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Thermal Management of Short-Range Distribution of Perishable Food Products Using Phase Change Materials in Packaging: Real-Time Field Data Acquisition

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Abstract: Maintaining a stable temperature is critical in ensuring the longevity of perishable foods, and frequent fluctuations due to short-range distribution conditions can negatively affect this stability. To mitigate these variations, an innovative modular packaging system utilizing phase change materials (PCMs) was employed in the transport and storage of horticultural products. This study's real-time thermal condition data, collected using a wireless data acquisition system inserted in the packaging, demonstrated the efficacy of PCM in increasing temperature stability within the crates of horticultural products. The field tests conducted over 8 h showed that PCM-equipped packaging boxes exhibited a temperature variation of less than 1 °C, compared to non-PCM boxes, which saw variations up to 3 °C. This marked reduction in temperature fluctuation signifies the potential of PCM in improving thermal and logistics management in food conservation, thus reducing food waste. However, it is essential to implement a system for PCM alveoli reuse to avoid adverse environmental impacts. Future research should focus on the PCM alveoli autonomy and quantity requirements for specific conditions, and integrate sensors to monitor transport dynamics to enhance the understanding of temperature stability in perishable food transportation.

Keywords: phase change materials; PCM; passive temperature control; temperature fluctuation; perishable food products; food preservation

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1. Introduction

Addressing the escalating food demands of an increasing global population is a challenge of unparalleled importance. As per the Food and Agriculture Organization [1], the world's population is projected to hit 9.7 billion by 2050. Consequently, the need for a sustainable and secure food supply is more critical than ever. Regrettably, nearly a third of the food produced worldwide for human consumption, approximately 1.3 billion tons annually, is wasted [2]. These wastage levels lead to serious financial and environmental repercussions. They contribute to climate change through notable greenhouse gas emissions during food production and distribution. Additionally, the decay of food loss and waste releases methane, further worsening the situation [3–9]. Beyond these environmental implications, food wastage undermines food security, as it signifies inefficient use of resources dedicated to food production. Therefore, a reduction in food waste is a vital goal in our pursuit of a sustainable and equitable food system [10].

Refrigeration is fundamental for food preservation. It reduces the growth of microorganisms and enzymes, lengthening the shelf life of perishable products, ultimately reducing food waste and sustaining food safety [11]. Thus, efficient storage and transportation of food at regulated temperatures are key in minimizing food losses and promoting food security [10].

Prior studies indicate that temperature fluctuations during food transportation [8] and storage [12–14] can be detrimental to food quality and shelf life. These fluctuations, caused by a host of factors, including ambient temperature changes, subpar refrigeration, and operational procedures, such as door openings, need to be controlled effectively to maintain food quality. Despite some of these factors being unavoidable, our research proposes a means to minimize their impact on temperature stability.

Thermal energy storage is primarily categorized into Sensible Heat Storage (SHS), Latent Heat Storage (LHS), and Thermochemical Storage. While SHS is the most basic form of energy storage, relying on the material's specific heat capacity and density, it offers limited energy storage. LHS, conversely, leverages phase transitions (solid to liquid, liquid to gas, and solid to solid) for energy storage, resulting in a higher storage density at specific temperatures. This is where phase change materials (PCMs) come into play. Thermochemical storage, although having the highest energy storage capacity, grapples with long-term stability issues in controlled environments and has a complex and costly development process [15].

PCMs have garnered considerable attention in the field of refrigeration systems, particularly in the realm of preserving temperature stability [16,17]. This interest is primarily owed to their remarkable latent heat capacity, which can be leveraged to maintain consistent temperatures and, hence, enhance the preservation of food during transportation [18]. The potential of PCMs in curbing food waste and securing food quality has been rigorously studied and is increasingly acknowledged as a promising solution [19].

As shown in Figure 1, PCMs can be broadly segregated into two main types: solid–solid and solid–liquid, each exhibiting distinct thermodynamic properties. The former includes materials such as polymers and polyalcohols, which undergo a phase transition between different solid states. While this type of PCM has its applications, the solid–liquid class is most frequently employed due to its significantly higher latent heat of fusion. This facilitates greater energy storage and release during the phase transition process [15].

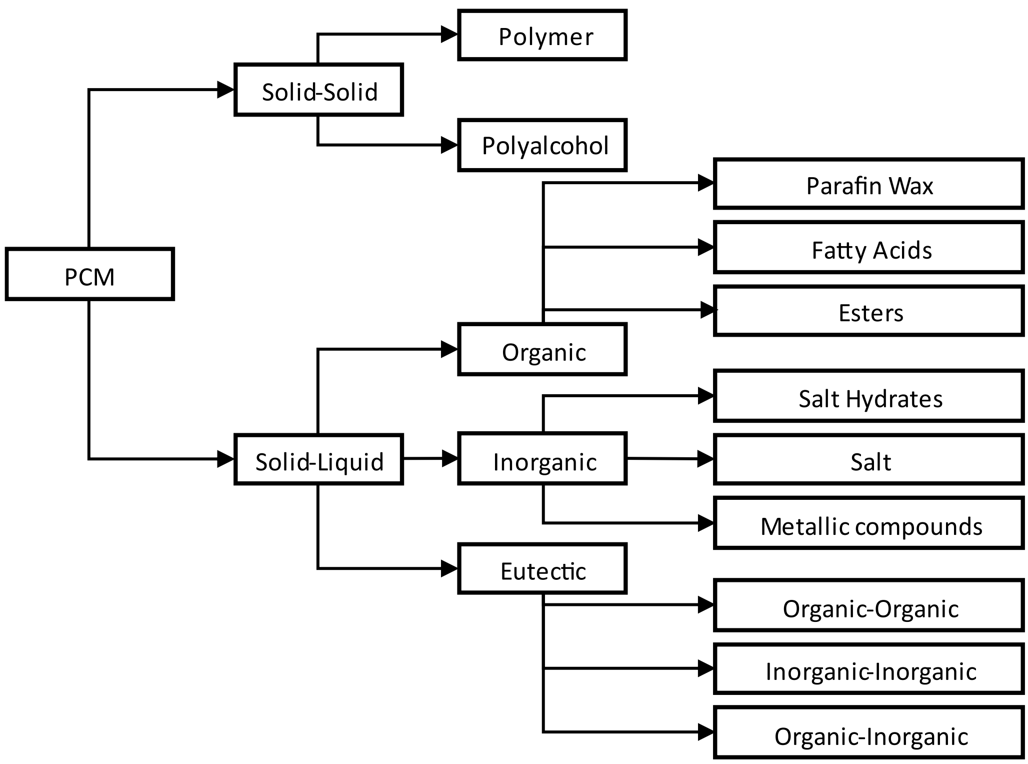


Figure 1. Schematic representation of PCM categorization, adapted from [15].

Solid–liquid PCMs can be further bifurcated into organic, inorganic, and eutectic categories, each with unique characteristics and applications [20,21]. Organic PCMs encompass substances such as paraffin waxes, fatty acids, and esters. Inorganic PCMs, on the other hand, primarily include salt hydrates, salts, and metallic compounds. Lastly, eutectic PCMs are mixtures that form a unique composition that melts and solidifies at a single temperature and can be comprised of organic–organic, inorganic–inorganic, or organic–inorganic combinations. This diversification of PCM categories allows for a wide range of potential applications, tailoring their usage according to the specific thermal management requirements. Several studies have explored the thermal performance of various fruit packaging crates [22–26]. Studies also analyzed the utility of PCM pouches for active and intelligent packaging [27,28], and the measurement of temperatures and relative humidity during the transportation of horticultural goods [8].

In [28], the authors deployed a transient three-dimensional computational fluid dynamics model to examine the application of PCM in packaging alveoli for fruit storage. This study showed that such alveoli can effectively slow the heating rate of fruits when exposed to non-ideal temperatures. The PCM, acting as a "thermal buffer", was found to increase the shelf life of the produce by maintaining optimal temperatures over extended periods.

Meanwhile, reference [24] provides experimental evidence of the thermal response of two types of food alveoli, comparing their performance with and without the integration of PCM. The authors demonstrated that aluminum foil alveoli, in conjunction with PCM, delayed the heating process effectively. These findings imply that PCM could be a promising solution for the preservation of cold storage food products in packaging.

In [29], researchers undertook an in-depth investigation of the use of PCM panels in a freezer subjected to repeated power loss over a 2-week period. The findings revealed that freezers equipped with PCM panels helped to maintain product temperatures closer to the optimal range, even during power loss incidents, leading to minimal impacts on food quality. This research not only underscores the potential of PCM to enhance the preservation of frozen food during power outages, but also evidences the potential for PCM to enhance overall food quality in regular storage conditions.

These studies underline the potential advantages of integrating PCM into food packaging for the preservation of perishable goods, making it a topic worth further exploration in real-world conditions.

This study aims to apply insights from previous works to real-world situations, evaluating the effectiveness of PCM in maintaining temperature stability for horticultural products during transportation. The transition from controlled environments to real-life scenarios is crucial, as it tests novel technologies under practical conditions, revealing challenges otherwise unseen. Specifically, for PCM, studying its performance in real-world transportation provides evidence of its efficiency, fostering its broader adoption in food preservation and helping mitigate food waste.

2. Materials and Methods

The study was conducted in the context of a distribution route originating from ALBIFRUTAS, a company located in Castelo Branco, Portugal. The focus was to evaluate the impact of PCM on maintaining temperature stability during the transportation of horticultural products. The experimental setup involved crates of oranges, wherein half of the crates were equipped with PCM-filled alveoli, and the rest were loaded with empty alveoli, serving as controls.

2.1. PCM Alveoli and Crates

The crates used for the study boasted an innovative design with enhanced thermal attributes, enabling improved temperature stability. Their modularity facilitated efficient transportation, storage, and public sale display [22–26]. Fabricated from polypropylene, each crate measured 600 mm in width, 400 mm in depth, and 90 mm in height. Figure 2 provides a visual representation of the crates: Figure 2a illustrates an assembled empty crate; Figure 2b shows the crate equipped with PCM alveoli; Figure 2c displays the crate with PCM alveoli and an attached lid.

(**a**) (**b**) (**c**)

Figure 2. Crate (**a**), with PCM alveoli (**b**), and lid (**c**).

The main novelty of these crates consists of the PCM alveoli, depicted in white in Figure 2b, comprising a polypropylene macro-encapsulation of the RT5HC PCM. The RT5HC PCM is an organic material, recognized for its high latent heat capacity and tight temperature range, making it ideal for enhancing temperature stability during horticultural goods' transportation. The key properties of the RT5HC PCM are presented in Table 1.

Table 1. Properties of the RT5HC PCM [30].

Property	Value
Melting temperature amplitude [°C]	5 to 6
Congealing temperature amplitude [°C]	6 to 5
Heat storage capacity ±7.5% [kJ/kg]	250
Latent and sensible heat in a temperature range of −2 °C to 13 °C [Wh/kg]	70
Density solid [kg/L]	0.88
Density liquid [kg/L]	0.76
Heat conductivity (both phases) [W/(m·K)]	0.2
Volume expansion [%]	13
Flash point [°C]	115
Max. operation temperature [°C]	30

As shown in Figure 3, the PCM alveoli were sized to fit the crate's bottom, enhancing temperature stability during the transportation of horticultural goods. In this experiment, half the crates included alveoli filled with the RT5HC PCM, while the remaining crates held empty alveoli for control comparison.

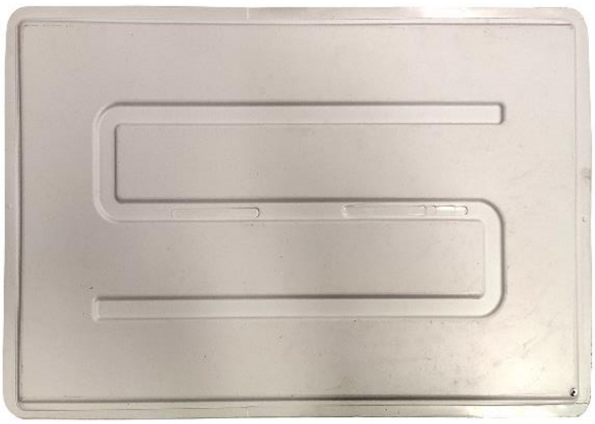


Figure 3. PCM alveoli.

2.2. Cargo Distribution Characterization

The investigation involved monitoring crates filled with oranges, as depicted in Figure 4. The crates, having been stored at approximately 5 °C overnight, were transported to the ALBIFRUTAS warehouse. Here, they were placed among the cargo prepared for real-time distribution.

Figure 4. Crate outfitted with PCM alveoli, loaded with oranges, and equipped with sensors for data acquisition.

As illustrated in Figure 5, the crates were strategically positioned on the van's floor, adjacent to the right wall and near the rear door. Each of the two sets of crates, one with PCM and the other serving as a control without PCM, were equally loaded with 48 oranges.

Figure 5. Placement of the experimental and control crates within the overall cargo configuration.

The cargo comprised a variety of horticultural products—fruits and vegetables—destined for a range of establishments, such as restaurants, hotels, and local grocery stores. Figure 6 provides a visual representation of the diverse cargo arrangement. Notably, the cargo was grouped based on client orders rather than produce type.

Figure 6. Overall arrangement of the diverse horticultural produce within the van's cargo area.

2.3. Distribution Vehicle and Refrigeration System

Examining the impact of common routines, such as the opening of doors for unloading and the effect of sun exposure during transportation, is crucial for understanding the temperature behavior within the crates. Thus, data can be gathered for the field performance of the PCM alveoli. This information is fundamental in assessing the packaging's effectiveness in maintaining temperature stability, thus preserving the quality of the produce during transportation and storage.

Data were gathered during a delivery run conducted by an IVECO Daily van, shown in Figure 7, which belongs to the ALBIFRUTAS distribution company. The van was tasked with the delivery of a wide variety of horticultural products to multiple establishments, including restaurants and local grocery stores.

Figure 7. An IVECO Daily van from the ALBIFRUTAS fleet.

The vehicles are equipped with a Hwasung HT-250RT-ESC refrigeration system. However, as the measurements were conducted during the winter, the refrigeration system was turned off. To minimize thermal losses and enhance temperature control under varying external conditions, the vans are also fitted with insulation.

The delivery of the produce took place between 8:00 h and 14:05 h. The route, illustrated in Figure 8, traversed the northwestern region of Castelo Branco, Portugal.

Along this route, there were six stops, during which the doors were opened for unloading cargo. This routine resulted in temperature fluctuations, as observed in the Section 3. The weather in Castelo Branco during this period was sunny with no cloud cover, with temperatures ranging from 1 °C (around 8:00 h) to 10 °C (around 14:00 h). The sun exposure, coupled with the refrigeration system being turned off, created ideal conditions for testing the potential of PCM as a solution to mitigate the impacts of unforeseen conditions that are typical in real-world scenarios.

Figure 8. Delivery run route.

2.4. Data Acquisition System and Final Test Assembly

The primary goal of this study is to emphasize the role of PCM in maintaining temperature stability during transportation. To track temperature changes and systematically interpret the collected data, a data measurement and transmission system was established. The study will compare temperature fluctuations in crates with and without PCM, thereby demonstrating the effectiveness of PCM in maintaining temperature stability.

2.4.1. Sensing Modules

The study measures the temperature and relative humidity around different horticultural products during their transportation journey. Other approaches for agricultural and agrifood parameters monitoring were followed in the past [31]. For this purpose, a SHT30 sensor, shown in Figure 9a, capable of reading the air temperature with a precision of ±0.3 °C, is utilized. The sensor is connected to a LOLIN D1 mini pro V2.0 microcontroller, shown in Figure 9b, through a LOLIN SHT30 v2.1.0 shield. The system is powered by a 3.7 V 500 mAh lithium battery, as shown in Figure 9c. This setup is assembled as shown in Figure 9d and housed in a 3D-printed protective box showcased in Figure 9e. The sensor box is designed with numerous perforations, ensuring adequate ventilation. This feature facilitates a direct interaction between the sensors and the ambient air, thereby enabling precise and accurate measurement of the atmospheric conditions. More details can be found in [32].

The sensors are numbered from 1 to 20 to ensure easy identification, as shown in Figure 10. Alongside this, the sensors are also labeled with a smaller number. That is the sensor reference used in the data communication system.

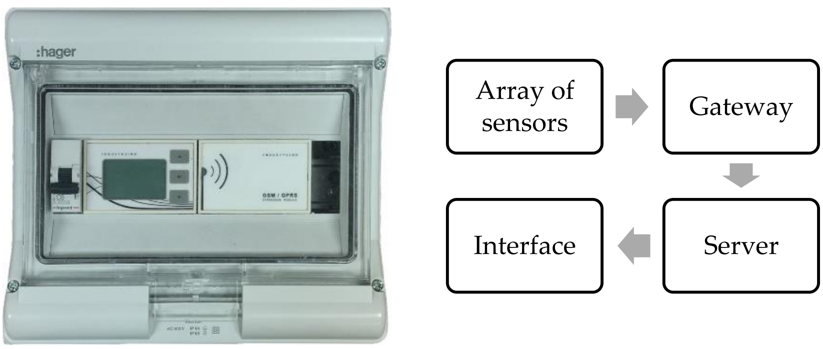
(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 9. Sensing Module Components: Temperature and humidity sensor (**a**), microcontroller (**b**), battery (**c**), assembled sensing module (**d**), and sensing module box (**e**).

Figure 10. Sensor placement among produce.

2.4.2. Data Communication System

The sensing modules are connected to a gateway, shown in Figure 11a. This gateway includes an Industruino microcontroller and a GSM/GPRS module, enabling real-time data transmission with GPS location tracking. The readings are collected and transmitted every five minutes and can be accessed live through the iTrack platform, specifically designed for this purpose. The overall system schematics are illustrated in Figure 11b.



(**a**) (**b**)

Figure 11. (**a**) Gateway module and (**b**) System diagram.

2.4.3. Temperature Monitoring and Data Communication System

The sensing modules' proximity to the horticultural products ensures accurate temperature readings, providing a more precise representation of the conditions during the distribution journey. For a clearer understanding of the results, Figure 12 illustrates the testing setup and the positioning of crates and sensing modules during the experiments.

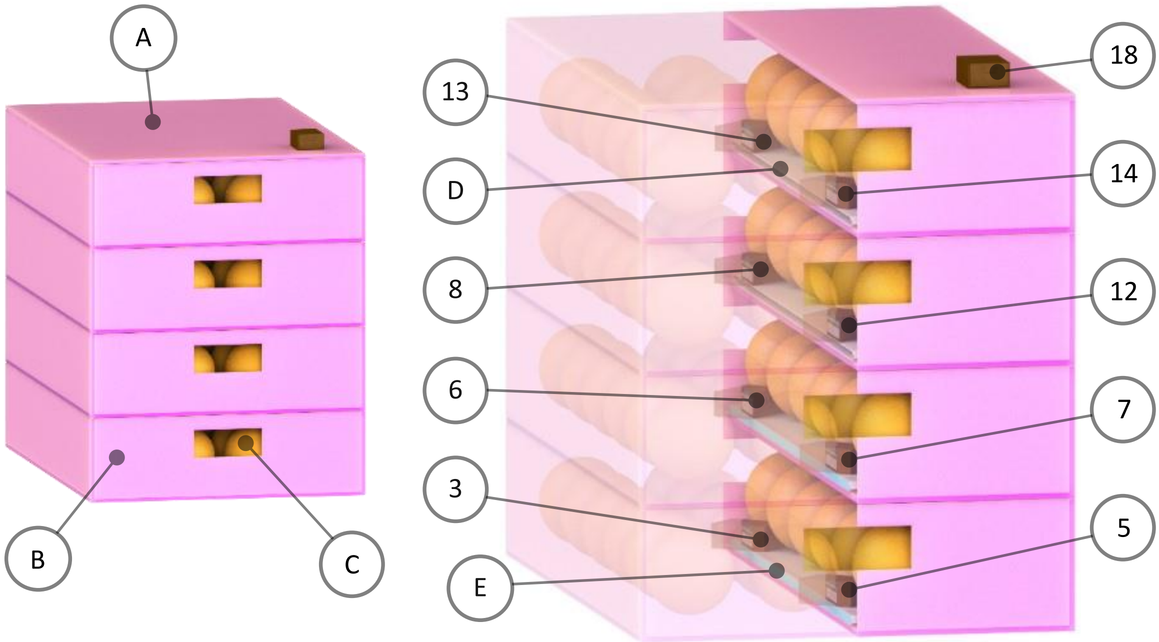


Figure 12. Arrangement of the crates, sensing modules, alveoli, and horticultural products as explained in Table 2.

Table 2. Elements of the testing arrangement.

Component	Description
A	Crate lid
B	Crate
C	Orange
D	Empty alveoli
E	PCM alveoli
3, 5, 6, 7, 8, 12, 13, 14, 18	Sensing module

The components displayed in Figure 12 are detailed in Table 2. The sensor reference number corresponds to the sensor ID in the iTrack platform.

Sensor positions within the crate are outlined in Table 3.

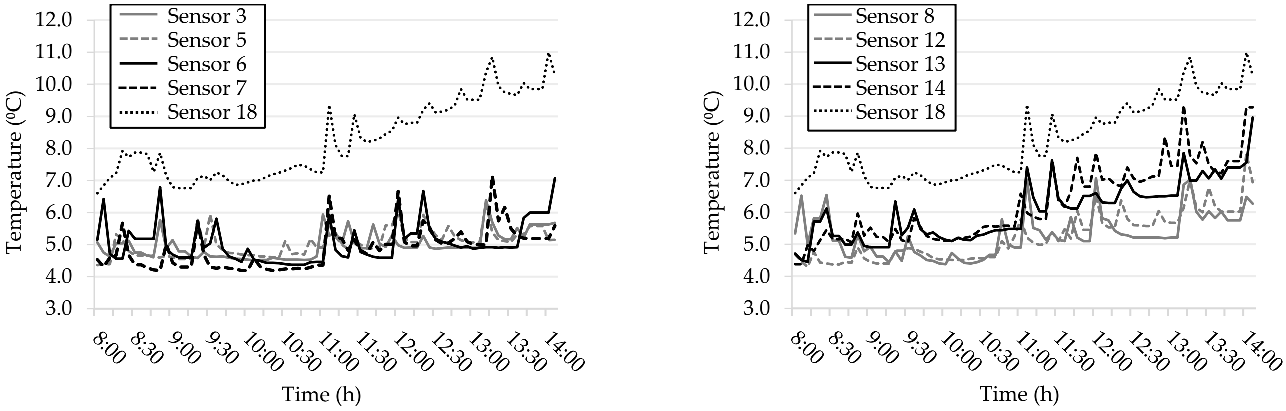
Table 3. Sensor position within the crates.

	Rear Side	Front Side
Crates with PCM alveoli	3 6	5 7
Crates with empty alveoli	8 13	12 14
Ambient temperature (cargo area)		18

The sensor placement within the crates is vital for results analysis since the rear sensors are more exposed when the rear doors are open. Furthermore, sensors near PCM alveoli or empty alveoli are expected to have different temperature readings. The comparison of ambient temperature with the measurements within the crates underscores the importance of monitoring temperature within produce crates for precise monitoring of food decay. The lid on the top crate aids in ensuring a more uniform temperature is measured across the column of crates.

3. Results

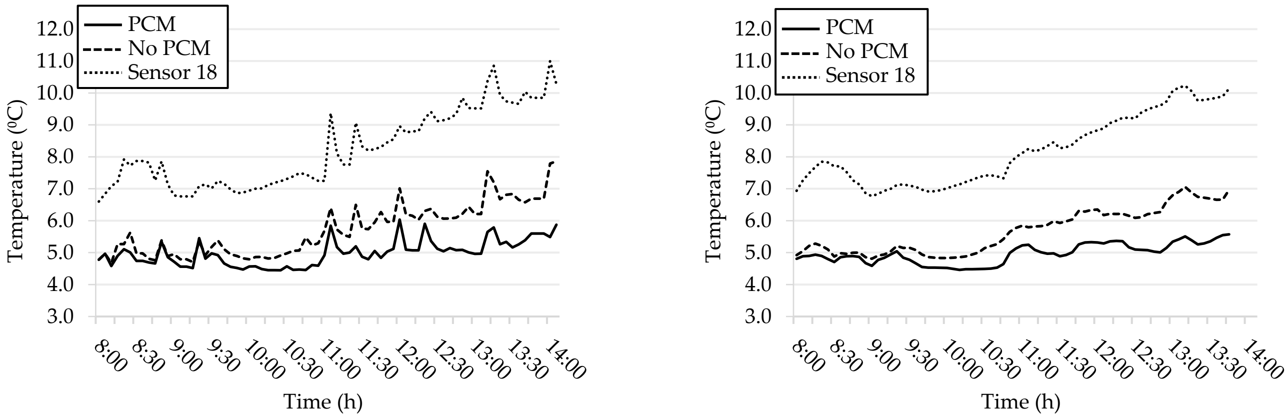
Crates equipped with PCM alveoli were observed to maintain more consistent temperatures during transportation than those without. Temperature spikes were noted during unloading events. Figure 13a,b compare temperature measurements between crates with PCM alveoli and those with empty alveoli. The graphs demonstrate temperature stability in crates equipped with PCM alveoli during transportation.



(**a**) (**b**)

Figure 13. Temperature readings in crates containing alveoli with (**a**) and without (**b**) PCM.

To analyze the stability of temperatures between crates with PCM and empty alveoli, the averages of all temperature readings in the PCM alveoli and empty alveoli were plotted. A four-measurement simple moving average was applied to mitigate the visual impact of temperature spikes during unloading, allowing for an easier overall visual comparison. Figure 14a,b display the average temperature and four-measurement moving average comparisons for both types of alveoli.



(**a**) (**b**)

Figure 14. Comparison of average temperatures (**a**) and four-measurement moving average temperatures (**b**) for the van cargo area, in crates with alveoli containing PCM and empty alveoli.

4. Discussion

The results clearly demonstrate that the application of PCM alveoli in crates significantly enhances temperature stability during transportation. In Figure 14a, there is a noticeable difference of approximately 2 °C by the journey's end, marking a considerable deviation. Furthermore, the 4-measurement moving average of the temperatures shown in Figure 14b indicates that the temperature of the produce in crates with PCM alveoli remains mostly within the melting temperature range of the selected PCM (5 °C to 6 °C).

This implies that the phase change process within the alveoli was not finished by the end of the journey. It is important to consider that the temperature spikes caused by the stops move the four-measurement moving average temperatures.

In contrast, there is considerable variation among crates with empty alveoli, as depicted in Figure 13b. However, Figure 13a highlights a relative uniformity among the temperature measurements within the crates containing PCM alveoli, when the temperature fluctuations caused by the door openings during unloads are not considered. This uniformity suggests that PCM's thermal buffering capacity significantly contributes to temperature stability within the crates.

Of note, while the peak amplitudes during unloads are similar for crates with and without PCM, there is a distinct difference in temperature recovery post-unloading. Crates with PCM tend to return to temperatures near 5 °C after each stop, whereas those without PCM show a significant increase in temperature. This observation underscores the effectiveness of PCM in limiting temperature fluctuations, particularly in scenarios where external conditions may introduce thermal stress, such as during unloading.

This study, in line with previous research, supports the necessity of temperature monitoring directly among the food products, as opposed to single-point measurements, such as sensor 18. The results highlight that temperature readings of the cargo area alone are inadequate for accurately representing the conditions experienced by the perishable food products within the crates. Therefore, direct measurement within the crates is crucial for effective monitoring of food storage quality during transportation.

5. Conclusions

The results from this study clearly highlight the efficacy of utilizing PCM in ensuring temperature stability during the transportation of horticultural products. Comparisons between average temperature readings in crates equipped with PCM alveoli and those with empty alveoli underscore the significant benefits of using PCM in maintaining consistent adequate temperatures. As a result, the incorporation of PCM alveoli can significantly improve the quality of food storage, leading to a reduction in food loss and waste.

This research emphasizes the advantages of PCM integration in maintaining temperature stability within the transportation crates. The data suggest that the widespread implementation of PCM across all transported crates could enhance overall temperature control within the cargo area, mitigating temperature spikes caused by door openings and achieving faster temperature stabilization post-unloading. Nonetheless, additional research is necessary to substantiate these findings and to fully explore the potential of PCM in large-scale applications for improved temperature control in produce transportation and storage.

However, the benefits of using PCM come with certain caveats. The use of PCM alveoli in a reusable manner is a significant point to address. The environmental impact of discarding used PCM alveoli can potentially outweigh the benefits of increased preservation if a system for collecting and reusing them is not implemented. These alveoli could follow the same reuse cycle that reusable horticultural crates follow.

Future research should aim to determine the autonomy of the PCM alveoli and investigate the required quantity of PCM for specific produce types, distribution routes, and climatic conditions. Increased frequency of temperature readings, while reducing sensor battery life, could offer more detailed insights into temperature fluctuations, particularly during unloading events. This will necessitate a careful balance between sensor battery life and the accuracy of temperature readings, potentially utilizing a dynamic measuring rate in correlation with van movement and cargo area luminosity.

To this effect, integrating an accelerometer and a light sensor could provide valuable data on van movement and door opening events, respectively. Correlating these occurrences with temperature fluctuations could yield a more comprehensive understanding of how transportation events impact temperature stability.

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