visual fungal detection.

**Irrigation**

Irrigation is useful to prevent fungal contamination because water stress contributes to plant susceptibility to fungal growth. However, irrigation during anthesis period of corn is not recommended because it can lead to Fusarium contamination.

**Post-Harvest Prevention**

To protect grains after harvest especially during storage all the factors that are favorable for fungal growth should be controlled. These conditions include grain condition, environment condition, microbial interactions and use of antifungal (Binder, 2007).

**Crop Management**

Handling of the grains after harvest should be done in a manner to protect them against any damage because broke down grains are more susceptible to molding compared to intact commodities. Also, farm staffs should receive appropriate training to raise their awareness for hygienic handling of the feed ingredients. All the containers and instruments used for processing and storage of the feed should be clean, dry and free of insects, soil and molds (Alberts *et al.*, 2017). In addition, during storage of the grains after harvest they should be protected from water. Seeds also should not be contaminated with soil because fungal are natural inhabitant of the soil which can contaminate the crops, so they should always be laid on the platforms during storage in the farm. For corn silage preparation controlling anaerobic condition is important factor to prevent fungal contamination. Sealing of the silo, compactness
and unloading of the silos are important factors that control oxygen dispersal in to the silo. In this regard, dry matter content of the silage should be 350-450 g/kg for grass and 300-350 g/kg for corn to provide sufficient compaction in the silo. It was reported that in well preserved silos the ability of the molds for germination had been reduced after three months.

Drying of the Seeds

Moisture content of the seeds is very important to control fungal infestation after harvest, so it is important to make sure that the grains are fully ripened before harvest to reduce the fungal growth (Cardona et al., 2014). Also, moisture content of the crops should be evaluated immediately after harvest and in case it is necessary, crops should be dried to the recommended moisture content. For example, immediate drying of nuts to moisture content about 6% after harvest and cool storage of them can inhibit fungal growth (García-Moraleja et al., 2015; Atungulu et al., 2019). Meanwhile, rapid methods should be used for drying of the seeds to make sure that mold does not have time to infest on the crops. Sun drying of the crops in humid environment leads to mold infestation (Alberts et al., 2017). In this regard, several methods had been developed to dry crops after harvesting. High-temperature cross-flow and in bin natural air drying are two methods which are used in US for drying of rough rice. Because in natural air drying there is no control on the air temperature and moisture, so over drying and wetting of the seeds are common which can attribute to many quality and safety defects. To provide conditions for safe storage of the seeds managing equilibrium moisture content (EMC) by controlling relative humidity of the air inlet is recommended (Lawrence et al., 2015). To have better control on drying, new low heat in bin drying is introduced for being used in on farm drying systems. This technology restricts delivery of the air which is too wet or too dry. This system is equipped with sensors to control ambient air conditions, moisture content and temperature of the seeds in the whole bin mass and these data can be available through internet. This system is also equipped with advanced fan and heater control that can automatically adjust the EMC of the whole mass in the maximum and minimum rate which is required.

In the drying process of feed and pet food, traditional drying methods (e.g., hot-air convection heat transfer) cannot stand against their rival, the so-called infrared heating (IR), in terms of inactivation of mold spores and eventually mycotoxin development (Wilson et al., 2016). For most seeds used as feedstuffs (nut, rice, etc), advanced and novel drying technologies such as IR drying and microwave drying play an important role in controlling the dominant factors for fungal contamination growth such as moisture content and water activity (Dhib, 2007; Erbay and Icier, 2010; Sandu, 1986). The specific nature of chemical composition of different parts of feedstuffs (e.g., shell and kernel) allows different penetration depth of microwave radiation into them. The effect of infrared and microwave drying on reduction of mycotoxin in food and feed has been studied extensively and desired outputs have been achieved (Hamanaka et al., 2011; Moskovskiy, 2013; Pettersson and Åberg, 2003; Wang et al., 2014). One of the advantages of employing controlled dielectric microwave heating is its negligible effect on the product qualities including taste, color, and odor.

In a recent study on contaminated nut seeds by aflatoxin-producing fungal strains, the microwave heating return interesting results. By using this type of heating, 46.4% and 20% reduction of moisture content and water activity was reached for nut seeds, respectively. The microwave dielectric heating has showed impressive ability to reduce mycotoxin colonization by 61.67% and 81.75% inside the nut shell and its kernel, respectively (da Silva et al., 2016).
Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems

The novel IR heating technique followed by specific period of tempering process has shown a promising outcome in drying and disinfection of rice as a cereal grain. Both freshly harvested and stored rice can benefit from the IR heating in order to diminish their A. flavus contamination (Moskovskiy, 2013; Wang et al., 2014). The IR heating assisted moisture removal in a significant amount as well as high heating rates. For a sample of fresh rice with initial moisture content (IMC) of 27.0%, a maximum of 5.3% moisture removal level was gained after IR heating followed by two hours of tempering (Wang et al., 2014). The resulted A. flavus reduction for rough rice with the minimum and maximum IMCs treated with this heating and tempering procedure was 2.5 and 8.3-log reduction, respectively. To take advantage of IR heating, the dried storage rice could be rewetted to gain reasonable IMC (14.7 to 19.4%) since the rewetting eases disinfection process. The same IR heating process but with only one hour tempering helped the rewetted rice to lose 7.2-log reduction on the amount of A. flavus. Although fresh or rewetted rice grains with higher levels of IMCs need less tempering period, but at least 20 to 30 minutes of this process is needed. The recommended routine to disinfect and dry freshly harvested rice at once is; first the rice grains should be heated up to 60uC using IR heating technique, then the product needs to be tempered for two hours, and finally the rice temperature is declined by means of natural cooling. By following these steps, a final moisture content of 16.5 to 22.0% (based on IMC) was measured. The tempering step is shortened for rewetted rice depending on its initial moisture (Wang et al., 2014). The processed rice with lower moisture content is now safe to be stored. The rice samples investigated in Wang et al., (2014) are polished and therefore, are barely used as animal feed due to their high price in the market. The broken rice (broken during drying, transportation, or milling) is used as animal feed in some places and since it has a same chemical composition as polished rice, following the recommended IR heating and tempering procedures, is helpful in the safe storage and the mycotoxin disinfection purposes.

One of the most important animal feed grains is maize. The IR heating technique with intermittent heating durations dries the corn at higher rate with a more controlled process (Wilson et al, 2016). The microbial load on a corn sample with the initial moisture content of 24% and the final value of 13% was lessened from 4.79 ± 0.15 to 2.03 ± 1.2 log CFU/ g of corn. As expected, the IR drying left no change on the dried corn color (Wilson et al., 2016).

The IR heating technique is advantageous in sterilizing and reducing the growth of mycotoxin-producing microorganisms (Sorour, 2006). These microorganisms are naturally formed contaminating agents and their toxin is very detrimental to animals. The intensity of IR heating has a linear relationship with decontamination rate of these microorganisms. The rice samples with an initial 26% moisture content, an IR radiation intensity of 0.5 kW, and tube rotation speed of 2.5, 8, 25.5 and, 42 rpm revealed a drop of 1236.0, 1266.9, 1214.2, 1197.5 CFU/g compared to initial value, respectively. The decrease in microorganisms on wheat surface was observed 737.4, 552.2, 601.4, and 516.2 with the same IR heating intensity, initial moisture content, and corresponding tube rotation speed of 2.5, 8, 25.5 and, 42 rpm, respectively (Sorour, 2006).

Modified Atmosphere Packaging

The growth of fungi and mycotoxins production can be inhibited through packing in modified and controlled atmosphere. The effect of modified atmosphere packaging on A. flavus and aflatoxin production was evaluated. In this study, the effects and interaction of different abiotic factors including temperature,
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water activity and CO2 levels on A. flavus growth and aflatoxins production documented that with simultaneous increasing of the levels of CO2 and reduction of aw fungal growth has been reduced. Likewise, at lowest examined aw (0.92) and maximum CO2 (80%), the growth of A. flavus was entirely stopped (temperature 30ºC). Also, at a particular aw (0.92), more levels of aflatoxin were produced by A. flavus isolates at temperature 30ºC rather than 20ºC. Also, at a constant aw, aflatoxin production was reduced with elevated CO2 in headspace until it became not detectable at 80% CO2 (Mousa et al., 2016).

Use of Additives

There are several additives that can improve anaerobic condition in the silos. Organic acid and their salts (acetic, propionic, formic, benzoic, sorbic and citric acids) and inorganic acids (sulfuric and phosphoric acid, sodium bicarbonate, etc.) and their salts are different groups of these additives. Plant extracts and essential oils from onion, lemon, turmeric, mint, oregano, thyme, ginger, sea algae, etc. can control fungal growth and mycotoxins contamination. Citrus peel is an agricultural side product which can be used in this regard.

Natural and synthetic fungicides are very common chemicals used to control molding of the crops. Usage of antifungal is a way to control mold contamination of crops. Due to side effects related to chemical fungicides which lead to resistant strains development, natural fungicides are introduced to replace synthetic materials. But considering the rich flavor of these ingredients, they should be used in the materials which this flavor in them is acceptable by consumer or the natural flavor of the material will cover off flavor of it. Another option is to identify and use active components of these materials instead of whole extract. Finally, antimicrobial effect of each individual antifungal can be synergized using two compounds together or combine fungicide effect of one antifungal combined with stress factors like low moisture or pH.

Inoculants of lactic acid bacterial are other additives which can be used to prevent fungal infestation. Antifungal activity of four lactobacillus strains isolated from fish intestines was investigated. It was reported that these bacterial strains are able to reduce mycelia growth rate, sporulation, spore germination percentage and mycotoxins production. By using these strains 97-99% reduction in AFB1 and OTA concentrations was reported (Veras et al., 2016).

Ozone Treatment

Ozone (O3) application can also suppress mycotoxigenic fungal infestation in the grains but there are still some constraints to apply this method (Miller et al., 2014). Ozone substance depending on its concentration, time and utilized form can decrease conidia germination or alter hyphae morphology of the fungi. Ozone treatment in wheat grains was investigated to evaluate growth inhibition of A. flavus and P. citrinum. The overall results presented that the significant decreases of A. flavus and P. citrinum growth at levels of more than 80% and 60%, respectively. And the complete inhibition of both fungi growth was seen after exposure to 60μmol/mol O3 within 180 min. (Savi et al., 2015). Savi et al., (2014) also examined the application of O3 for F. graminearum and DON inhibition on whole wheat grains which were artificially contaminated. They presented that 74.5% and 91.8% reduction in viability of F. graminearum spores were seen at O3 concentrations of 40 and 60 μmol/mol after 30 min exposure with O3. This growth inhibition was completely occurred after 180 min in both concentrations. It also was recorded that DON level was generally reduced in wheat grains but this reduction in outer parts
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(pericarp) of grains was more than inner parts (endosperm). The application of gaseous O3 treatment was beneficial to overcome spore germination, growth of F. verticillioides in vitro and in situ used for maize grains. O3 agent was effective in germination reduction within first three days because after that again germination would be increased (Mylona et al., 2014).

DETOXIFICATION OF THE CROPS AFTER MOLD INFESTATION

Applying good farming practices are the best approach to control mycotoxicoses in livestock and poultry. However, considering the complexity of the activities in the farms it is not always possible to control feed contamination, so it would always be necessary to consider methods to detoxify feeds after they are contaminated (Grenier et al., 2013). Physical, chemical and biological strategies have been developed to eliminate, decrease or inactivate the bioavailability of mycotoxins contamination in food and feed in order to prevent negative impact of mycotoxins on human and animal health (Armando et al., 2012; Hernandez-Mendoza et al., 2009).

Physical Methods

Sorting and Cleaning

Mechanical or physical processes can reduce mycotoxins concentration in crops by removing dust, heavily mold infested grains, broken seeds, etc. Different equipment are available for this task which selection of the equipment is based on properties of the kernel (shape, size, density) and extent of contamination. For example, heavily Fusarium infested grains due to lower density compared to intact grains can be separated using gravity separators (Cheli et al., 2013). A novel patent technique based on gravity difference is developed using an apparatus which float grains in a tank which by vacuuming or over floating remove AF contaminated corn grains and reduce more than 80% AF concentration by removing less than 15% of the corn grain (Zhu et al., 2016). High speed optical sorting and mid infrared technology are another potential technologies that can be used for selection of infected kernels.

Milling and Shelling Processes

Different fractions of seeds have different contamination levels, so milling and shelling can be used to reduce concentration of mycotoxins. It was reported that shelling process reduced fumonisin B1 concentration up to 80% in the brown rice and milling process decreased total fumonisins concentration in white rice to undetectable levels (Abbas et al., 1998). Iqbal et al., (2012) have also found that different fractions of rice contained different aflatoxin contamination levels. They examined the level of total aflatoxins in paddy rice, parboiled rice, brown rice, white rice and broken rice using HPLC with fluorescence detector. The result showed that about 45% of all samples were positive to aflatoxin contamination with different amounts. But the mean of aflatoxin concentration was highest in paddy rice and lowest in white rice. The higher contamination in paddy rice is related to its hull and bran parts, because aflatoxin is more concentrated in outer layer of grain than kernel. So white rice in which husk, gram and bran are removed has very low levels of aflatoxin. Another processing technology which alters mycotoxins concentration is wet milling. Wet milling of ZEA contaminated corn can contribute two products with
different contamination. Starch which is toxin free and a byproduct used as animal feed which consist of Bran and germ which is concentrated in ZEA (Bennett and Anderson, 1978).

Heating

Though, mycotoxins are generally heat stable but it had been found that fumonisins found in corn and processed corn-based food products reduced at temperatures higher than 175°C that can happen in frying and extrusion cooking. In extrusion cooking, high heat and pressure are used together to generate a shear stress which can reduce mycotoxins such as ZEA and reduce its estrogenic activity. Extrusion processing is used extensively to cook and process cereal grains in the production of breakfast cereals, snack foods and pet foods. Extrusion processing combines high temperatures with high pressures and severe shear forces. These combinations of forces can act to destroy microorganisms, denature proteins and detoxify toxic substances (Jouany, 2007). Also small OTA reduction was reported following extrusion cooking (Magan and Olsen, 2004). It was reported that applying of super heat thermal process on contaminated wheat with DON was effective in reduction of concentration of DON. It showed that temperatures between 110-185°C could reduce the toxin, but higher temperature and longer heating duration was more effective for DON reduction. So that, heating at 185°C for 6 minutes reduced DON level up to 50% (Cenkowski et al., 2007). Microwave heating was applied to dry Brazil nut seed lead to 46.6% moisture content and 20% water activity reduction. Meanwhile fungal infestation reduced 61.67% inside and 81.75% on the kernel without any change in sensory attributes (Silva et al., 2016). Only small reduction of OTA level was reported after roasting of naturally contaminated or inoculated green coffee beans at 250°C for 15s (Turner et al., 2009). Mycotoxins level can be reduced in coffee cherries by quick drying. The patent claims that heating at 100 to 180 ◦F for 6 to 48 hours can reduce the water content (less than 20% wt), so the method reduces fungal growth and mycotoxins level. It was reported that the concentrations of aflatoxin, ochratoxin, fumonisin and DON were managed to the levels lower than 20 ppb, 5ppb, 5ppm and 5ppm, respectively (Zhu et al., 2016).

Irradiation

Detoxification of the solid food stuff using medium and long wave length ultraviolet A and B is a new method which has been used to reduce AFs in different crops (Zhu et al., 2016). The investigation on aflatoxin detoxification in foodstuff by irradiation of ultraviolet A and B (medium and long wavelength) was carried out. The result elucidated that this novel method removed nearly all aflatoxin from examined almonds within 60 s at 2000 lbs/h throughput. The advantage of this method is keeping the product unchanged in organoleptic properties (Zhu et al., 2016).In another study OTA contaminated animal feed samples were treated with UV light at 25 cm distance over the feed samples (0.1mWcm−2 at 254nmUV-C) and the same samples were also treated with sunlight. It was reported that seed samples containing 500 ppb ochratoxin were completely detoxified in 3 hours irradiation and 1 hour was enough to reduce ochratoxin level below EU maximum permissible limit for poultry feed (100 µg/kg). Meanwhile, in the sun treated samples after 8 hours ochratoxin reduced to 70-95 µg/kg (Ameer Sumbal et al., 2015).
Adsorption or binding agents are able to make complex with mycotoxins and prevent their adsorption to the blood and transferring to internal organs. Various types of adsorbents have been used to eliminate adverse effects of mycotoxins in contaminated feed on animals (Zhu et al., 2016). These binding agents can be inorganic (Clay mineral) or organic (microbial). Inorganic adsorbents are mainly phyllosilicates including smectite, hydrated sodium alluminisilicate (HSCAS) and especially bentonite and other minerals used are tectosilicates such as Zeolites or activated charcoal. It has been reported that some adsorbents such as activated carbons, zeolites and diatomaceous earth are capable to remove OTA in vitro (Armando et al., 2012). Another study was conducted in rat to investigate the ability of Calcium Montmorillite (Novasil,NS) to detoxify AFs in grains and showed that AFB1 urinary biomarkers reduced 20% after 24 hours and 50% after 48 hours (Robinson et al., 2012). Considering that usually animal feed is contaminated with more than one mycotoxin some other studies were carried out (Grenier et al., 2013). For instance, an in vivo study was conducted to compare bioavailability of aflatoxin and fumonisin individually and in combination using NS. In both scenarios mycotoxins bioavailability reduced but in combination less reduction was reported (Mitchell et al., 2014). In a dynamic in vitro gastrointestinal model study, results indicated that ZEA adsorption from contaminated wheat grains was reduced by using binding agents including activated carbon and cholestyramine (Avantaggiato et al., 2003). Some compounds are considered as mycotoxin adsorbents in digestive tract that inhibit mycotoxin adsorption through digestion. There are some investigated adsorbents such as hydrated sodium-calcium aluminosilicate that successfully adsorb AFB1 in feed and activated carbon for adsorption of patulin and OTA. Although several adsorbents are using in feed, the possibility of nutrients adsorption is a major drawback of these compounds (Bata, 1999).

Chemical Methods

Chemical treatments (bases, acids, oxidizing agents, aldehydes and bisulfite gases) detoxify mycotoxins through changing the bioavailability or structure of these toxins. Several chemical treatments (e.g. ammonia gas or ammonium hydroxide, 0.10% sodium hydroxide solution liquid, propionic acid solution bubbled with sulfur dioxide gas) have been utilized to change the structure of mycotoxins in order to convert them to substances with lower toxicity. These chemicals can make mycotoxins inactive and immobilized (Armando et al., 2012; Hernandez-Mendoza et al., 2009). As an example, ammonia, sodium and calcium hydroxide are chemical treatments that could destroy aflatoxins and significantly decrease the aflatoxin level in food and feed. The main issue in these treatments is destruction of nutritive substances (Armando et al., 2012). One patent approach for reducing mycotoxin is using beneficial additives such as glycerol-potentiating agents which are nontoxic, energetic supplement and strongly detoxify contaminated feedstuffs. The glycerol is potentiated by the combination of calcium hydroxide and hydroxyl ions (Zhu et al., 2016).

Oxidizing Agents

Oxidizing agents such as chlorine, Ozone and aqueous sodium bisulfate substances can also reduce mycotoxin levels in contaminated food and feed (Bata, 1999). Studies regarding binding chemistry, especially under harsh conditions of gastrointestinal tract, need to be investigated. Changes in pH and
the presence of bile, as important homoeostatic conditions that yeast cells encounter during passages through the GIT, are of particular interest (Armando et al., 2012) It should be noticed that chemical treatments have own disadvantages. Negative aspects of this method such as changing nutrient profiles and sensory quality as well as needed expensive equipment are not negligible. Another drawback resulted from chemical inhibitors such as fungicide is making molds and toxins resistant to destruction and the European Union (EU) has been restricted the use of chemical substances. Also nowadays people are seeking to use safe products without risks of pesticide (Armando et al., 2012; Bata, 1999; Hernandez-Mendoza et al., 2009; Piotrowska, 2014; Yang et al., 2016). Thus, establishment of new and relatively safe methods with broad usage such as biological measures using is crucial to manage toxigenic fungi during pre-harvest and post-harvest (Ponsone et al., 2012).

Additives

The leaf extracts from the Vasaka plant showed to be successful for degradation of AFB1. In fact, active components in the extract particularly alkaloids compounds degrade 69% and 80% of AFB1 after 6 and 12 h, respectively. And more than 98% degradation of AFB1 was seen after incubation for 24 hours at 37°C (Vijayanandraj et al., 2014). Also glucomannan extracted from yeast and antioxidant from yeast included to the diet of broiler chickens ameliorate mycotoxicosis in boiler chicken (Bortoluzzi et al., 2016).

Biological Methods

The biological decontamination has recently been emphasized due to using of new alternative safe methods as mycotoxin mitigation. Plant pathogens can be controlled by utilization of antagonist microorganism as a biological control (Yang et al., 2016). One advantage of biological removal of mycotoxins over chemical and physical detoxification is related to its less harmful effect on animal and human. It was reported that several microorganisms including bacteria (Lactobacillus acidophilus, L. plantarum, Acinetobacter calcoaceticus, Bifidobacterium animalis, and Oenococcus oeni), molds (A. niger, A. carbonarius, and A. fumigatus) and yeasts (Saccharomyces cerevisiae, Kloeckera apiculata, and Kluuyveromyces marxianus) can eliminate toxins from contaminated environments (Piotrowska, 2014). Mycotoxins can be decontaminated by binding to cell wall component of yeast. There is not sufficient information related to mycotoxins interaction with the cell wall. The presence of β-D-glucan in the yeast cell wall was correalted to remove mycotoxins such as zearalenone, AFB1, DON and OTA (Armando et al., 2012). One of advantageous yeast that can reduce bioavailability of mycotoxins is Saccharomyces cerevisiae because it is safe, probiotic and it has antimicrobial activity against some pathogenic bacteria (Armando et al., 2012). So considering them as feed additives could be beneficial since they are able to survive under gastrointestinal tract (GIT) conditions and improve animal performance by reducing the bioavailability of AFB1, ZEA and OTA at gut level. Another way that microorganisms can decontaminate mycotoxins is biodegradation (Armando et al., 2012). It is important to know that applying biocontrol method simultaneously with fungicides reducing their utilized levels in order to decrease fungal growth (Ponsone et al., 2012).
Bacteria Control

Lactic acid bacteria (LAB) and bifidobacteria are reported to have capability for reducing the bioavailability of aflatoxins through aflatoxins binding. These types of bacteria are of particular interest due to in large part to their GRAS status and their probiotic properties. The binding properties thought to be related to the bacterial cell wall (polysaccharides and peptidoglycan) as the site of aflatoxin binding. One of the most important factors for evaluating the ability of bacterial strains to reduce aflatoxins bioavailability in foods is the stability of the aflatoxin-bacterial cell complex; because if the complex is unstable and aflatoxin releases in gastric tract, the negative health impacts would be unavoidable. Some parameters including type of strains, conditions utilized during complex formation and the treatment used to assess stability are effective in the stability of aflatoxin-bacterial cell complex. Bacterial cells would be in exposure to environmental stresses such as pH and the presence of bile when they are passing through the gastrointestinal tract (GI). In fact, the property of binding the toxin by microorganisms is strain specific (Hernandez-Mendoza et al., 2009). The potential ability of eight strains of L. casei isolated from different environments (human, plant and dairy products) for binding the AFB1 in presence of bile salts was investigated. The stability of the AFB1 and bacteria complexes was evaluated as well. The result showed that all tested strains had to somewhat binding ability ranging from 14 to 49%. The highest binding amount of AFB1 was attributed to L. casei L30 strain. Also, as reported the isolated strains from human and cheese showed the most and least bound levels of AFB1, respectively. In addition, the result revealed that the L. casei L30 and AFB1 complex had a good stability during washing process. Furthermore, the evaluation of bile salt effect on the binding amount indicated that in higher concentration of bile salts, strains can hardly grow and would decrease the bound levels of AFB1 (Hernandez-Mendoza et al., 2009). Also, the Flavobacterium aurantiacum B-184 strain is able to detoxify aflatoxin in food and feed. The effective parameters in this process are pH, temperature and concentration of the bacterium cells. The mechanism involved in aflatoxin degradation by this bacterium is metabolism by living cells and the dead cells cannot metabolize aflatoxin (Bata, 1999). Lactic acid bacteria are of particular interest in reducing contamination due to their safe and beneficial properties on human health. Piotrowska investigated the ability of three LAB species on OTA decontamination. The live and dead cells from species L. plantarum, L. brevis and L. sanfranciscensis were used in MRS medium and PBS buffer environment at 1 and 5 mg/ml concentrations. All species reduced the initial content of OTA at different amount depending on the strain and biomass concentration. It was shown that higher concentration of bacteria (5 mg dw/ml) removed higher amount of OTA (20.53-35.01%). The reducing of OTA was less effective by L. brevis compared to two other species. L. plantarum and L. sanfranciscensis reduced the initial amount of OTA by 30 percent but L. brevis reduced 20.5 percent, it is related to inhibition of L. brevis by OTA. The tested live cells decrease the amount of OTA from 16.9% to 35% in MRS medium and 14.8% to 26.4% in PBS buffer. But dead cells decreased the amount of OTA in higher percentages (46.2% to 59.8%) (Piotrowska, 2014).

Yeast Control

Bio control using yeast is considered as most advantageous and potent approach because of its biological and nontoxic properties. One strategy to enhance the ability of yeasts to detoxify mycotoxins is providing some environmental conditions that can lead to optimal toxin degradation in both preharvest and post-harvest processes. The ability of several antagonist yeasts against development of OTA and
its producing mold have been investigated. The reduction of OTA using cultured yeast is proposed to happen with carboxypeptidases produced by most active species of yeast that convert OTA (OTA) to OTA-α with less toxic effect (Yang et al., 2016).

Yang et al., (2016) investigated the OTA removal using the yeast Yarrowia lipolytica. The effect of different conditions including temperature, pH, concentration of the yeast, and the initial concentration of OTA on the rate of degradation as well as assessment of toxicity of the OTA biodegradation products were further evaluated. Their experimental results revealed that Y. lipolytica has a strong potential to degrade OTA especially under conditions such as temperature at 28°C, pH of 4, high yeast concentration at 108 cfu/ml and the low initial concentration of OTA at 0.1 μg/ml. Therefore, it is a promising and safe OTA contamination control agent during pre- and post-harvest food processing operations. In addition, toxicity of OTA degradation products is significantly less than non-degraded OTA. Saccharomyces cerevisiae (S. cerevisiae) is also influential yeast for mycoroxin decontamination that usually binds AFB1, OTA and ZEA (Armando et al., 2012). S. cerevisiae was reported to be able to reduce bioavailability of several mycotoxins including AFB1, ZEA, OTA and fumonisin B1. Another benefit of yeast is that they also bind pathogenic microorganism and protect animal health. Yeasts are also source of protein and have probiotic effect. So they are the best binding agent available for detoxification of animal feed (Miller et al., 2014). Fuminosins removal by S. cerevisiae and lactobacillus acidophilus is physical adsorption and co-occurrence of AFB1 does not show any negative impact on removal of fumonisin B1 and vice versa (Pizzolitto et al., 2012).

Another evaluation was done regarding the potential ability of S. cerevisiae to bind OTA and ZEA at different tested concentrations. Also the effect of pH, bile and cell wall content on the binding efficiency was evaluated. The result revealed that all tested strains of S. cerevisiae were capable to bind OTA and ZEA. The percentages of mycotoxin binding were various among different strains of yeast and in different concentration of OTA and ZEA. This ability was higher when the mycotoxin concentration was low. In addition, the percentage of ZEA binding was enhanced for some strains of S. cerevisiae after exposure to simulated gastrointestinal tract. It was reported that acid pH (pH 2) and bile salts significantly increased the OTA and ZEA removal. Moreover, small cell wall content resulted to less mycotoxin removal (Armando et al., 2012).

Considering that organic and inorganic adsorbents are more effective to control aflatoxins, it is necessary to use other ways to ameliorate other mycotoxins in the feed. In this regard, best approach is to use microorganisms or their enzymes to convert mycotoxins to molecules which are not toxic (Grenier et al., 2012). This method is biotransformation which is based on exertion of byproduct or enzyme of microorganisms in the intestine of animals when are applied in animal feed. They can cause irreversible changes in the structure of mycotoxins molecules (Miller et al., 2014). Chemical method (alkali treatment) and microbial degradation through carboxylesterases would decrease the toxicity of FB1 via converting it to its hydrolyzed (Grenier et al., 2012). Another method is using bacteria or bacterial enzymes as feed additive in order to inhibit the intestinal adsorption of mycotoxins. In this regard, an In vivo study was conducted adding a feed additive consists of bacteria and bacterial enzyme to the diet of pigs which their feed was contaminated with DON and fumonisins. It was reported that usage of these additives could be suitable approach to control especially co-occurrence of DON and fumonisin B1 in feed (Grenier et al., 2013). It was reported that B. licheniformis CFR1 is able to reduce AFB1 concentration (94.7%) and is the best candidate for AFB1 biodetoxification (Rao et al., 2017).

The scope of usage for mycotoxins detoxifying microorganism is limited to particular mycotoxins but this is not the case of mycotoxins oxidative enzyme which can detoxify structurally different mycotoxins.
Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems

including AFB1, DON and OTA (Miller et al., 2014). It was reported that an oxidative enzyme produced by a fungal can convert AFB1 to a composition which is not toxic (Cao et al., 2011). The application of functional food as biocontrol method for mycotoxin detoxification in feedstuffs is interesting since they contain microorganisms that may bind mycotoxins in the gastrointestinal tract (GIT), so their absorption and then toxicity become reduced (Armando et al., 2012).

However the efficacy of biocontrol agents for decontamination depends on the cost of production and interactions with other chemical materials such as fungicides. One of the most effective ways for broad application of biological agents for mycotoxin detoxification is their utilization along with natural fungicides (Ponsone et al., 2012).

REFERENCES


Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems


Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems


Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems


Dearborn, D., Yike, I., Sorenson, W., Miller, M., & Etzel, R. (1999). Overview of investigations into pulmonary hemorrhage among infants in Cleveland, Ohio. Environmental Health Perspectives, 107(suppl 3), 495–499. doi:10.1289/ehp.99107s3495 PMID:10346998

Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems


Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems


Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems


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Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems


Reference on Mycotoxins Occurrence, Prevalence, and Risk Assessment in Food Systems


ADDITIONAL READING


Compilation of References


Compilation of References


AHDB. (2011). Resource use in the British beef and lamb processing sector. AHDB.


Compilation of References


Compilation of References


Compilation of References


Blahovec, J., Kourim, P., & Kindl, M. (2015). Low temperature carrot cooking supported by pulsed electric field-DMA and DETA thermal analysis. Food and Bioprocess Technology, 8(10), 2027–2035.
Compilation of References


352
Compilation of References


Compilation of References


Compilations of References


Compilation of References


Compilation of References


Compilation of References


Compilation of References


Compilation of References


FAO. (2012). Meat and health - Meat consumption role of meat in the diets. FAO.


Compilation of References


Compilation of References

Fricke, B., & Becker, B. (2010). Energy use of doored and open vertical refrigerated display cases. Paper presented at the International Refrigeration and Air Conditioning Conference, Purdue University.


Compilation of References


Compilation of References


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Compilation of References
Compilation of References


Compilation of References


Compilation of References


Compilation of References


Compilation of References


Compilation of References


Keklik, N. M., Krishnamurthy, K., & Demirci, A. (2012). Microbial decontamination of food by ultraviolet (UV) and pulsed UV light. In A. Demirci & M. O. Ngadi (Eds.), *Microbial Decontamination in the Food Industry* (pp. 344–369). Elsevier. doi:10.1533/9780857095756.2.344


Compilation of References


Compilation of References


Compilation of References


Compilation of References


Compilation of References


Compilation of References


Compilation of References


Compilation of References


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of harmful grain molds and mycotoxin, study of kinetics of grain quality degradation and mycotoxin development during drying, handling and storage, mathematical modeling and optimization of classical and novel grain drying and storage systems, and engineering methods for improving better utilization of byproducts from grain processing.

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