



Test and evaluation of a self-regulating low-energy clay tube irrigation system, *SLECI*, in Cova da Beira orchards

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Dedicatória

Ao meu avô, António José Almeida Cordeiro Frazão.

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Resumo

Os desafios crescentes da escassez de água e a necessidade urgente de práticas agrícolas sustentáveis em climas mediterrânicos impulsionaram a exploração e a adoção de tecnologias de irrigação inovadoras. Esta dissertação apresenta um estudo detalhado sobre o teste e avaliação de um sistema de irrigação baseado em argila, autorregulado e de baixo consumo energético (SLECI) em pomares de Cova da Beira, uma região caracterizada pelo seu clima mediterrânico e atividade agrícola significativa. A tecnologia SLECI, inspirada em métodos de irrigação ancestrais e princípios de engenharia moderna, visa oferecer uma solução sustentável para questões preocupantes no que toca a eficiência na utilização de água e conservação da biodiversidade na agricultura.

Esta pesquisa envolve uma análise abrangente de vários sistemas de irrigação, incluindo métodos tradicionais e modernos, com foco na sua aplicabilidade, eficiência e sustentabilidade em ambientes mediterrânicos. O projeto, implementação e desempenho dos SLECI foram avaliados criticamente através de testes de campo em culturas de cereja e pêssago, comparando a sua eficácia com sistemas convencionais de irrigação por gotejamento de superfície (SDIs). O estudo documenta a configuração, os componentes técnicos e as metodologias de monitorização empregadas para avaliar a eficiência do uso da água, o impacto do rendimento e a resposta do SLECI a condições climáticas variáveis.

Os resultados experimentais demonstram o desempenho superior do SLECI em termos de economia de água e adaptabilidade às mudanças climáticas, destacando o seu potencial para contribuir significativamente para práticas agrícolas mais sustentáveis. A capacidade de autorregulação do sistema, o baixo consumo de energia e a manutenção mínima sublinham a sua adequação para pomares mediterrânicos, oferecendo uma alternativa promissora a métodos de irrigação mais intensivos no que toca ao consumo de recursos.

Este estudo contribui com insights valiosos para o desenvolvimento e aplicação de tecnologias de irrigação sustentáveis, enfatizando a importância de integrar o conhecimento tradicional com engenharia moderna para enfrentar os desafios da escassez de água e da sustentabilidade agrícola. Os resultados sublinham o potencial dos SLECI para revolucionar as práticas de irrigação em climas mediterrânicos, pavimentando o caminho para uma maior adoção e investigação adicional em agricultura sustentável.

Palavras-chave

SLECI; SDI; Irrigação sustentável; Escassez de água; Water Use Efficiency;
Agricultura Mediterrânea

Abstract

The escalating challenges of water scarcity and the urgent need for sustainable agricultural practices in Mediterranean climates have driven the exploration and adoption of innovative irrigation technologies. This dissertation presents a detailed study on the test and evaluation of a self-regulating low energy Clay tube irrigation system (SLECI) in the orchards of Cova da Beira, a region characterized by its Mediterranean climate and significant agricultural activity. The SLECI's technology, inspired by ancient irrigation methods and modern engineering principles, aims to offer a sustainable solution to the pressing issues of water efficiency and biodiversity conservation in agriculture.

This research encompasses a comprehensive analysis of various irrigation systems, including traditional and modern methods, with a focus on their applicability, efficiency, and sustainability in Mediterranean environments. The SLECI's design, implementation, and performance were critically evaluated through field tests on cherry and peach trees, comparing their effectiveness with conventional surface drip irrigation systems (SDIs). The study documents the setup, technical components, and monitoring methodologies employed to assess the SLECI's water use efficiency, yield impact, and response to varying climatic conditions.

Experimental results demonstrate the SLECI's superior performance in terms of water savings and adaptability to environmental changes, highlighting its potential to significantly contribute to sustainable agricultural practices. The system's self-regulating capability, low energy requirement, and minimal maintenance underline its suitability for Mediterranean orchards, offering a promising alternative to more resource-intensive irrigation methods.

This study contributes valuable insights into the development and application of sustainable irrigation technologies, emphasizing the importance of integrating traditional knowledge with modern engineering to address the challenges of water scarcity and agricultural sustainability. The findings underscore the potential of the SLECI to revolutionize irrigation practices in Mediterranean climates, paving the way for broader adoption and further research in sustainable agriculture.

Keywords

SLECI; SDIs; Sustainable Irrigation; Water Scarcity; Water Use Efficiency;
Mediterranean Agriculture

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Nomenclature

General symbols:

| | |
|---------------------------|------------------------------|
| $2Na_2CO_3 \cdot 3H_2O_2$ | Sodium Percarbonate |
| a_u | Wind function coefficient |
| b_u | Wind function coefficient |
| $CO_2 + NaCN$ | Sodium Cyanide |
| CO_2 | Carbon Dioxide |
| CK | Deionized Water |
| D | Vapor pressure deficit |
| ET | Evapotranspiration |
| ET_0 | Reference evapotranspiration |
| e_a | Actual vapor pressure |
| e_s | Saturation vapor pressure |
| f_u | The wind function |
| H_2O | Water |
| N_2 | Nitrogen |
| O_2 | Oxygen |
| O_3 | Ozone |
| Q_1 | Minimum flow rate |
| Q_2 | Transitional flow rate |
| Q_4 | Maximum flow rate |

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| R_n | Net radiation at the surface |
| u | Wind speed at a height of 2 meters |
| V | Volume |
| γ | Psychrometric coefficient |
| λ | Latent heat of vaporization |
| θ_{fc} | Field capacity |
| \emptyset | Diameter |
| Δt | Elapsed time |
| ® | Registered Trademark for the product or service |
| °C | Degree Celsius |
| ™ | Trademark |

Acronyms:

| | |
|--------|--------------------------------|
| CAP | Common Agricultural Policy |
| CPIs | Center-Pivot Irrigation System |
| DI | Deficit Irrigation |
| EC_e | Electrical Conductivity |
| EC | European Commission |
| EP | Energy Productivity |
| ER | Energy Ratio |
| EU | European Union |
| FI | Flood Irrigation |

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| G | Total weight of the equipment |
| GAEC | Good Agricultural and Environmental Conditions |
| GHG | Global Anthropogenic Emissions of Greenhouse Gases |
| GWP | Global Warming Potential |
| IoT | Internet of Things |
| <i>IR</i> | Irrigation water applied to a respective yield |
| IPMA | Instituto Português do Mar e da Atmosfera |
| LCD | Liquid Cristal Display |
| LEPA | Low Energy Precision Application |
| LoRaWAN | Long Range Wide Area Network |
| LSB | Least Significant Bit |
| MB | Micro Bubbles |
| MED-WET | Improving MEDiterranean irrigation and Water supply for smallholder farmers by providing Efficient, low-cost and nature-based Technologies and practices |
| MNB | Micro Nano Bubbles |
| NB | Nano Bubbles |
| NEG | Net Energy Gain |
| NFC | Near Field Communication |
| NIs | Nano-Irrigation system |
| PRI | Partial Root-zone drying Irrigation |
| QR | Quick Response |
| RDI | Regulated Deficit Irrigation |

| | |
|---------|--|
| SDIs | Surface Drip Irrigation System |
| SE | Specific Energy |
| SIs | Sprinkler Irrigation system |
| SLECIIs | Self-regulated Low-Energy Clay Based Irrigation system |
| SSDIIs | Sub-Surface Drip Irrigation system |
| SSIIs | Sub-Surface irrigation system |
| T | Economic lifetime of the equipment in hours |
| TTNv3 | The Things Network v3 |
| TW | Depreciated equipment weight |
| W | Used time of the equipment |
| WFD | Water Framework Directive |
| WUE_y | Water Use Efficiency per unit of yield |
| WUE | Water Use Efficiency |
| Y | Yield |

1. Introduction

1.1. Background

Over the last few decades, the agricultural sector has been compelled to adopt measures, regulations, and new technologies focusing on efficiency and productivity, thereby compromising the inherent resilience and adaptability naturally found in this economic sector, as well as its biological diversity either on plants or wildlife (Outhwaite *et al.*, 2022). The world population is growing at a never seen pace (Sadigov, 2023), and besides the socio-economic consequences on the populations, the countries where these effects are more visible are usually countries characterized by general low-income population and have been facing multiple problems also in food safety, declining soil fertility due to overexploitation, and at increasing environmental degradation issues (Maja *et al.*, 2021; Balogh *et al.*, 2020). Rudel (2020) states that this problem requires research regarding sustainable intensification and industrialization of the agriculture sector, and that is an ongoing process. Theoretically, this would increase agricultural production without further damaging the surrounding ecosystems, but in practice various problems are encountered such as a difficult trade-off between agricultural development and environmental protection and raising producers' awareness of this sustainable intensification and its economic and ecological benefits. This problem coupled with intensive monoculture preferred by large-scale producers, which has globally contributed to the global food supply for decades, has significantly impacted environmental sustainability, and even though crop diversity has been identified as one of the most important factors to stabilize grain production at a global level, long-term studies also show that it stabilizes the grain production on a field level (Li *et al.*, 2021). Consequences of this monoculture generalization amongst producers include the homogenization of rural landscapes and boost of erosion processes (Brychta & Podhrázká, 2020), soil contamination and drop in fertility (Purwanto & Alam, 2020), fauna and flora reduction from widespread fertilizer use in terrestrial, freshwater and marine organisms (Raven & Wagner, 2021), as well as the utilization of chemical pesticides leading to various negative effects on the health of the soils and the general public (Bisht & Chauhan, 2020).

Adding to the already mentioned problems regarding biodiversity presence on the crops, there is also other sectorial challenges related to an exponential decrease in available labour (Hill *et al.* 2021), rising consumer demand for transparent products and eco-friendly crops, and an increasing desire for high-quality agricultural products

(Maheshwari, 2024). Therefore, there is an urgent need to shift the agricultural production paradigm to minimize environmental impact and promote local fauna and flora, without compromising crop productivity. According to Stein-Bachinger *et al.* (2022), a more heterogenic landscape (promoting semi-natural habitats and diversified croplands), sustainable farming system (promoting crop choice considering rotation, animal husbandry, and soil management) and more sustainable crop management (considering the type and amount of fertilizers and the frequency of use and toxicity of pesticides) will naturally interact increasing the biodiversity on the crop and consequently its yield output.

The Common Agricultural Policy (CAP) has been pivotal in ensuring food safety and fostering agricultural productivity in the European Union (EU) for six decades (EC, 2022). Originally designed to address post-World War II food shortages and market instability, the CAP has continually adapted to changing economic, social, and environmental contexts. Transitioning towards a model supporting a barrier-free market characterized by common standards and high-quality products reflects the EU's broader goals of economic integration and consumer protection. In 2021, the CAP strategic plan was formally adopted by the European Council for the 2023-2027 period (EC, 2022). This reviewed document still focuses on specific objectives, linked to the common EU goals for social, environmental, and economic sustainability in the agricultural economic sector. The strategic plan aims to contribute to climate change mitigation and adaption, promote sustainable energy, development, and efficient management of natural resources as also halt and reverse the biodiversity loss while enhancing ecosystem services. There's also an alignment with the European Green Deal multiple objectives and strategies by targeting the pesticide use and nutrient loss in the member states through a tight control from the European Commission and by compromising to until 2030 reduce these parameters in 50% by: reducing nutrient runoff into water bodies, encouraging the expansion of organic farming (member states are encouraged to increase the organic farming coverage by 25% in 2030), promote high-diversity landscapes which will mitigate the nutrient runoff and boost the local biodiversity of the regions (member states are expected to bring at least 10% of agricultural areas under these such conditions), good agricultural and environmental conditions (GAEC) standards, such as GAEC 4, which requires the establishment of buffer strips along water steams to prevent their pollution from fertilizers and pesticides, or even GAEC 7, that mandates crop rotation to improve the Europeans agricultural soils health and reduce the use of chemical inputs (member states must meet these GAEC standards in order to receive financial support and incentives).

Figure 1 illustrates the increasing focus on this symbiosis in the European Commission policies ever since 1957.

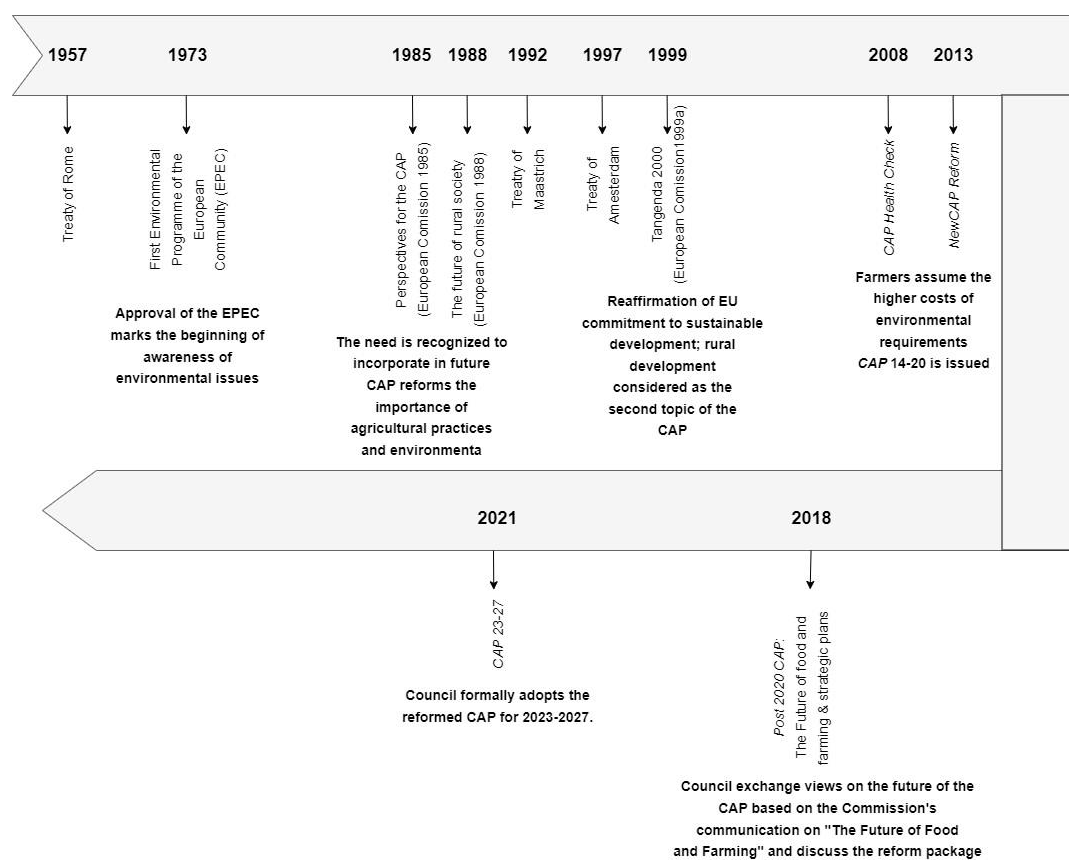


Figure 1. Timeline of the European politics to face agricultural and sustainability problems among the state members (adapted from de García-Tejero et al., 2014; European Council, n.d)

In light of a scenario in desperate need of sustainable development, and considering that approximately 70% of fresh water is allocated to agriculture (The World Bank, 2022), a significant portion of which is ultimately wasted due to evaporation or soil characteristics, the MED-WET initiative and its technology emerge to address the primary challenges of agricultural irrigation in Mediterranean climates, the escalating scarcity of water resources over time. In order to integrate a comprehensive view of the spectrum concerning different climatic realities, this project involves multiple universities from Germany, Egypt, Malta, Morocco, and Portugal, aiming to attain a holistic understanding of diverse climatic conditions.

Figure 2 depicts in a visual clear way (through the analysis of precipitation and evapotranspiration), the deprecation and uncertainty about the mediterranean weather and climate, to which these populations and agricultural crops are subjected, and so also the urgent need for a comprehensive full spectrum analysis of the Mediterranean agricultural irrigation matter.

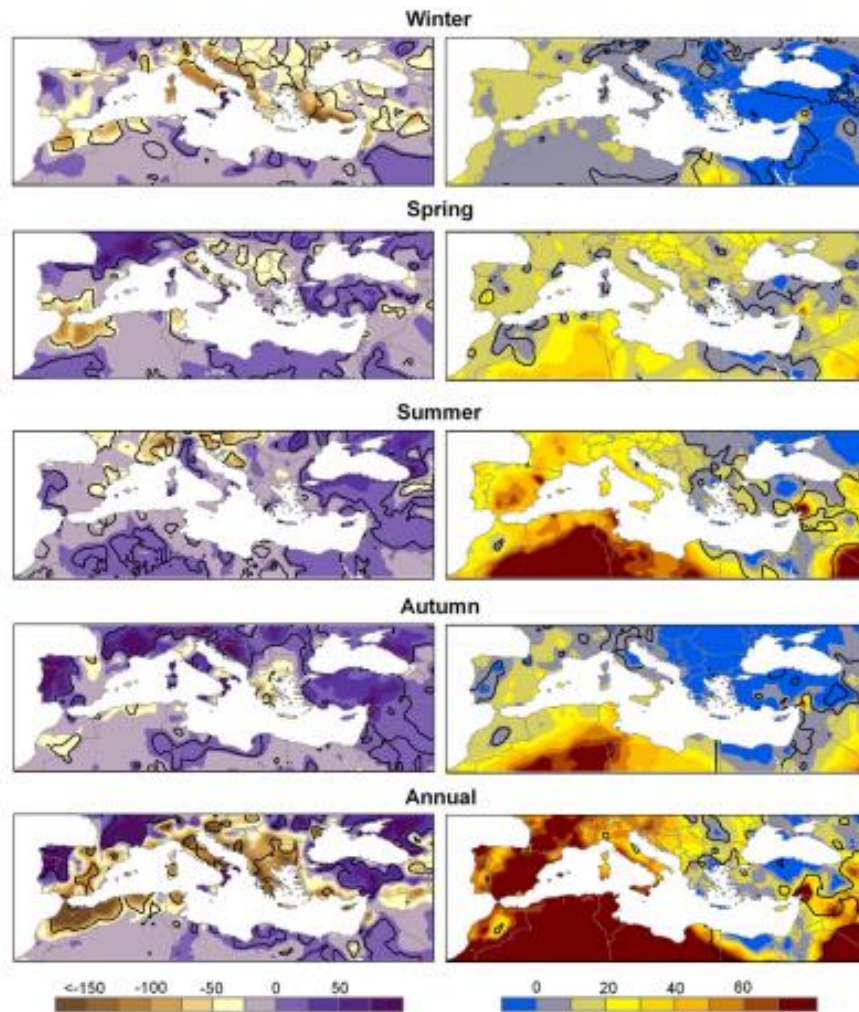


Figure 2. Seasonal and annual climatic evolution in the Mediterranean region between 1950 and 2022. The colors indicate the magnitude of changes in precipitation (left) and evapotranspiration (right), in millimeters. (Adapted from García-Ruiz *et al.*, 2011)

As evidenced, from 1950 to 2022 there has been a significant alteration regarding water availability caused by less annual rain and higher evapotranspiration indices all over the full extension of the Mediterranean region from Portugal to the Middle East, starting to cause an alarming situation especially at the southern Europe and Northern Africa regions.

1.2. Study problem and its relevance

When delving into the study and assessment of agricultural irrigation challenges and when choosing the irrigation technology to use, first we need to understand the type of climate and type of crop in which we are working and performing irrigation. In this case study, we will examine the results of peach and cherry tree crops under the Hot Summer Mediterranean Climate¹. This particular kind of climate can pose challenges for agricultural irrigation due to the limited availability of this vital resource for any crop or way of life. Additionally, climate changes (Rocha *et al.*, 2020) and irregularities in rainfall patterns across different seasons (FAO 2009) make this Mediterranean climate highly unpredictable, therefore water consumption for most crops in this climate becomes equally unpredictable.

Figure 3 provides a comparison of the water consumption in liters per fruit for apple trees under a variety of different irrigation technologies (Blueberries Consulting Magazine, 2019).

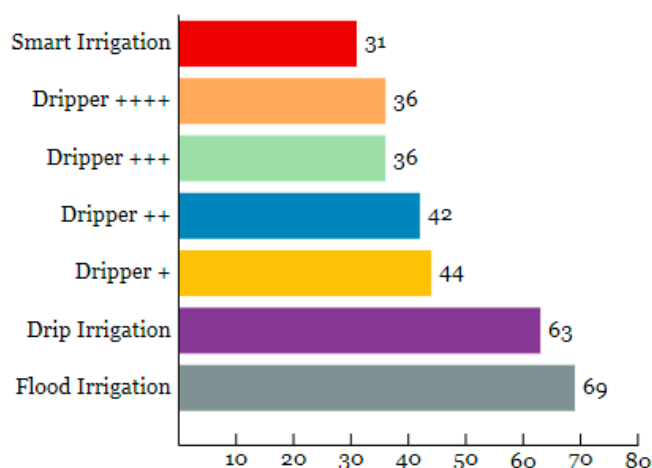


Figure 3. Effect of irrigation technification on the water footprint of an apple in liters per apple (adapted from de Blueberries Consulting Magazine, 2019)

As evidenced, each irrigation technology has its advantages and water consumption, but as the years go through and technology evolves, the benefit of the agricultural producers following up with irrigation technologies and have a higher technification level

¹ Köppen-Geiger classification

on their fields are clear. For example, Flood irrigation (FI) methods are ancestral and have been around the agricultural irrigation scenario for centuries, but when compared to a more recent technology such as Smart Irrigation, the environmental and sustainability costs are clear, with the FI system using 69 *liters/apple* and Smart Irrigation using only 31 *liters/apple*, which means a 56.5% reduction on water consumption to produce the same amount of food.

On another matter, and focusing on decision making and groundbreaking agricultural policies, a symbiotic relationship between Agriculture and the Environment is crucial for sustainability and rural development. According to the Eurostat (2023), in 2020 there were 9.1 million farms in the EU, using 1.55 million hectares of the available land for agricultural production, meaning that almost two-fifths (37.8%) of the EU's total land area was farmed. García-Tejero *et al.* (2014), emphasise the importance of responsible land and water management to preserve natural habitats and embrace environmental sustainability in the agricultural sector. However, improper practices can degrade soil, water, and biodiversity. Sustainable agriculture should prioritize responsible soil and water management, implementing techniques to meet current and future population needs. Preserving resources without compromising environmental identities is essential, emphasizing a rational application of technology and economic sustainability. Even though, FAO (2023) was issued 9 years later, it still agrees with this prioritizing and resource allocation, suggesting some key policies to achieve the major objective of global environmental sustainability in the agricultural sector, by reforming well-established practices that have been widely recognized as potentially harmful to the surrounding environment. This can be achieved by increasing the investment in research and development through improving technologies and practices, redirecting agricultural support, and leveraging trade for sustainable development. Aligning policies and incentives with long-term objectives and rolling back measures that distort markets and trade also take part in the suggested measures.

According to the European Commission Report (EC, 2012), the primary causes of the detrimental effects of the mismanagement of water resources and consequently their scarcity are interconnected. These include climate change, poor land use planning, economic activities such as energy production, industry, agriculture, tourism, urban development, and recent demographic changes. The pressure exerted by these elements of our daily lives manifests in the form of pollution emissions, overuse of water, physical alterations in water bodies, and extreme scenarios such as floods or droughts. There is thus a pressing need for better implementation and integration of the objectives of new

water management policies into other areas of political action, wherein the Common Agricultural Policy (CAP) reemerges. Over the past decades, alarming trends have been observed, confirming and justifying the increase in water scarcity in EU member states. Projections suggest that by 2030, approximately half of the member states will experience such situations in their river basins. Reviewing reports from recent years, the European Commission for Water Scarcity and Drought Situations emphasizes the untapped potential for water resource efficiency in sectors with high water consumption, such as agriculture, industry, distribution networks, buildings, and energy production. The revision of this report presents policy pricing implementation as an example solution, known to provide significant incentives for more efficient water use by raising consumer awareness and stimulating innovation and adoption of new habits and policies. One of the essential prerequisites for the implementation and application of such policies is the monitoring of consumption. Concluding the report, the review commission proposes a reform of the CAP to provide a new perspective on funding and consistent improvement of irrigation efficiency in line with the objectives of the Water Framework Directive (WFD), while preventing possible rebound effects. This reform includes reducing water consumption, as the agricultural sector consumes 24% of this precious natural resource in the European continent.

Keeping in mind the information provided by the EC and the Eurostat throughout the last decade, we can see that measures are being implemented, but not at the pace they should be so that our planet's most vital resource can be assured to the future generations for the single purpose that they can still flourish in a biodiverse environment, which is concerning.

Coupled with this issue of inefficiency in water resource management, Wang & Meng (2013) also state a lack of scientific and technological knowledge on behalf of most agricultural traditional producers when it comes to selecting the irrigation system and technology that best suits the needs and conditions of each producer and the developed crop, shedding light on the challenges and requirements of this specific economic class on the scientific and technological agricultural knowledge and comprehension. Also in this regard, Brouwer (1985) presents a comprehensive set of topics and parameters, still considered relevant today, to be taken into account when a producer chooses the irrigation system or technology, with the most relevant ones being the natural conditions, type of crop, the producer's previous experience with irrigation systems, labor requirements, and finally the cost-benefit analysis of the system or technology. Regarding natural conditions, soil type is considered one of the most important factors,

as some soils (primarily sandy ones) have higher infiltration rates, requiring more regular but smaller amounts of water. In cases where there is a variety of soils within a single irrigation scheme, the use of sprinkler or drip irrigation is recommended. Next, we have the slope condition, according to which the producer would prefer sprinkler or drip irrigation on steeper or irregularly sloping land. Climate conditions should also be considered, as strong winds, for example, can disrupt water dispersion by sprinklers. Concerning the type of crop, sprinkler and drip irrigation are generally used for high-value crops such as vegetables and fruit trees, due to the high investment per hectare. Drip irrigation is more suitable for isolated trees or row crops. Previous experience with irrigation should also be considered, as an inexperienced farmer or producer in the use of irrigation technologies may lead to unexpected complications in the process, resulting in higher costs than benefits. Labor costs must be taken into account, as some technologies always require labor costs for installation, operation, and maintenance. For example, surface irrigation, where the uniform distribution of water throughout the crop is entirely dependent on gravity, requires precise soil levelling, regular maintenance, and a high level of farmer organization to operate the system as efficiently as possible. Finally, the costs and benefits of the process must be considered. Before choosing an irrigation method, construction, operation, and maintenance costs should be estimated and taken into account for all available options. In the final decision-making process, these costs should then be compared to the expected benefits of the harvests.

1.3. Objectives and contributions

The climate and its changes, particularly in the context of Mediterranean territories, have been part of international discussions and agendas of the countries involved for some years now, especially regarding the management of water resources. Given that a significant portion of the available freshwater in rivers and aquifers is dedicated to the agricultural sector, agricultural irrigation and its proper management, technological and scientific training of producers, and awareness-raising on this issue are crucial points to consider for a sustainable future. Furthermore, problems in obtaining water resources and their mismanagement have serious repercussions on the sustainability of regions and their populations, not only because water is a vital resource for all living organisms on the planet but also because it is essential in the agricultural sector, which is tasked with the mission of feeding the growing world population.

This study is based on the premise that, in partnership and close collaboration with academic, governmental, and business entities in a developing region that suffers from water scarcity and widespread drought year after year, it is essential to evaluate and test an innovative clay-based agricultural irrigation system, the self-regulating low energy clay tube irrigation (SLECI), which shows great promise in water savings.

The Cova da Beira region has been characterized for decades not only by drought in the hottest months but also by demographic aging. Therefore, the objectives of this dissertation also include raising awareness and opening up the discussion on topics such as water resource conservation and good management, which are already scarce in themselves, amongst not only the agricultural community but over the general population, through the presence and representation of the dissertation thematic and results on various national and international sustainability and industry events.

It is often challenging for agricultural producers in this region to understand, accept, and keep up with all the technological advancements provided by the market and research sector in recent years. Hence, one of the objectives of this dissertation is to explain, in the simplest possible terms, not only the technologies available on the market but also the more experimental technologies within the economic reach of a few producers. The aim is to support not only the academic community but also the community of agricultural producers in choosing, better understanding, and interpreting the irrigation system to be chosen based on soil type, geographical location, and agricultural culture to be irrigated.

1.4. Document organization

This dissertation is divided into five parts, each one devolving into a specific different work component.

On the first chapter, “Introduction” starts a background is performed where the general challenges of the agricultural are discussed, such as water scarcity, the need for sustainable practices and the impact of climate change on the mediterranean agriculture. Then, “Studie problems and its relevance” explore the issues related to mediterranean agricultural irrigation and the importance of efficient water use. The “Objectives and contributions” sub chapter focuses on outlining the goals of this study, including a more comprehensive evaluation of the SLECI system and its potential benefits.

The second chapter, “State of the Art” describes the technical specification of several irrigation system commonly used by agricultural producers around the globe and also provides a systematic comparison and review between them.

The third chapter, “Materials and methods” provides a detailed description and list of the SLECI systems and its main components and also provides a short summarized installation guide for the technical irrigation components and monitoring electronics used in the field.

The fourth chapter, “Experimental results and Discussion” provides an overview of the experimental conditions and key events during the irrigation season, presents and discusses the test field results obtained both in the cherry and peach trees crops while also comparing some metrics between crops and irrigation systems.

Lastly, the “Conclusions” chapter summarizes the overall findings of the study and the performance of the SLECI system, while providing recommendations for future research and potential improvements to the SLECI system.

2. State of the Art

Crovella *et al.* (2022) state that irregular precipitation patterns have always characterized the Mediterranean region with its hot, dry summer months. Therefore, Mediterranean irrigation has always demanded more cautious, responsible, and sustainable water management. Through the centuries, this region has always been an innovation cluster when it comes to agricultural irrigation technologies development, from the ancient flaps or aqueducts to cutting-edge technologies, always aiming to achieve a balance between sustainability and productivity concerning the various human, economic, and natural resources related to the activity sector.

The Portuguese Cova da Beira region, as a practical example of the Mediterranean weather soil and crop characteristics, has been selected to host this case study, and according to Galego *et al.* (2021), the most portrayed technologies in the Portuguese scenario are the drip irrigation system, central-pivot irrigation system, deficit irrigation system and then the underground irrigation system.

This study aims to examine, evaluate and assess the hydric sustainability of a novel irrigation system, the Self-regulating, Low Energy, Clay based Irrigation (SLECI) system integrated into a Mediterranean climate case study while comparing and appraising its main differences with other conventional and new irrigation systems that have a strong representation amongst the Mediterranean at the cherry and peach trees agricultural producers. In this chapter, different agricultural irrigation technologies will be introduced and compared, by the end of it, a proper choice can be made taking into consideration soil, crop, weather, and water consumption information regarding each tech.

2.1. Non localized irrigation methods

This kind of technology proves to be highly useful and versatile for irrigating extensive areas, especially those with topographical irregularities. However, without proper dimensioning, protection, and maintenance, the system can become erosive to both the soil and the crop being irrigated. Considering that most Mediterranean region terrains exhibit irregular topography, the limited water flow infiltrated into the soil poses a constant challenge, potentially resulting in high rates of runoff and water dispersion, as well as soil erosion and crop damage.

The most representative technologies embracing this system are the sprinkler (Figure 4) and center-pivot irrigation (Figure 5) systems, and in both of them, the importance of proper sizing is emphasized. While the installation cost is not necessarily high, when not sized and implemented by an irrigation engineer, it can lead to water losses (Sousa *et al.*, 1999). Ho *et al.* (2022) present research findings confirming that irrigation and its water efficiency are significantly low for coffee crops, suggesting that more advanced technologies could enhance this efficiency. However, coffee crops utilizing this irrigation system are more efficient than those relying on micro-basin technologies, which is an ancestral technique to collect surface run-off, increase water infiltration, and prevent soil erosion.



Figure 4. Sprinkler irrigation system (retrieved from Patel & Prajapati, 2020).

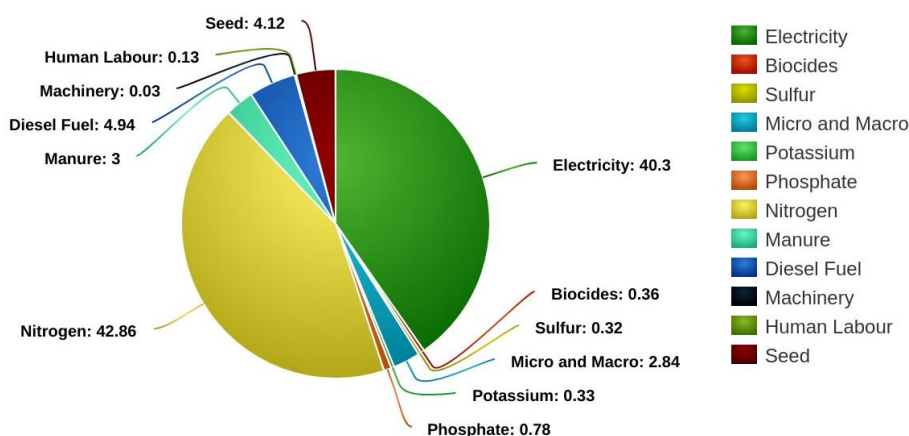


Figure 5. Centre-pivot irrigation system (retrieved from Irrigazette, 2024).

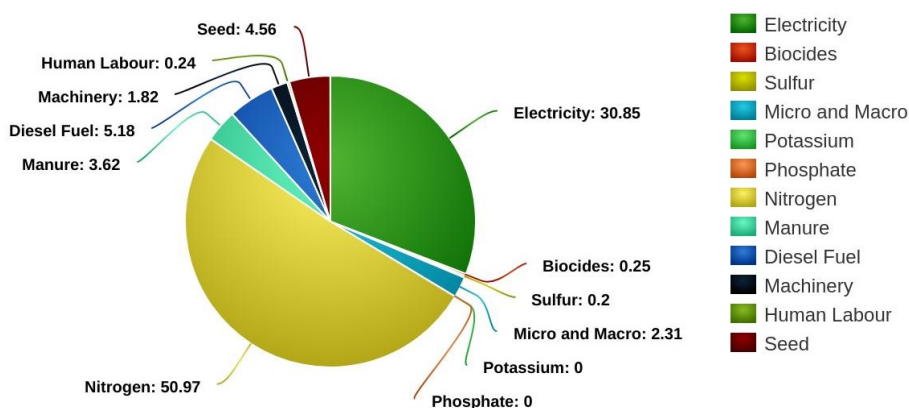
2.1.1. Sprinkler Irrigation system (SIs)

This system is used to apply water to crops in a controlled manner, simulating rainfall. The water is distributed through a network of pipes, usually by pumping, and then sprayed into the air through sprinklers so that it breaks up into small water drops that fall to the ground. The efficiency and uniformity of water distribution are critical factors in sprinkler irrigation, as they directly affect crop yield, water conservation, and the overall effectiveness of the irrigation system (Darko *et al.*, 2017). The importance of proper planning and dimensioning of this irrigation system, considering natural and topographic characteristics, is once again emphasized in Rudolph *et al.* (1996) with his experiments and studies regarding water content distribution in unsaturated soils, but mechanical and technical parameters must also be dimensioned and considered as Sithole *et al.* (2023) did in his system dimensioning considering pump characteristics.

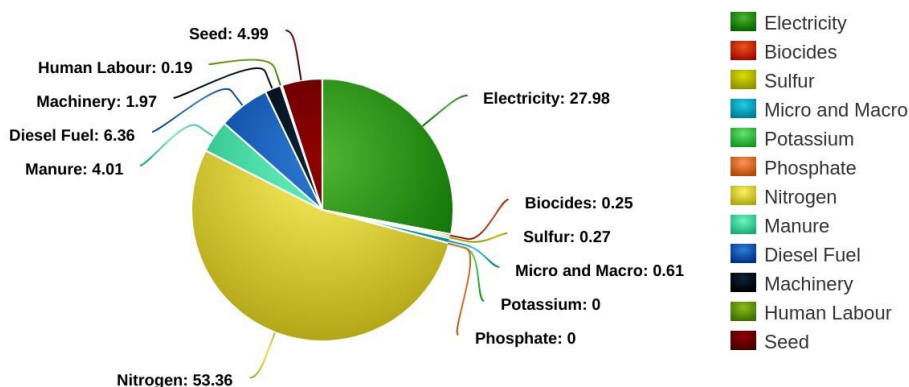
Kaab *et al.* (2024) presents a detailed comparative study which focus in energy expenditure and environmental impacts assessment thought out the barley production life cycle in the Iranian region between the three most commonly used methods amongst this kind of crop producers, the Flood irrigation (FI), Sprinkler irrigation (SI) and Surface Drip irrigation (SDI). Figure 6 depicts the share of energy sources used in the process of malting barley, under the three studied irrigation system. In a general way, the use of nitrogen chemical fertilizers as the primary driver responsible for energy consumption is highlighted for all three irrigation systems, with electricity usage following up close. Therefore, in a way to reduce the total energy consumption the authors suggest to either decrease the usage of nitrogen-based fertilizers or consider less energy-intensive alternatives.



a) Share of energy sources used in the process of malting barley, under the FI system



b) Share of energy sources used in the process of malting barley, under the SDI system



c) Share of energy sources used in the process of malting barley, under the SI system

Figure 6. Shares of energy sources in malting barley production under different irrigation systems (adapted from Kaab *et al.*, 2024).

The authors then present an energy indices study regarding the production process of this particular culture, shown in Table 1. The energy consumed by different equipment, such as machinery or pumps is measured in $MJ kg^{-1}$, and it is calculated according to Equation (1), presented in Elsoragaby *et al.* (2020).

$$TW = \frac{G \cdot W}{T} \quad (1)$$

Where T represents the economic lifetime of the equipment in hours, W represents the use time of the equipment in $h ha^{-1}$, G represents the total weight of the equipment in kg and then TW represents the depreciated equipment weight per $kg ha^{-1}$. This energy equivalent if equipment allows to calculate the different indices including the

energy ratio (ER), energy productivity (EP), specific energy (SE), net energy gain (NEG) and water use efficiency (WUE), which are computed by Equation (2) to Equation (6).

$$ER = \frac{\text{Output energy}}{\text{Input energy}} \quad (2)$$

$$EP = \frac{\text{Production}}{\text{Input energy}} \quad (3)$$

$$SE = \frac{\text{Input energy}}{\text{Production}} \quad (4)$$

$$NEG = \text{Output energy} - \text{Input energy} \quad (5)$$

$$WUE = \frac{\text{Production}}{\text{Water Use}} \quad (6)$$

Where ER is a ratio with no dimension and it is also greater than 1, EP is based on $kg MJ^{-1}$, SE is based on $MJ kg^{-1}$, NEG is based on $MJ ha^{-1}$ and WUE is based on $kg m^3^{-1}$.

Table 1. Energy indices in malting barley production under different irrigation systems (retrieved from Kaab *et al.* (2024))

| Items (units) | FI | SDI | SI |
|-----------------------|----------|----------|----------|
| ER | 1.4 | 1.72 | 2.07 |
| $EP (kg MJ^{-1})$ | 0.1 | 0.12 | 0.15 |
| $SE (MJ kg^{-1})$ | 9.85 | 8.15 | 6.48 |
| $NEG (MJ ha^{-1})$ | 38526.82 | 60612.93 | 85311.36 |
| $WUE (kg (m^3)^{-1})$ | 1.20 | 1.79 | 1.70 |

By the information provided in Table 1, it can be seen that the SI system ranks first, followed by the SDI and FI systems, respectively. The SI system, when it comes to the

malting barley production in the Iranian region seems to outperform the other irrigation systems when it comes to energy efficiency, yield per unit of energy consumption, energy consumption per unit of production and the difference between the input and output energies.

2.1.2. Center-pivot Irrigation system (CPIs)

A center-pivot irrigation system is a type of sprinkler irrigation system where the sprinklers are mounted on a single pipeline rotating around a central pivot point (Baiamonte *et al.*, 2020). This allows the system to irrigate a large circular area by rotating around the pivot point and applying water as it moves.

The system is then composed of a long pipeline with sprinklers mounted along its length and a central pivot where the pipeline is anchored, and it's all driven by an electrical motor that rotates the pipeline around the pivot point. According to the field dimensions and outline, the system may also include an end gun sprinkler at the end of the pipeline, pressurized by a booster pump for better uniformity to irrigate the corners, which are usually critical spots (Irrigazette, 2024).

Some design considerations must also be taken into account, such as a proper sprinkler selection (impact, spray, LEPA) (Baiamonte *et al.*, 2020), optimized operation speeds taking into consideration the different seasons to improve uniformity (Omer *et al.*, 2020) or to include towable pivot versions to irrigate multiple circles with a single system (Irrigazete, 2024).

Baiamonte *et al.* (2020) also state that the CPIs are a more efficient system and less time-consuming system than other traditional irrigation methods like FI method, and they allow to uniformize the water application rates across the field when properly designed. It can also be automated and remotely controlled and is suitable for a spread variety of crops.

Overall, the CPIs is a fully configurable system and able to be adapted to the widest variety of field outlines and topographies, but mostly recommended for larger areas (Brik *et al.*, 2022). On the other hand, it is not accessible to every kind of producer and a bad implementation can be chaotic in sustainable agriculture terms, so the CPIs is a system with a crucial need of technical knowledge (provided by mechanical and irrigation engineers) and maintenance attention.

2.2. Deficit Irrigation (DI) concept

Concerning the scarcity of water at certain times of the year, the agricultural producer always have the option to apply less water than the recommended amount for the specific crop for the full irrigation campaign or during a certain phase of drier weather, or plant development while never neglecting the plant's developmental cycles to minimize the impact of this deficit irrigation on production and final yield (González-Altozano & Castel, 2003; Rosa *et al.*, 2008; Pérez-Pérez *et al.*, 2014; Tura *et al.*, 2020). This way, deficit irrigation (DI) is considered more of an irrigation concept or set of techniques fully focused on water rationing and saving, instead of an irrigation technology *per se*.

Romero *et al.* (2022) provide a review focusing on the state-of-the-art of various physiological irrigation strategies aimed at saving significant amounts of water and improving the utilization of this natural resource (WUE_y) and the quality of grapes and wine. There are many strategies and techniques for applying this concept on the field, and this author opted for his own customized deficit irrigation (DI), regulated deficit irrigation (RDI), and partial root-zone drying irrigation (PRI) in vineyards, aiming to study improve WUE_y , grape quality, and water management efficiency, designing a sustainable and climate- change-resilient agricultural system.

In another study, Abdelkhalik *et al.* (2020) present a different approach to exploring the benefits of deficit irrigation in sweet pepper plants by applying reduced values of irrigation water requirements (IWR). Thus, the author employed 100%, 75%, and 50% of the IWR through the different stages of plant development, concluding that for this kind of crop, when applying 75% of IWR during the harvesting period results in a considerable reduction in yield quantity. However, the water savings are remarkable in relation to full irrigation. This 75% strategy led to an improvement regarding the marketable fruit quality in terms of soluble solids and polyphenol contents.

In a general review, Tura *et al.* (2020) state that for the deficit irrigation to be an economically viable practice, there must be a balance between revenue lost and savings at yield production costs, always considering that the crops under constant water stress face serious yield reductions. Also, the interaction between water quality and DI showed that when both kinds of stresses are coupled together, tremendous reduction also occurred on regards of total dry biomass and total yields. Thus, it is recommended that a proper and cautious assessment of the soil, water, and crop characteristics is conducted before adopting this kind of technique. Also, in semi-arid regions such as the

Mediterranean one, it is preferable to adopt different drought-tolerant crops instead of more susceptible crops to couple with these techniques.

2.3. Surface Drip Irrigation system (SDIs)

The introduction of surface drip irrigation systems into the daily routines of agricultural producers has completely revolutionized the sector in terms of water resource conservation, yielding reductions in consumption on the order of 25 to 35% (Darouich et al., 2014). Figure 7 provides an illustrative example of the application of such technologies in vineyards, featuring a rigid hose with an external dripper, but there are also options with internal drippers. The system setup can be configured depending on the crop type and field structure, but the usual spacing between drippers is 0.75 cm (Galego *et al.*, 2021), although this spacing is often configurable for the external dripper system. Internal dripper hoses have the distance between drippers fixed. Therefore, this irrigation system presents several key advantages, including its adaptability to terrain with irregular geometries, precise application of nutrients or fertilizers without the risk of clogging, low operational flow rate on the order of 2.2 L/h, and, above all, the reduced cost of system installation. However, the conversion from another irrigation technology to drip irrigation ultimately proves to be quite expensive, constituting its primary disadvantage (Shock, 2013).



Figure 7. Drip Irrigation system example, when applied to vineyards (Shock, 2013).

Table 2 shows the various typologies of this technology available to producers, tailored to their specific production needs and areas. Therefore, the design of such systems should always consider the terrain's topography to meet recommended water pressures and flows, the length of the irrigated area, soil textures, and the filtration capacity of different water filters to prevent clogging in the tape or tubing. This requires prior planning for the uniform distribution of water along the entire tape, through a weighted selection process, and irrigation lengths and needs periodic flushing and maintenance of the tapes.

Table 2. Different typologies of the Surface Drip Irrigation system.

| Type of system | Internal Ø (cm) | Wall thickness (mm) | Dripper spacing (cm) | Dripper water flow (L/h) |
|---|-----------------|---------------------|----------------------|---------------------------|
| Dripping tape | [0.95, 3.49] | [4, 35] | [5.08, 91.44] | [0.265, 3.18] |
| Tubbing (drip line) with internal drippers | [1.04, 2.03] | [23, 47] | [30.48, 152.40] | [1.51, 6.81] |
| Hard hose with external drippers | [0.318, 3.81] | [29, 125] | custom | [0.50, 4.00] ² |

2.4. Nano-Irrigation system (NIs)

The NIs is a low-flow localized irrigation system, and it stands out as one of the best technologies for water retention in the soil. The drippers have a flow rate of around 0.7 L/h (Galego *et al.*, 2021), an extremely low value, enabling the irrigation of large crop areas with minimal water and energy consumption. These technologies also offer low installation and maintenance costs, thanks to their operation at very low pressure.

Hatif & Ghazal (2024) present a comparative study between NI and a SSDI (sub-surface drip irrigation) which is a SSI technology, being both technologies applied to a broccoli crop in Central Iraq. The authors use metrics such as Water Use Efficiency (WUE) (kg/m^3), Root Length (cm) and Yield ($kg/hectare$) so that a proper comparison

² Larger diameter hoses and higher rate micro sprinkler drippers are available for hard hose systems.

can be carried out. Results are shown in Figure 8, and as it can be seen, the NI outstands the SSDI technology on every comparison metric, registering values of 13.9 kg/m^3 , 19.68 cm and 6110 kg/hectare against 2.45 kg/m^3 , 12.3 cm and $5908.3 \text{ kg/hectare}$ for WUE, Root Length and Yield, respectively. Therefore, it can be concluded that in this particular case, the NI system consumed much less water while achieving higher productivity. Also, the NI system displayed a significant effect on the broccoli plants root length and growth rate, which is always a biological advantage.

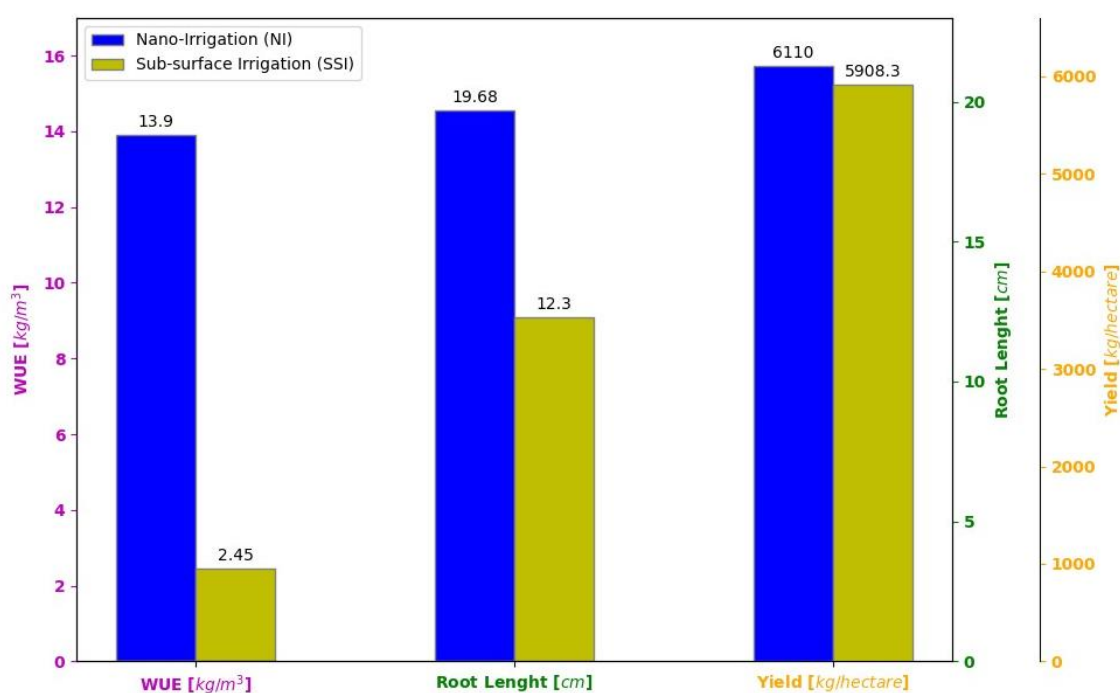


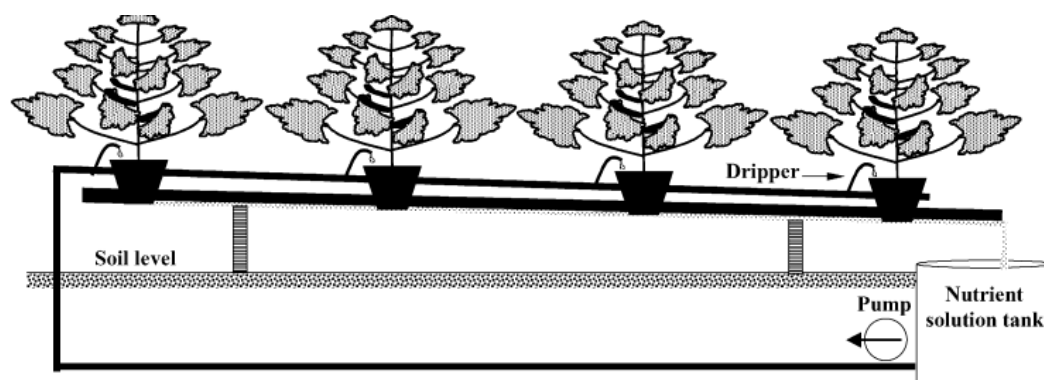
Figure 8. Comparison data between the NI and a SSI technology (sub-surface drip irrigation), focusing on Water Use Efficiency (WUE), Root Length and Yield when applied to a broccoli crop in central Iraq (Hatif & Ghazal, 2024).

2.5. Sub-surface irrigation systems (SSIs)

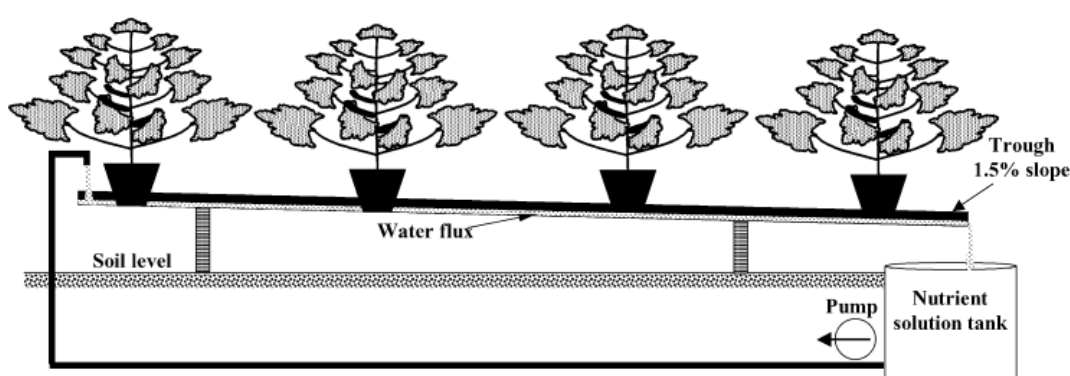
The SSI technology remains under constant investigation, with one of the presented advantages focusing on the direct irrigation of the plant's roots, thereby enabling a reduction in water loss due to evaporation. However, this technology also entails higher installation costs, increased susceptibility to damage from wildlife in the area, such as

rodents or moles, and a high risk of clogging due to the accumulation of salts and sediments in the emitters (Galego *et al.*, 2021).

Rouphael *et al.* (2006) carried a greenhouse experiment during the spring-summer period, in a way to determine the influence of two distinct irrigation systems (SDI and a SSI technique named bench technique) and two different nutrient solution concentrations (2.0 and 4.1 dS m^{-1} for non-saline and saline nutrient solutions respectively) on electrical conductivity (EC_e), growth, yield, fruit quality, yield water use efficiency and mineral composition on a greenhouse zucchini squash crop. Figure 9 and Figure 9.B represent the system layout for the SDI and the SSI technique respectively. This particular study concludes that using a non-saline nutrient solution (2.0 dS m^{-1}) presents a more rapidly increase of the EC_e , greater fruit quality and WUE_y but also a slight yield decreases when compared to the SDI. Unlike the SSI, SDI technology would then be more suitable for saline solutions (4.1 dS m^{-1}), by limiting yield reduction, taking advantage of the quality effects of saline irrigation waters and improving the WUE_y .



a) SDI layout.



b) SSI layout.

Figure 9. Layout of both systems used in the trials (retrieved from Rouphael *et al.*, 2006).

On another study, Coltro *et al.* (2017) proposes the transition from the ancestral FI system (Figure 10A) to a novel SSI system, the SSDI (Subsurface drip irrigated rice cropping system) (Figure 10.B), when applied to rice crops and also presents the economic and biologic positive effects of this transition. A general improvement is stated on the rice production chain from farm to transportation and then distribution to retail stores. The transition from the obsolete FI technology to the more recent SSDI translated into 50% less water consumption (approximately $2800 \text{ m}^3 \text{ t}^{-1}$ on packed rice at retail stores), 90% less electrical power consumption (approximately 2000 MJ t^{-1} on packed rice at retail stores), 30% less eutrophication (process where a water body becomes overly enriched by nutrients, leading to an over growth of undesired plants and weeds on the crop), 66% less acidification (process where the soil pH decreases over time), 66% lower GWP (Global Warming Potential) with fewer GHG (global anthropogenic emissions of greenhouse gases) emissions (approximately $1200 \text{ kgCO}_2 - \text{eq t}^{-1}$ on packed rice at retail stores) and a 15% higher yield mainly due to the new SSDI system

and reduced GHG emissions most considering avoiding methane emissions to the rice field from the electrical energy source and water pump.

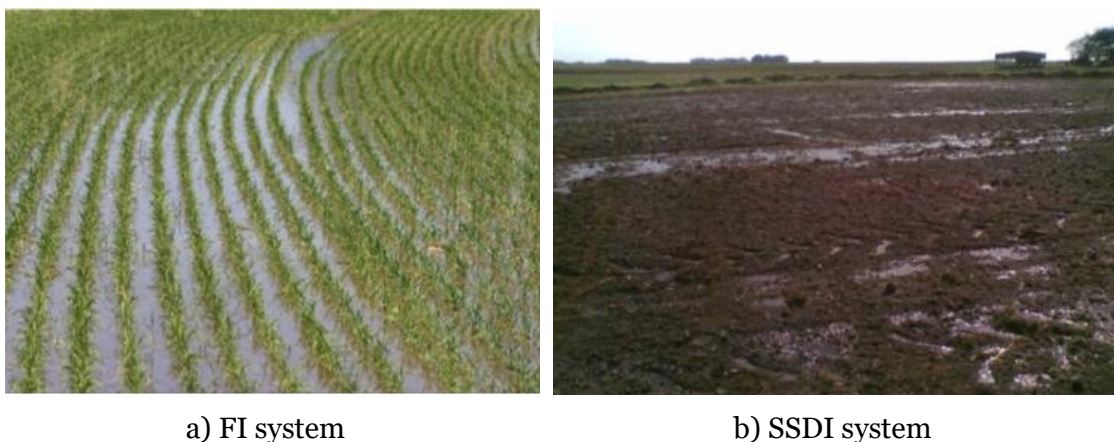


Figure 10. Visual comparison of both irrigation systems, applied to a Brazilian rice crop (retrieved from Coltro *et al.*, 2017).

Overall, there is not a better solution for all cases when comparing the SDI technology and the SSI system (Rouphael *et al.*, 2006). Both irrigation methods present their advantages, so depending on the irrigation water quality, the most suitable system must be considered, taking into consideration that the SDI will always be more attractive when dealing with low quality irrigation water sources. On the other hand, when ancestral but still consistently used by rice producers FI system is compared to the SSDI systems (Coltro *et al.*, 2017), the SSI system provides advantages on every economical and water sustainability aspect, so a migration to this kind of new technologies must be taken into consideration.

2.6. Soil Oxygenation (CO_2 nano bubbles)

According to Wang *et al.* (2023), soil compaction is an increasingly evident issue, affecting approximately 68 million hectares worldwide, resulting from agricultural exploitation involving heavy machinery and the growing level of industrialization in this sector. This new technology, therefore, emerges more towards balancing the physical and chemical properties of soils and combating this problem rather than solely addressing water resource scarcity.

The soil oxygenation process is always initiated from the irrigation water supply, and there are various techniques for achieving it, with the primary ones being direct oxygenation from the water source or through the utilization of macro bubbles (ordinary bubbles), micro bubbles (MB), or nano bubbles (NB).

Wang *et al.* (2023) delve into various techniques for oxygenating the irrigation device (or source), which can be achieved using different technologies and processes. Examples include Mechanical Oxygenation (Figure 11.A), employing a water pump and diffuser stone; Venturi Oxygenation (Figure 11.B), where a Venturi device is introduced at the outlet of the source to oxygenate the irrigation system; and Chemical Oxygenation (Figure 11.C), where sodium percarbonate ($2Na_2CO_3 \cdot 3H_2O_2$) is added to water (H_2O) to generate oxygen through the chemical reaction between them, with different reagents potentially added in this latter technique. However, in the discussion of its results, the author mentions a new technology that achieves a better combination with the liquid medium, also obtaining a higher concentration of dissolved oxygen therein, through macro, micro, or nano bubbles created by a dedicated generator for this purpose.

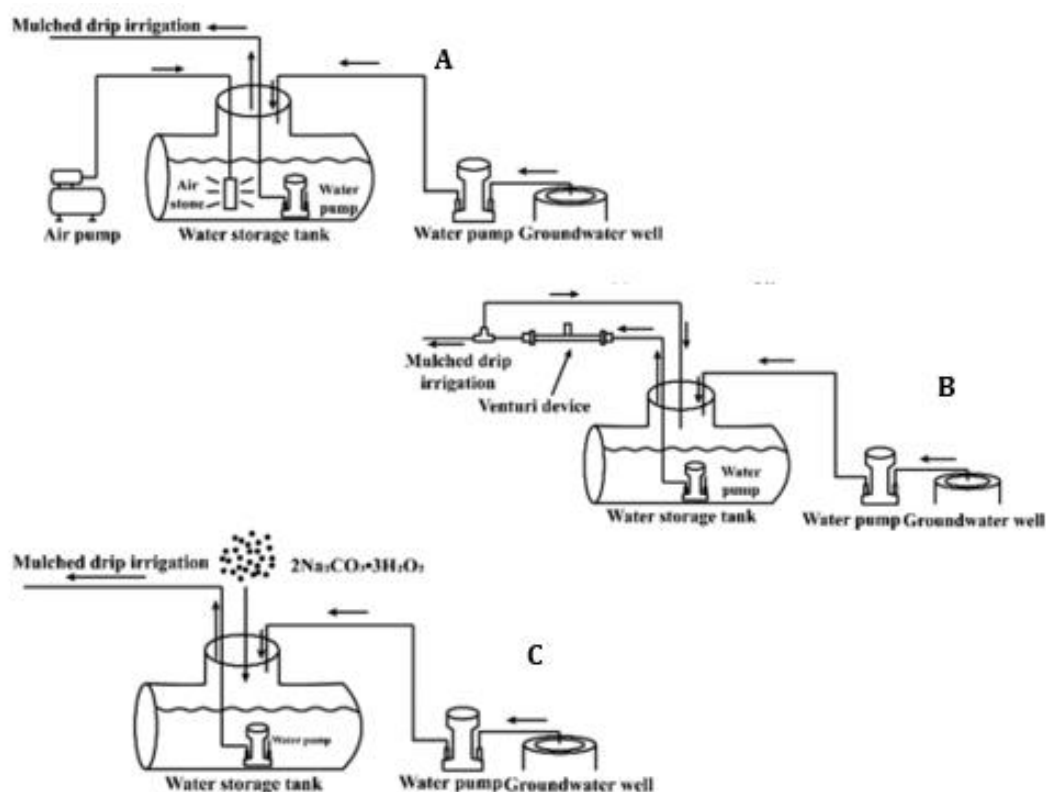


Figure 11. Schematic diagram of each method of oxygenation of the irrigation device (or source). A) Mechanical Oxygenation; B) Venturi Oxygenation; C) Chemical Oxygenation (adapted from Wang *et al.*, 2023).

Khan *et al.* (2020) provide a simplified depiction of the general MNB irrigation system, as illustrated in Figure 12. In the conventional method, bubbles are generated through gas dissolution under pressure in an aqueous medium and also releasing gas as the bubble pressure decreases. Here, the main components of the system include: a gas tank or dissolution tank, where the irrigation water is oxygenated; a water pump, which pumps water at a certain pressure to meet the gas in the respective tank; an air compressor, to inject air into the gas tank. In this system, the high-pressure gas-water mixture enables its supersaturation and dissolution, thus, the gas precipitates out of the water in the form of MNBs due to sudden decompression.

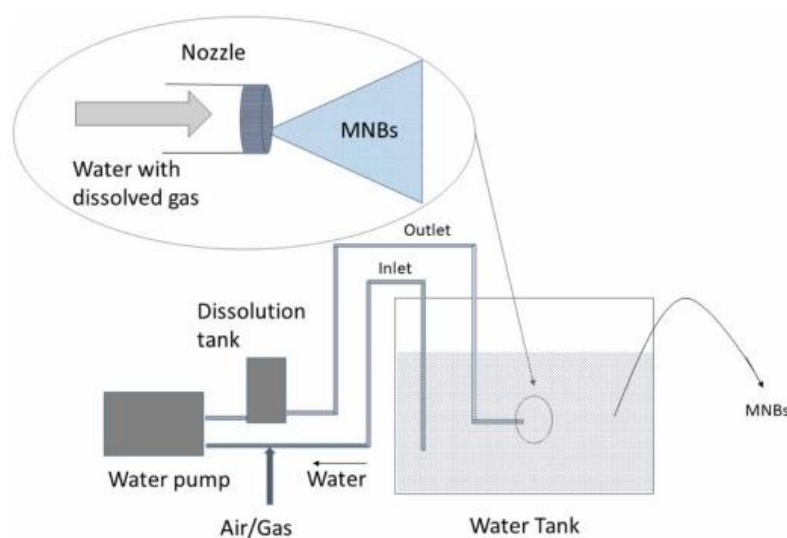


Figure 12. Schematic diagram of an MNB system (adapted from Tasaki *et al.*, 2007).

Thus, there are three distinct types of bubbles utilized in this type of technology. Macro bubbles or common bubbles, with diameters ranging between 100 μm and 2 mm, which quickly reach the water surface and eventually collapse. In contrast, there are nanobubbles (NB), which typically have a diameter $<1 \mu\text{m}$ but when they assume a diameter $<100 \text{ nm}$, they remain suspended in the liquid medium randomly and for an extended period, thereby altering the physical properties typically observed in water. Figure 13 succinctly illustrates the behaviour of the three distinct types of bubbles generated for soil oxygenation in liquid media.

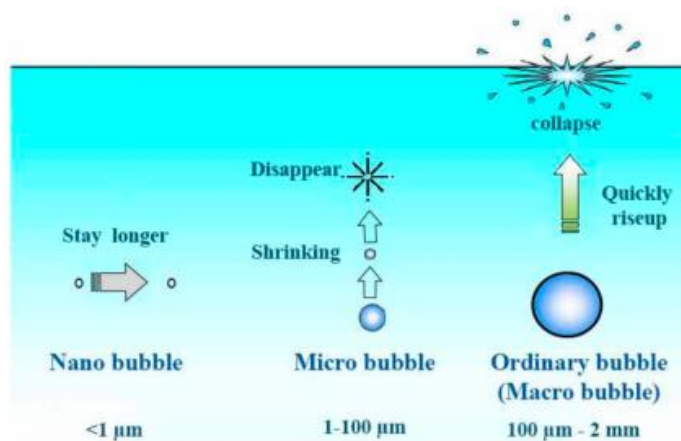


Figure 13. Behavior of macro, micro, and nano bubbles in liquid medium (Khan *et al.*, 2020).

Thus, nanobubbles (NB) are the type of bubble applied to soil oxygenation, where a significant financial and intellectual investment has been observed. According to Pal *et al.* (2022), research into this innovative component has primarily focused on the process of generating and injecting NB of O_2 (oxygen), CO_2 (carbon dioxide), N_2 (nitrogen), and also O_3 (ozone). Besides the longevity of these bubbles, the author also asserts advantages such as the high solubility of these gases in water, increased leaf length, root length, biomass, plant height, and soil quality, among others. The author presents a more in-depth study regarding NB generated based on CO_2 (carbon dioxide). According to the author, these specific NB may offer advantages in terms of increased photosynthetic activity of plants due to the permeability characteristics of the leaves of these plants. Zhu *et al.* (2021) also present promising results regarding the utilization of CO_2 through the absorption/capture of this gas for agriculture after a combustion process, thus also contributing to limiting or mitigating the effects of climate change, envisioning a permanent reduction in the concentration of CO_2 , a greenhouse gas. However, the efficient utilization and harnessing of CO_2 post-combustion remains a challenge.

Figure 14 schematically represents a practical example of an agricultural irrigation system based on CO_2 nanobubbles (NB), suggested by Pal *et al.* (2022). In the case of the branch depicted in Figure 14.A in closed systems such as hydroponic cultures, the NB dissolved in water can be: sprayed under the leaves of plants to enhance their photosynthetic activity (Figure 14.A.3); dissolved in irrigation water, providing supersaturated oxygenation (Figure 14.A.4); or sprayed into the environment of the closed system for a specific period, increasing the CO_2 concentration in the system (Figure 14.A.5). In the case of the branch shown in Figure 14.B in open systems or fields, NB dissolved in water can be used: to reduce soil alkalinity (Figure 14.B.1); integrated

with other irrigation systems, with drip irrigation being the most commonly used by the majority of producers (Figure 14.B.2); and also through spraying techniques, similar to those in closed systems, as presented in Figure 14.A.3.

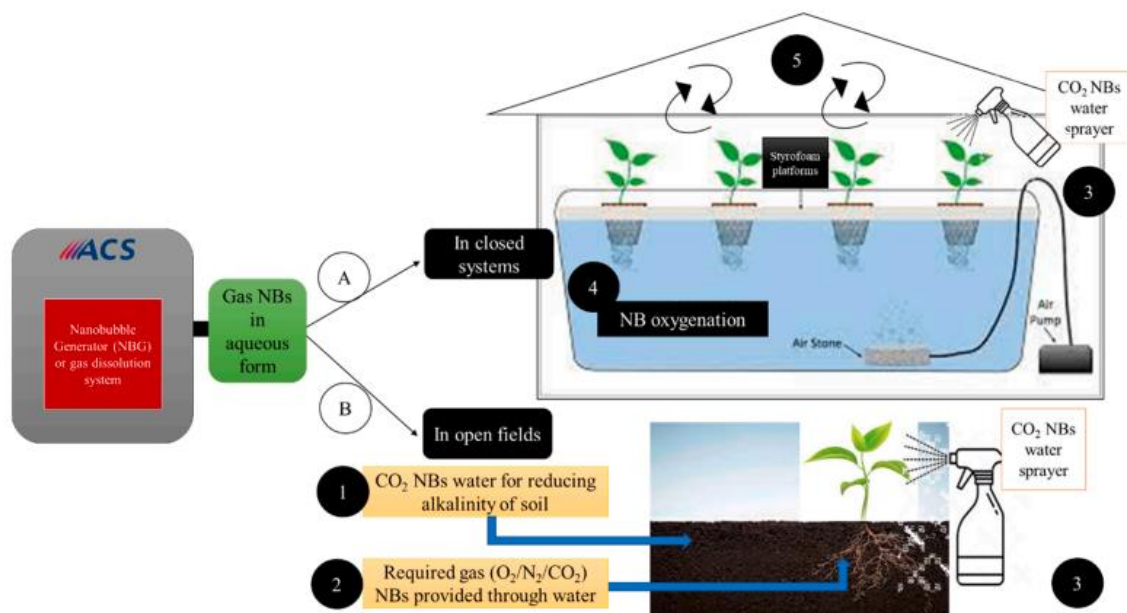


Figure 14. System schematic of CO_2 nanobubble (NB) application in agriculture. A) In closed systems, for example, hydroponic cultures; B) In open systems or fields (Pal *et al.*, 2022).

In Figure 15, results obtained regarding the use of CO_2 based fertilizers are presented and compared with other fertilizers in parameters such as: plant growth (cm), where I), (II), and (III) indicate the groups of plants: control fertilized with deionized water (CK), 20% $CO_2 + NaRcn$ (sodium cyanide), and 100% CO_2 , respectively (Figure 15.A); concentrations of CO_2 around the plants (ppm) (Figure 15.B); photosynthesis rates ($\mu mol CO_2 m^{-2} s^{-1}$) (Figure 15.C); plant height (cm) (Figure 15.D); as well as biomass generated (g) in cotton cultivation (Figure 15.E).

Figure 16 presents results obtained with the implementation of this technology in tomato cultivation, in terms of final product quality, leaf length, and root density.

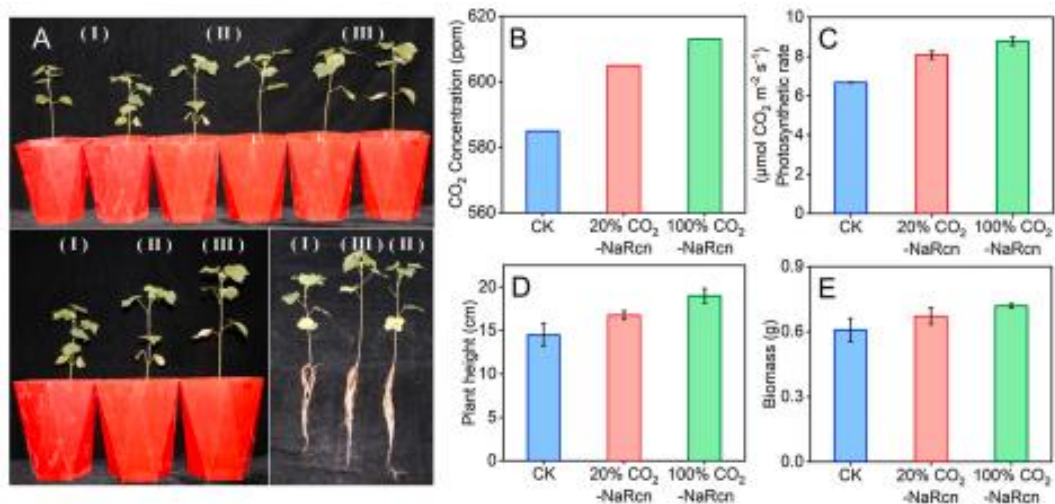


Figure 15. CO₂-based fertilization effects on cotton cultivation. A) Plant growth; B) Concentration of CO₂ around the plant leaves; C) Photosynthesis rates; D) Plant height; E) Plant biomass (adapted from Zhu *et al.*, 2021).

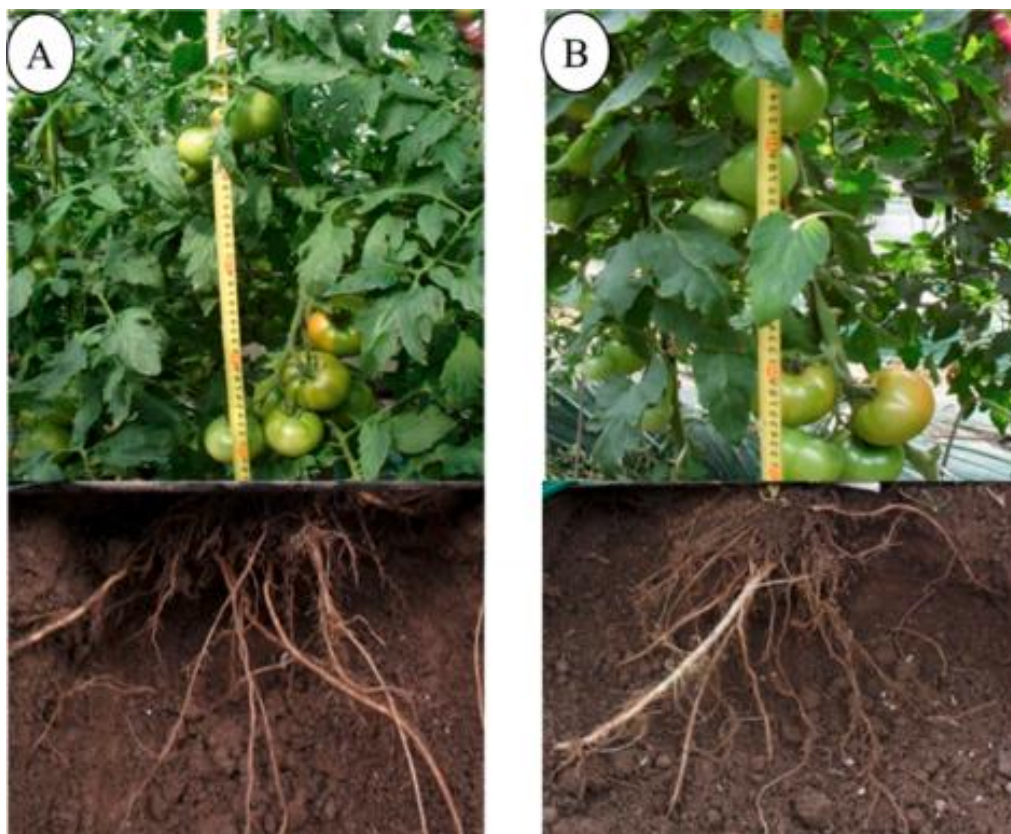


Figure 16. CO₂ nano-bubble oxygenated irrigation water effects on tomato cultivation, for controlling the quality of the final product, leaf length, and root density. A) Control plant, irrigated with non-oxygenated water by CO₂ nano-bubbles; B) Plant irrigated with oxygenated water with CO₂ nano-bubbles (adapted from Pal *et al.*, 2022).

Marcelino *et al.* (2023) provide a systematic review that includes the description of this technology, and state that in a way to ensure the economic success and sustainability of this irrigation technology, technoeconomic analyses must be conducted for the various application of NB and integrations with other technologies. As this technology accessibility expands, more integrations will emerge, therefore versatility and scalability will be key features for the widespread deployment of this technology.

2.7. Responsive Drip[®]

The Responsive Drip[®] is a final product resulting from the symbiosis of two previously mentioned technologies in this chapter, namely the NIs and the SSIs. This new irrigation technology utilizes a piping system (GrowStream[™]) that is fully responsive to the irrigation and fertilization needs of plants. Akbar *et al.* (2023), mention that this technology is based on two essential stages: root signals and the Response of GrowStream[™], followed by the initiation of irrigation, in that respective order.

In the subsurface, the life of plants and their roots is extremely dynamic, where all plants are characterized by a wide spectrum of chemical signals in the rhizosphere (root zone). One of the most important functions is the absorption of water and different nutrients. Depending on the environmental variables (temperature, wind, rain, etc.), the emission of root signals allows plants to absorb the necessary elements from the soil, thereby achieving constant adaptation to the environment and its respective growth, vital for their development. The GrowStream[™] technology uses this interpretation of signals emitted by roots to create a symbiotic relationship between plant roots, soil, and available water resources, employing approximately 100,000 nano-pores ranging from 10 to 900 nm in diameter per square centimetre of piping, the functionality of which is visible to the naked eye, as demonstrated in Figure 12. These characteristics facilitate the natural flow of water within the piping. It directly interprets the water potential difference and system pressure. In summary, the water potential difference alone can ensure flow in the system in the absence of system pressure, but both parameters guide the internal flow of the piping if there is available water height.



Figure 17. Installation and test run of the GrowStream™ tubing

In conclusion, this technology proves to be extremely efficient, low-pressure, low-energy-cost, and low-maintenance, ensuring long-lasting, balanced, and stable irrigation of crops. It has undergone successful testing in various climates, fauna, and flora, ranging from the Mediterranean climate of Monterey in California, United States of America, to the tropical savanna climate found in Nigeria. However, the main limitations of this system undoubtedly include the high installation costs and the availability of replacement parts, particularly in remote areas, in the event of any system issues. It is worth noting that conclusive data regarding resistance to rodents and different types of wildlife that may interfere, damage, or disrupt the system, soil disturbances during mid-season agricultural operations, and pressure drops in the main line and system clogging situations are currently lacking.

2.8. Conclusive Remarks

This chapter presented an overview of various irrigation methods, including non-localized systems like sprinklers (SIs) and center-pivots (CPIs), as well as localized systems like surface drip irrigation (SDIs), nano-irrigation (NIs), and subsurface irrigation (SSIs). It also discussed emerging technologies like soil oxygenation with CO₂ nanobubbles and the responsive drip system. The advantages, limitations, and applications of some methods and technologies were discussed. Also some evaluation studies, where the main focus is the effectiveness, efficiency and sustainability of the systems were assembled establishing a comparison between irrigation systems, but not the less, the need for more studies of this kind is also emphasized, mainly on the cutting-

edge technology namely the soil oxygenation through CO_2 nano bubbles and the *Responsive Drip*®. This sets the stage for Chapter 3, which will describe the materials and methods used to test the SLECI system.

3. Materials and Methods

After presenting the most representative agricultural irrigation technologies available in the market, ranging from the simplest to the emerging experimental technologies that are not accessible to all producers, this chapter aims to provide a detailed overview of the new technology that underwent testing and comparison with the DIs, at two field tests, one of peach trees and other of cherry trees. Additionally, it covers all the materials and methods involved in the monitoring and evaluation processes, including the lands, crops and sensors.

3.1. The SLECI system (SLECI) technology and general setup

For centuries people have been using fired clay in irrigation techniques. The roots of this practice can be traced back to ancient Rome with the development of the *Oya* technology (Figure 18.A). Known as SLECI - Self-regulating Low Energy Clay tube Irrigation, this method uses clay components (Figure 18.B) that are inspired by the irrigation principles of *Oyas*. These clay tubes uses their nature to accurately interpret moisture levels allowing for self-regulation and energy conservation during the water distribution process through the irrigation line. In essence, the SLECI components combine different irrigation technologies, such as NIs and SSIs into a single system, following the DI principle.



a) Ancient *Oya* technology
(Chapin, 2023)



b) SLECI elements before
installation

Figure 18. *Oya* technology vs SLECI technology.

The key elements needed for this irrigation setup include a water tank, two water filters (50 μm and 1 μm) to avoid blockages in the system, a thin-walled DN16 irrigation hose and one SLECI component for each tree. The SLECI components are placed underground and covered with a thin layer of sand (Figure 19.A). This layer is placed in a hole that is 6-8 mm wide (Figure 19.B), which is created using a gasoline-powered auger (Figure 19.C). The main reason for this sand cluster is to help water move deeper into the soil, where the roots of the plants are consistent, about 60 cm below the surface. In this way, only the target fruit trees get water, so less water is wasted on weeds and undesired in the field, besides the water savings due to less evaporation and evapotranspiration. A diagram showing the SLECI setup from the side is shown in Figure 20 to make things clearer.

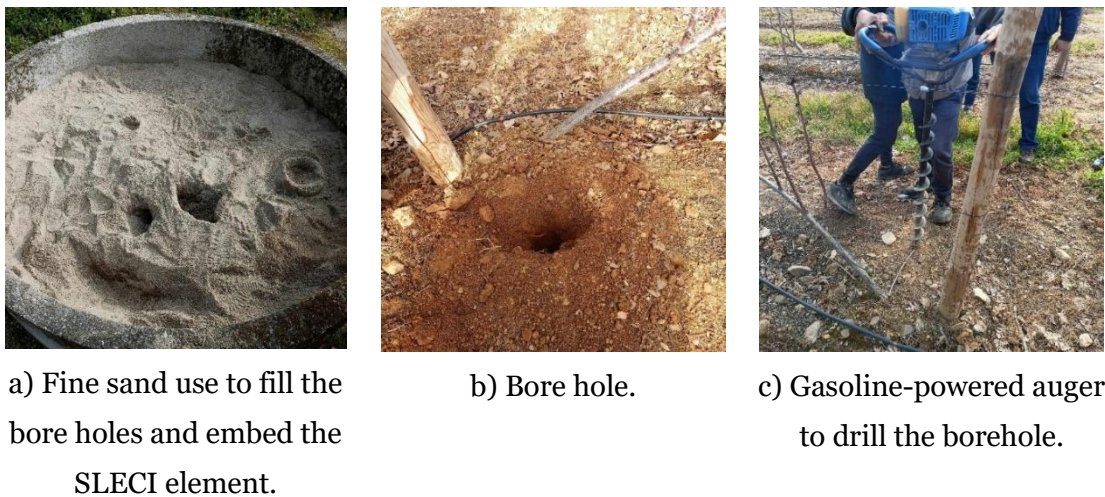


Figure 19. SLECI bore hole drilling process and components used

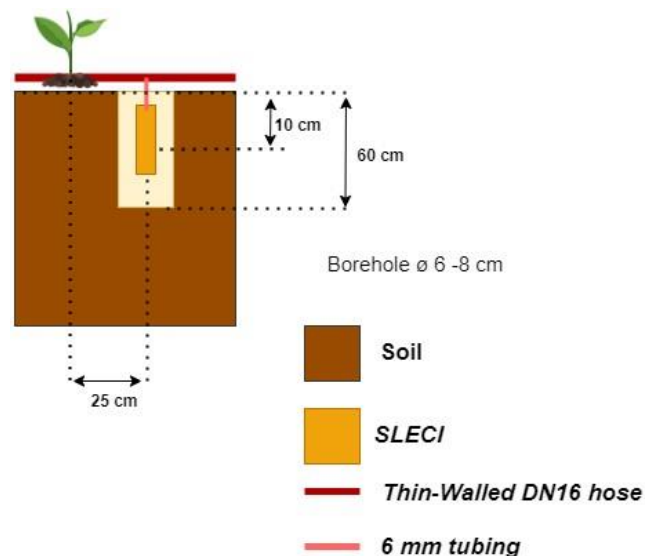


Figure 20. Schematic side view of the SLECI after installation

Once these elements are all set according to Figure 21 and a water pressure of around 0.2 bar (2.9 psi) at the end of the line is ensured, irrigation can properly start. Worth noticing that to set the system, there may be a need for some extra irrigation accessories and components like T connections or taps, for example, depending on each case and on each terrain properties or previous systems installed as shown in Figure 22.

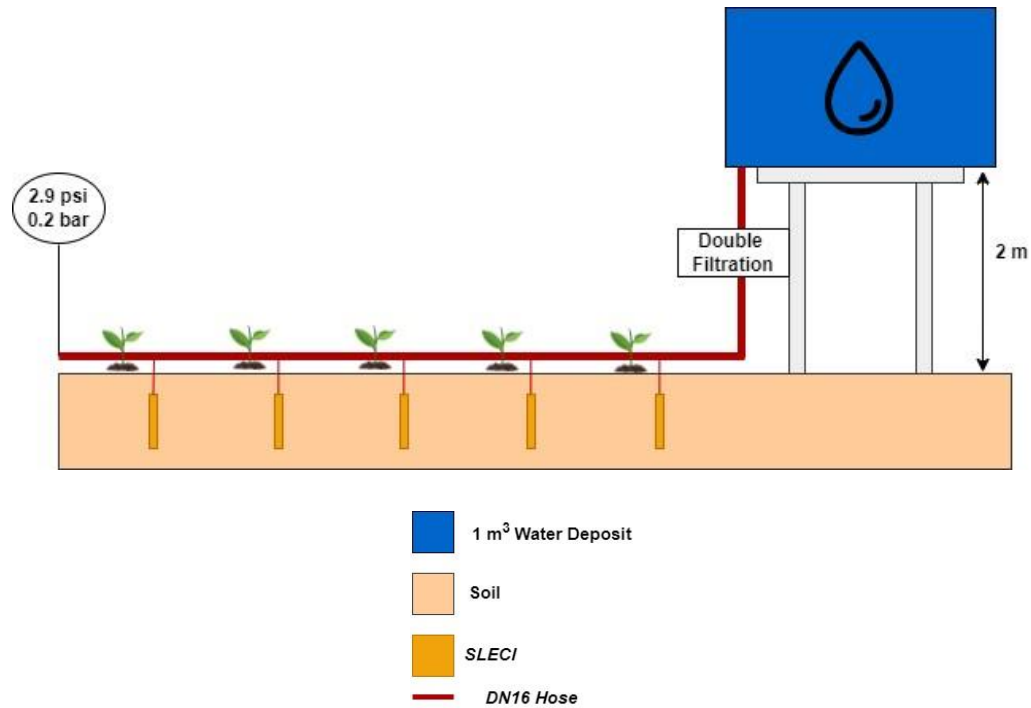


Figure 21. Schematic representation of the ideal installation of SLECI, considering no slope on the irrigated field



Figure 22. Extra accessories and components needed to put the system up and running on the Portuguese test fields.

3.2. Technical irrigation components

Each field has different characteristics, and so each field or orchard needs proper system dimensioning and adequate irrigation hardware selection. As mentioned before, the key components to ensure irrigation on the SLECI are: a) a water tank; b) water filters, and c) thin-walled *DN16* irrigation hose.

3.2.1. Water tank

The water source for both systems is a basin (Figure 23), and once the water is pumped from there it goes through some initial filtration before being stored in a $1m^3$ water tank (Figure 24). This water tank is fixed in a treated steel structure at roughly $2m$ height so that the recommended pressure of 2.9 psi (0.9 bar) is assured at the end of the irrigation line. This way, from the water tank forward, the whole system works just by gravity and fluid dynamics with no energy or electrical consumption to ensure proper irrigation, but on the other hand, the SLECI are quite sensible to the field topographies (such as field slope) and a careful study and assessment must be conducted to ensure that the water tank is at the correct height to ensure irrigation and the well-functioning of the elements.



Figure 23. Peach trees test field irrigation water source basin



a) Cherry trees field test water deposit



b) Peach trees field test water deposit

Figure 24. Water tanks for the two field tests

3.2.2. Water filters

On both fields, when the water is pumped from the respective basins, it goes through a filtration system before being stored in the water tank. For the Cherry Trees field test, it is a 130 μm water filter (no sand filter), while for the Peach Trees, it is also a 130 μm but together with 2 sand filters (Figure 25). This filtration system before the tank is to prevent the SDIs from clogging, because either for the SLECI or the SDIs the irrigation water source is the same. The SLECI, due to its porous characteristics needs some extra filtration, in this case a 50 μm (optional) and a 1 μm water filter (mandatory). These filters are encapsulated (Figure 26) and placed at the outlet of the water tank before the water flow reaches the clay tube elements. Figure 27 represents in a schematic way how the water flows inside the 50 μm and 1 μm water filters capsules.



Figure 25. Primary water filtration system before the 1 m³ water tank, at the Peach Trees field test



Figure 26. SLECI's filtration system and capsule in the back, to be placed by the water tank output

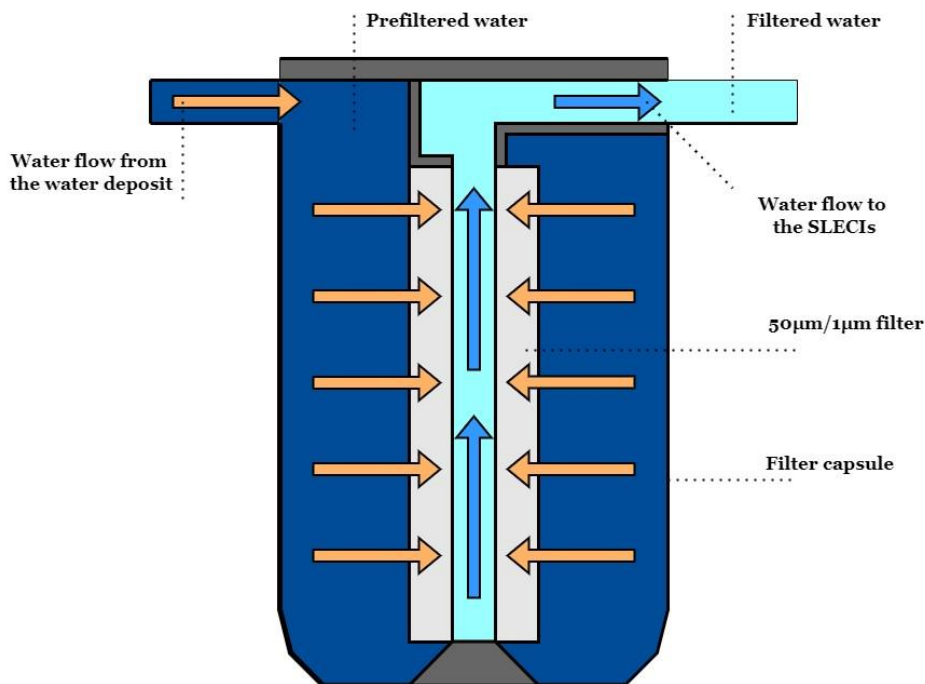


Figure 27. Schematic representation of the water flow inside the SLECI's filtration system capsules

3.2.3. Thin-walled DN16 hose

The *DN16* hose is the visible part of the SLECI's at the surface while its clay tube elements are buried, as Figure 28 shows. This hose is of general use in agriculture, especially on the SDIs, but instead of fixing drippers at the hose, the clay elements are fixed through a simple connector. This way, the SLECI's can be considered of extreme versatility, easy installation and of simple transition when the producer decides to discard its old irrigation technology and adopt this new one.



Figure 28. The SLECI's thin-walled DN16 hose

3.3. Field tests summary and SLECI installation

The main purpose of both field tests is to compare the SLECI technology with the most commonly found technology amongst agricultural producers, SDIs. That way, the Cherry Trees and Peach Trees test field were located at Seminário do Fundão (40.13347763178621, -7.483322202207046) (Figure 29.A) and Mata da Rainha, at Catraão (40.1190023, -7.3749630) (Figure 29.C), respectively. The test fields information is summarized in Table 3 and the installation process extended from the 13th to the 16th February 2023.



a) Cherry trees field test



b) Cherry field test location.



c) Peach trees field test



d) peach trees field test location

Figure 29. Portuguese test field sites location. A) Cherry Trees test field at Seminário do Fundão; B) Peach Trees test field at Mata da Rainha

Table 3. Test field summary.

| | Field Test 1 | Field Test 2 |
|----------------------------|-----------------------------------|-----------------------------------|
| Climate³ | Hot-summer Mediterranean (Csa) | Hot-summer Mediterranean (Csa) |
| Soil Type | Clay | Loamy clay |
| Water Source | Basin | Basin |
| Crop practised | Cherry | Peach |

3.3.1. Cherry Trees field test

Installation at the Cherries Trees test field was carried out on the 13th and 14th February 2023.

The test plot consisted of 80 trees around 4 years old, 20 trees distributed in 4 rows, each with an irrigation line extension of roughly 20 meters and distanced 2 meters from each other, as shown in Figure 30. The two irrigation systems (SLECI and SDI) are distributed in the 4 irrigation lines, two for each, which means 40 trees per irrigation system.

The field test water source is a basin and the water is pumped and immediately filtered by a 130 μm water filter (no sand filter), and then goes through a T connection to split the water flow in half. One half is used directly on the SDIs and the other half is stored at the water tank for the SLECI, but before getting there it still has to be filtered at the outlet of the tank by the 50 μm and 1 μm water filters in a way to avoid the SLECI clogging.

Before getting to each irrigation technology, the water must first go through a water meter, for monitoring purposes, and then it once again proceeds through a T connection, to split the water flow between the two irrigation lines.

By the time of installation, water pressure was accessed at the end of both SLECI irrigation line, and a value of 0.2 bar was registered. Then, after this successful test run, the clay tube elements were ready to be buried and irrigation ready to be started. Figure 31 illustrates the SLECI elements, on the moment of the test run, and ready to be buried on de fine sand.

³ Köppen-Geiger classification

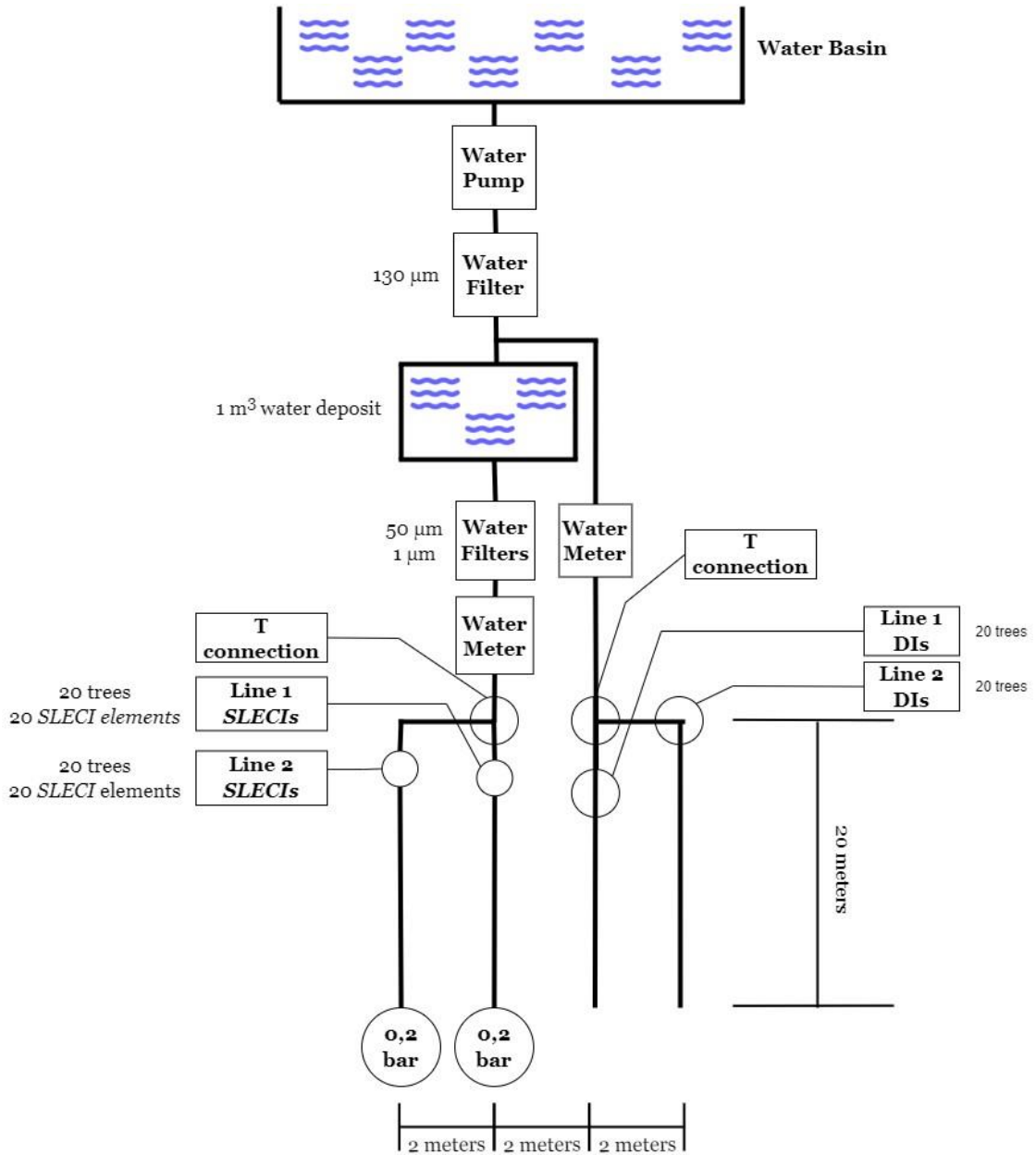


Figure 30. Cherry Trees test field Irrigation scheme



Figure 31. SLECI main line before installation underground, at the moment of the test run

3.3.2. Peach Trees field test

Installation at the Peach Trees field test was carried out on the 15th and 16th February 2023.

The field plot assigned for the tests consisted of 3 main irrigation lines, making a total of 97 already develop and pruned peach trees. That way, it was decided that two rows, amounting to 49 trees should be irrigated with the SLECI technology and then one row with a total of 48 trees should take the SDIs. Figure 32 shows the detailed irrigation schematic of the test field, similar to the approach adopted in the cherry trees test field. Besides the similarities there is a slight terrain slop to be registered. It was decided to fix the 1 m³ water tank still at 2 m height, for an extension of 50 m on both SLECI lines.

The main difference between this test field and the cherry trees one is the filtration method right after the water basin, which on this case is established by a 130 µm and 2 water sand filters.

Similarly to the peach trees test field, by the time of installation, the water pressure was checked by the end of both irrigation lines, and a pressure of 0.32 and 0.23 bar was registered for irrigation lines 1 and 2, respectively. Noticeably, water pressure by the end of irrigation line number 1 of the SLECI is slightly higher than recommended, but the decision was made by the international technical partners to keep with the testing under

these conditions, so that a study of the system behaviour under these conditions on a field practical test could be conducted and further conclusions could be reached in the future.

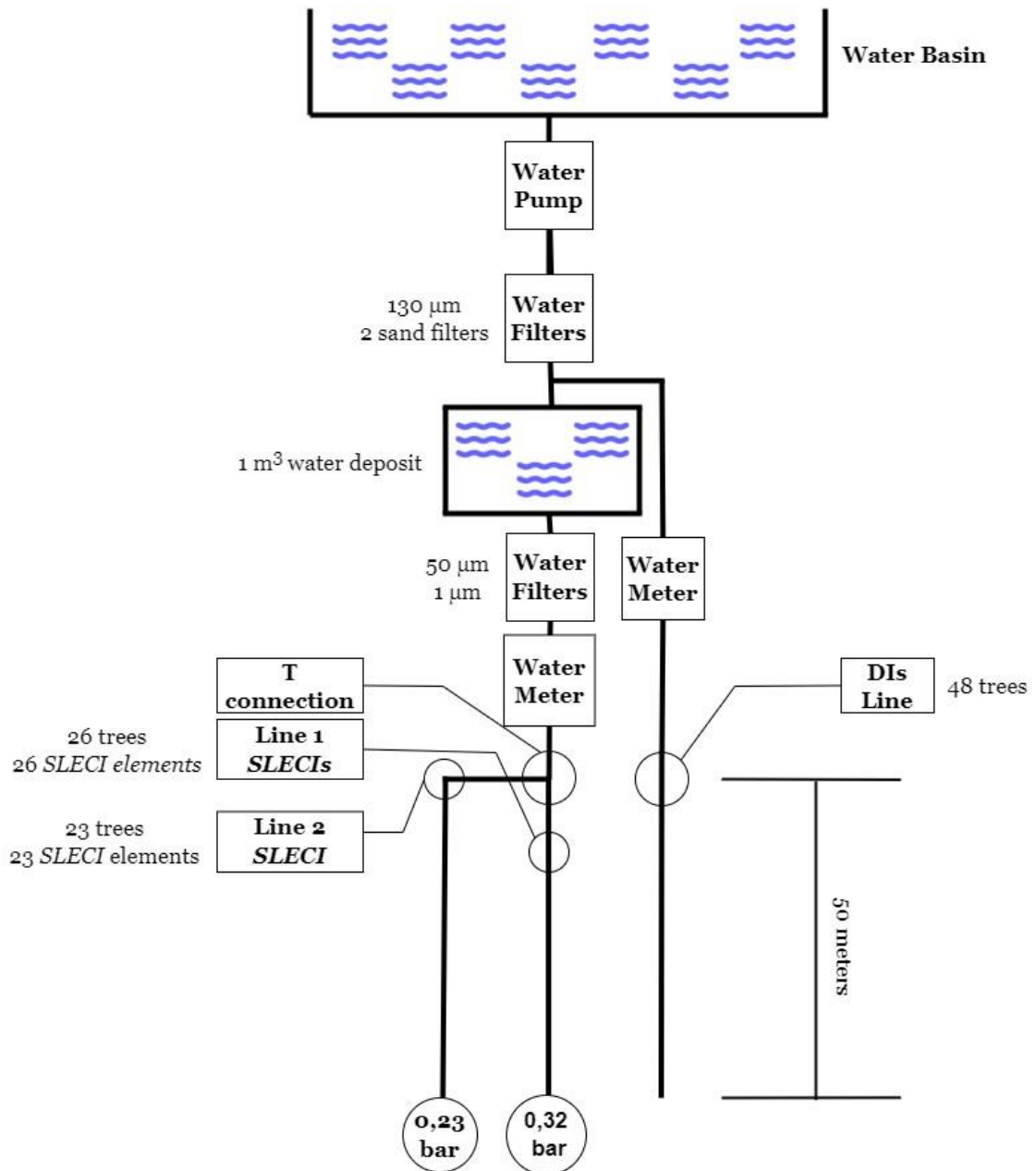


Figure 32. Peach Trees test field Irrigation scheme

3.4. Monitoring components

So that proper installation of the SLECI, testing, evaluation and comparison with the SDIs technology when applied to cherry and peach trees could be conducted, a monitoring system is required.

3.4.1. Digital pressure gauge

Because the SLECI is a fully mechanical irrigation system powered only through gravity, pressure changes must be carefully monitored and interpreted. Thus, a digital pressure gauge (Figure 33) is essential to check water pressure at installation and through the whole irrigation season. A regular water pressure inspection at the SLECI main irrigation line end, will ensure a correct functioning and avoid extra costs related to hydric stress of the plants or to a malfunctioning on the system.



Figure 33. Digital pressure gauge

Digital pressure gauges often work by converting the physical pressure of the water into an electrical signal that can be numerically displayed. The core component of these gauges is a pressure sensor, that due to robustness and longevity when compared with resistive sensors (Bandorf *et al.*, 2006) is usually a piezoresistive pressure sensor and as Hong-quan (2015) mentions in the study he conducted to design and build a digital pressure gauge based on a STM8S microcontroller. This device's purpose is then to measure a force exerted by water against a surface area which is then converted into an electrical signal and displayed in a digital format.

3.4.2. Smart water meter

The smart water meter device used is an *Axioma Qalcosonic W1* (Figure 35). This water meter provides important information regarding water flow rates, water consumptions, air temperatures amongst other less relevant information for this study.

The device uses an ultrasonic flow meter. This kind of flowmeters, making use of dynamics of ultrasonic energy transmission in liquid mediums, provide an accurate measure of water flow rate (Masasi *et al.*, 2017), and thought that data, an accurate water consumption. Figure 34 provides a detailed schematic of the most common configurations on this meters, mounting the transducers following the direct transmission Z method (Figure 34.A), the single reflection V method (Figure 34.B) and the multiple reflection W method (Figure 34.C). These configurations should be adopted taking the monitoring needs and water flows to be expected, for example, the Z method where transducers are mounted on different sides of the pipe, provides more accurate readings when submitted to larger diameter pipes with higher flow rates, meanwhile the V and W methods are better suited for smaller diameter pipes and lower water flow rates.

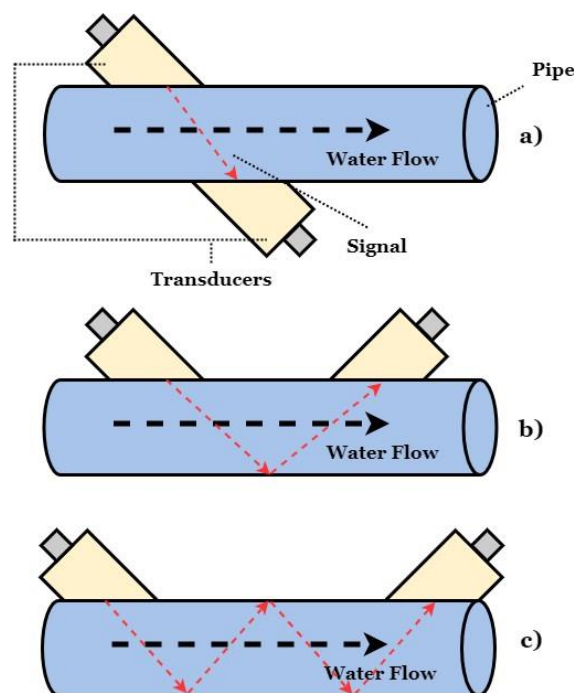


Figure 34. Common ultrasonic flow meter mounting configuration. a) Z method; b) V method; c) W method (adapted from Masasi *et al.*, 2017)

Thus, the receiving transducer must be perfectly aligned with the emitting one to receive the reflected signal (or direct signal in the Z method case). Then, the flow meter

software, taking into consideration parameters such as the pipe material and wall thickness, is able to accurately calculate the water that flows through the meter and from there, also calculate water consumptions.

The *Axioma Qalcosonic W1* has multiple communication protocols available, such as *M-Bus Wireless*, *NB-IOT* or *LoRaWAN*, and its battery lifetime can go up to 16 years, depending on the chosen communication protocol. NFC and optical interfaces are also integrated for data exporting in a .csv (comma-separated values) file or for parametrization of the meter. Besides all that, it is also possible to retrieve the smart water meter volume consumption and current flow data or check for multiple warning through direct reading of the device, as it can be seen in the representation of the device's 9 digit multi-line LCD in Figure 36. Table 4 shows the detailed technical information regarding the smart water meter.



Figure 35. *Axioma Qalcosonic W1* smart water meter

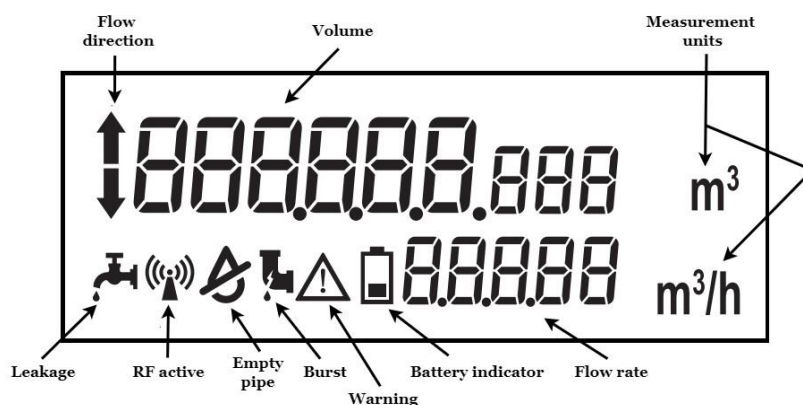


Figure 36 . Water meter 9 digits multi-line LCD for direct reading of the data and warnings (adapted from Qalcosonic W1, n.d)

Table 4. Axioma Qalcosonic W1 technical parameters.

| | |
|---|-------|
| Nominal flow rate, Q_3 [m^3/h] | 1.6 |
| Nominal diameter [\emptyset] | DN15 |
| Minimum flow rate, Q_1 [m^3/h] | 0.005 |
| Dynamic range, Q_3/Q_1 [m^3/h] | 315 |
| Transitional flow rate, Q_2 [m^3/h] | 0.08 |
| Starting flow rate, [m^3/h] | 0.001 |
| Maximum flow rate, Q_4 [m^3/h] | 2.0 |

The different flow rates are calculated using Equation (7).

$$Q = \frac{V}{\Delta t} \quad (7)$$

Where, V is the volume, measured in cubic meters (m^3), and Δt is the elapsed time for the correspondent volume of water consumed, measured in hours (h).

Thus, all volumes provided by the manufacturer are given in cubic meters per hour elapsed (m^3/h).

The nominal flow rate, Q_3 (m^3/h) is the flow rate under nominal operating conditions. This means the ideal flow rate conditions for which the device has been designed for its multiple applications and when subjected to a load.

The nominal diameter (\emptyset) DN15 means the device has a 15 mm of nominal diameter, so both the inlet and outlet connections have approximately 13.5 mm pipe inner diameter.

The minimum flow rate, Q_1 (m^3/h) is the lowest flow rate where the water meters can measure within the maximum permissible error of the device.

The transitional flow rate, Q_2 (m^3/h) is the flow rate at which the maximum permissible error registers a decrease.

The maximum flow rate, Q_4 (m^3/h) is the highest flow rate at which the meter will be within the maximum permissible error.

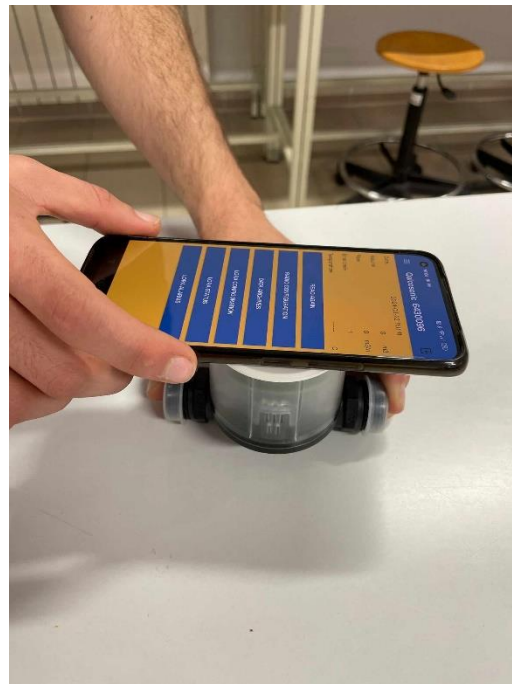
3.4.2.1. NFC interface

First, to successfully operate with this interface, the user must have an Android device compatible with NFC (Near Field Communication) technology. Then the whole interface is based on the meters optical interface on the top part of the meter (Figure 37.A), so with the NFC option turned on, the device must be placed on the optical head, just as shown in Figure 37.B.

When communication is established, is possible to move into the next stage, which is the Qalcosonic W1 app interface. The moment after the meter has been recognised, the initial menu will pop up, as shown in Figure 38.



a) Axioma Qalcosonic W1 optical interface on top of the meter



b) Placement of the Android device so that communication can be established through NFC

Figure 37. NFC communication from the meter to the Android device setup.

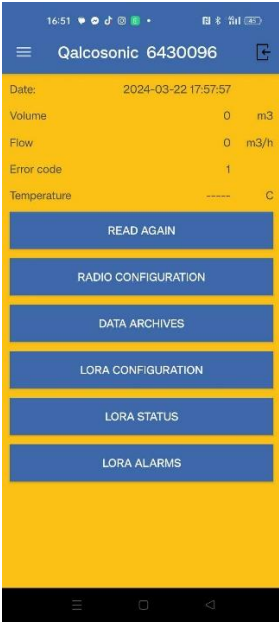


Figure 38. Water meter app initial menu.

Then, the user must choose the button “DATA ARCHIVES” and will be redirected to the proper page (Figure 39), where he can choose to get access to hourly, daily, monthly or annual data.

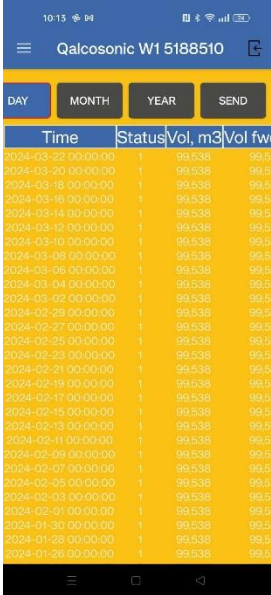


Figure 39. “DATA ARCHIVES” page.

By hitting the “SEND” button, the sharing window will pop up (Figure 40) and the file will be locally saved at the directory: /internal storage/Android/data/com.axioma.qalcosonic.configurator/files/Download.

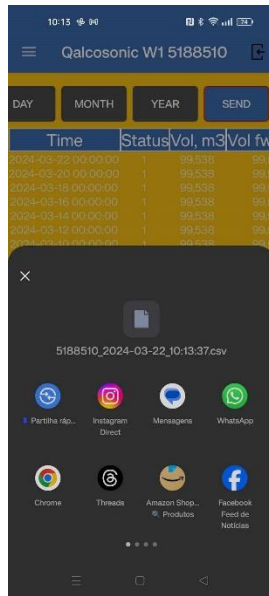


Figure 40. Sharing window for data file sharing and download.

Finally, the downloaded file will be presented in the format shown in Figure 41, evidencing the smart meter serial number and the date and time of the data acquisition through the NFC interface.

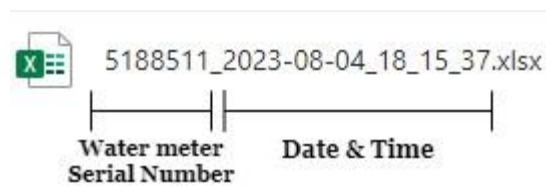


Figure 41. Downloaded file format, with the water meter serial number and acquisition date and time on the file description.

3.4.2.2. LoRaWAN and The Things Network interface

LoRaWAN (Long Range Wide Area Network) is a protocol for wireless, low-power, wide area networks (LPWANs) designed to wirelessly connect battery-operated devices to the internet in regional, national or global networks. The communication is then

established through devices, who communicate with a gateway that loads the devices data to the server, which on this case study is TTNv3 (The Things Networks v3). Figure 42 shows a simplified scheme of the system set-up and interface between components.

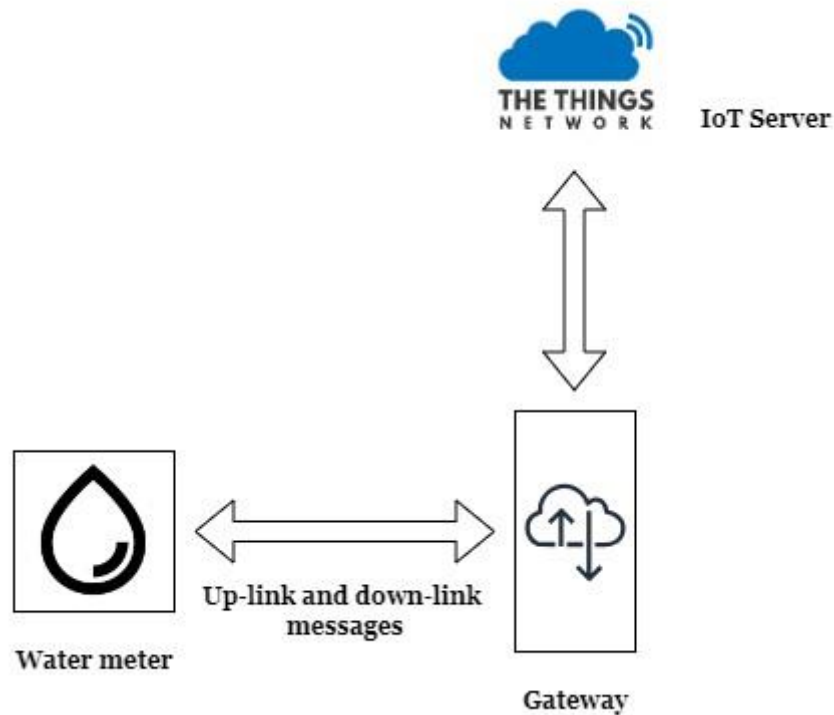


Figure 42. Data flow within a TTN (The Things Network) IoT server network.

On the LoRa and LoRaWAN interfaces, up-link messages are the ones containing the data-load from the sensor that after being received must be decrypted. Then, the downlink are status messages exchanged between the gateway and devices, so that the user may have access and be notified of possible network error on the communication chain, and they can also be used to remotely set some device configurations remotely.

Now devolving into the interface itself, the user must first sign up to the TTNv3 platform, and after that an application must be created, which will be linked to this specific user. To do so, the user has a “+ Create Application” button (Figure 43).

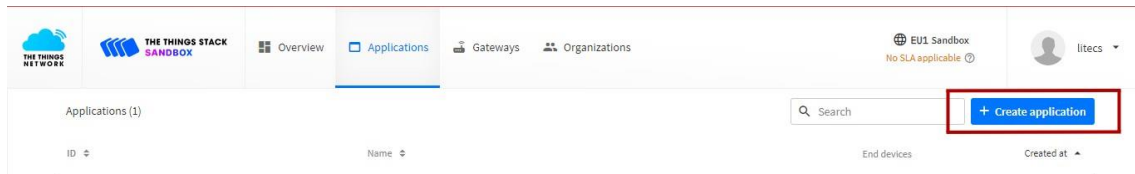


Figure 43. First steps after registering on the TTNv3 (The Things Network v3) platform.

Now, the user will be redirected to a “Create application” page, where he shall provide a suitable ID for the application, a name for the application (optional) and also a description (optional) (Figure 44).

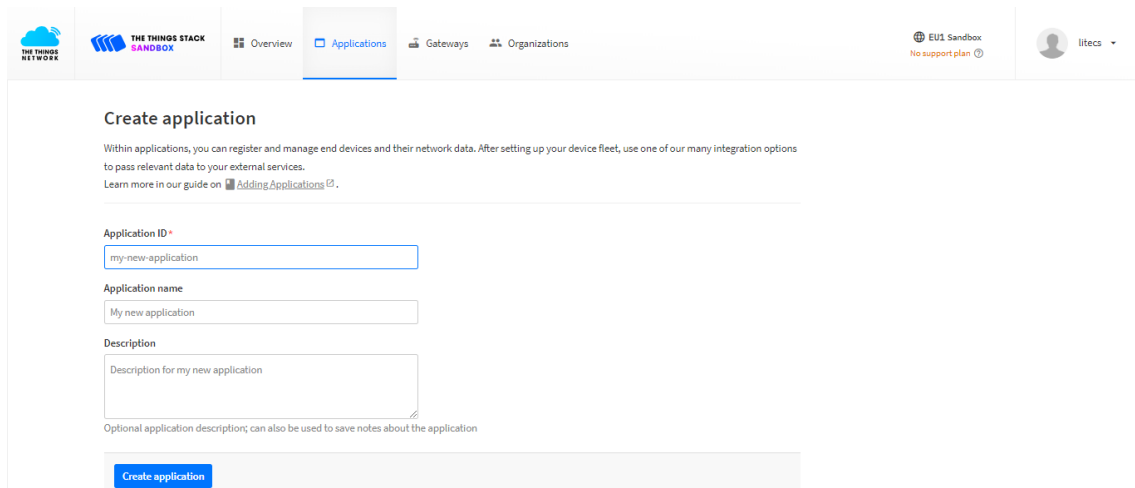


Figure 44. Creating an application on the TTNv3 (The Things Network v3) platform

After the application has been created, everything is set so that different sensors and devices can be added to the application. To do so, the user must go to the “end devices” tab, by the right side, and then select the register end devices button. After this, the user will have to fill some technical data regarding the end device he wants to add (Figure 45).

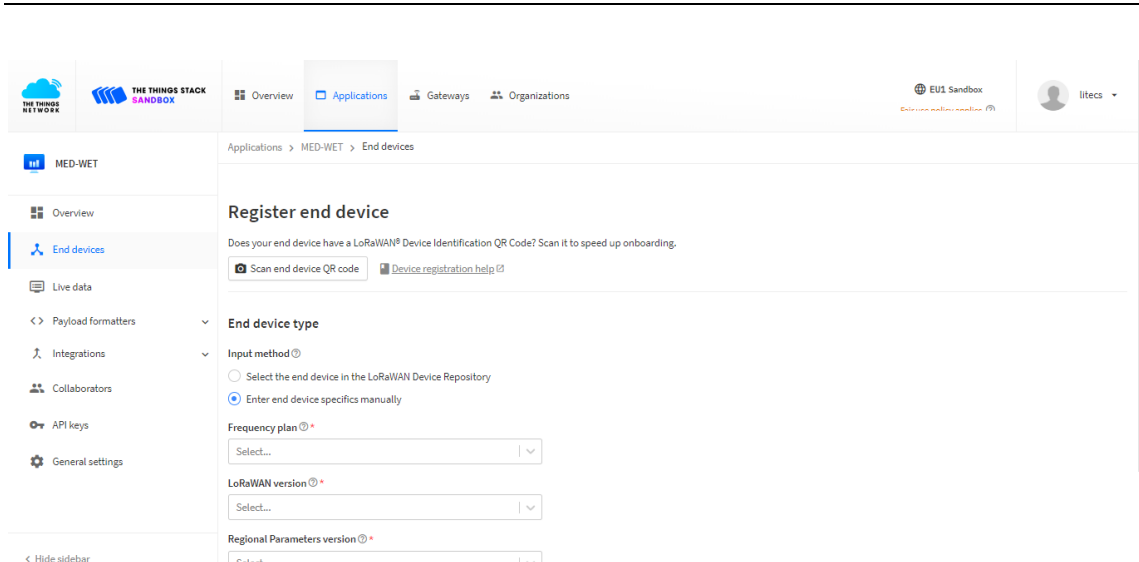


Figure 45. Adding end devices to the TTNv3 (The Things Network v3) platform.

On this case study, the end devices were the water meters, and since they are not included on the LoRaWAN device repository and do not have a QR code to be scanned, they had to be manually registered on TTNv3. To register them, the technical information was filled, namely the frequency plans (Europe 863-870 MHz (SF9 for RX2)), the LoRaWAN version of the end devices (LoRaWAN Specification 1.0.2), the regional parameters version (RPO01 Regional Parameters 1.0.2 revision B) and finally the JoinEUI (or AppEUI) and the DevEUI for each end device. After this process, the end devices were up running and already loading information for the gateways (Figure 46).

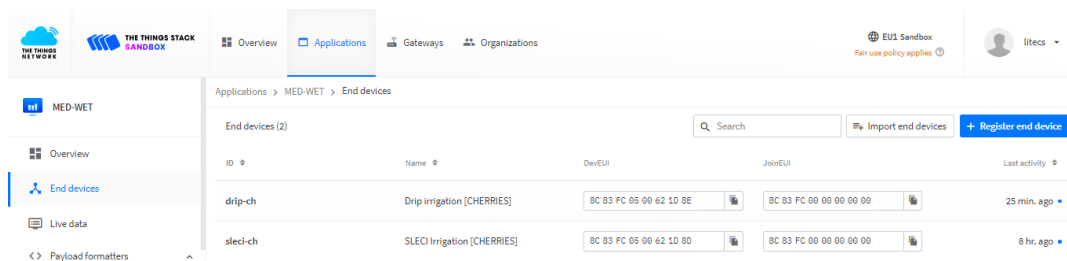


Figure 46. TTNv3 (The Things Network v3) platform final layout, with 2 end devices successfully registered.

After communication has been assured with the IoT server, data has to be storage somehow. This way, we made use of TTNv3 storage integration, which is the most

is retrieved from Instituto Português do Mar e da Atmosfera, n.d), such as soil water content (trough field capacity (θ_{fc}) percentages), reference evapotranspiration (ET_0), average air temperatures, average air humidity's, daily rainfall and cumulative rainfall values.

3.4.3.1. Soil water content

The soil water content parameter was determined through field capacity (θ_{fc}) percentages. This value is then dependent on the field's aptitude to sustain water, whether it is from rain or from irrigation. In other words, when this parameter reaches 100% the soil is completely moisturized and soaked, and when this parameter reaches 0% the soil is completely dry. Theerawitaya *et al.* (2023) and Zotarelli *et al.* (2021) present studies of this parameters on herbaceous crops (which according to the author have quite similar water requirements to fruit trees) and peach trees respectively, with both authors concluding that the most propitious time to trigger irrigation on these kinds of crops would be when $\theta_{fc} = 25\%$.

3.4.3.2. Evapotranspiration (ET_0)

Evapotranspiration (ET) means the loss of water from the soil surface through multiple combined processes and water evaporation natural phenomenon, such as plant transpiration, photosynthesis, soil transpiration amongst others (Brown, 1996). Thus, ET_0 is the reference (or potential) evapotranspiration, a more commonly used parameter in agriculture and plant water requirement estimations, which is commonly calculated using a weather-based model, known as the Penman equation, represented in Equation (8) (Valiantzas, 2006):

$$ET_0 = \frac{\Delta}{\Delta + \gamma} \cdot \frac{R_n}{\lambda} + \frac{\gamma}{\Delta + \gamma} \cdot \frac{6.43(f_u)D}{\lambda} \quad (8)$$

Where, ET_0 is potential – open water – evaporation or evapotranspiration (mm/d); R_n is net radiation at the surface ($MJ/m^2/d$); Δ is the slope of saturation vapor pressure curve ($kPa/^\circ C$); γ is psychrometric coefficient ($kPa/^\circ C$); λ is latent heat of vaporization (MJ/kg); f_u is the wind function, calculated by Equation (9) and D is vapor pressure deficit (kPa), calculated by Equation (10).

$$f_u = a_u + b_u u \quad (9)$$

Where, a_u and b_u are wind function coefficients and u is wind speed at 2m height (m/s).

$$D = e_s - e_a \quad (10)$$

Where, e_s represents the saturation vapor pressure (kPa) and e_a is actual vapor pressure (kPa).

Even though this model does not regard any consideration about soil or water heat exchanges and energies involved in these processes. According to Shuttleworth (1993), Linacre (1993) and Allen *et al.* (1998), the assumption of discarding these variables is acceptable for monthly or daily ET_0 estimations in practical hydrological applications.

3.4.3.3. Average air temperature, average air humidity, daily and cumulative rainfall

These are the most visible weather parameters and the ones that are most related to climate changes and have most influence on the crops and soil health because of their extreme unpredictability through the last years (Mahato, 2014; Corwin, 2020). Besides directly influencing the agricultural sector, these parameters are the general motor of crop yield and of extreme importance to be monitored in a way to make a proper assessment and evaluation of the SLECI and to study its behaviour under different natural conditions.

3.4.4. Water Use Efficiency

According to Bwambale *et al.* (2022), in agricultural irrigation terms, the Water Use Efficiency (WUE) is defined in terms of crop yield per amount of water to produce this referred yield. However, due to a general scarcity and concern with water stocks, this concept has gained a multi-area purpose throughout many different industries with the common goal of finding the best way to do things and saving the most water possible.

The concept can also be used in a way to compare irrigation systems and crop yields between different irrigation methods and technologies. Wang *et al.* (2020) conducted a comparative study on peach trees, between different irrigation system, using Equation (11).

$$WUE = \frac{Y}{IR} \quad (11)$$

Where, Y stands for the yield (kg) and IR stands for the irrigation water applied to the respective yield (m^3). In this study, Equation (5) was applied to each technology, in way to compare the SLECI and the SDIs technologies.

3.5. Conclusive Remarks

This chapter detailed the setup and implementation of the Self-Regulating Low Energy Clay Tube Irrigation (SLECI) system, including the technical components and field test information. The SLECI system was under direct comparison with the conventional Surface Drip Irrigation Systems (SDIs) in cherry and peach orchards. Key elements such as water reservoirs, filtration systems, and monitoring tools were described, emphasizing the importance of proper installation and maintenance to ensure accurate results. The chapter concluded with a summary of the field test setups and the initial conditions for both cherry and peach trees. Moving forward, Chapter 4 will present the experimental results and discuss the performance of the SLECI system compared to the SDIs.

4. Experimental Results and Discussion

On the following chapter, the results regarding weather information and technical data provided by the smart water meters are presented, together with a status report on both crops for the 2023 irrigation period. Appendixes A and B provide graphic information regarding the data cross-check for average air temperatures, average air humidity, daily and monthly cumulative rainfall, water consumption and water flows for both irrigation systems on the cherry and peach trees test field, respectively.

4.1. Introduction

The 2023 irrigation campaign was characterized by out of season rainfalls during the late spring/early summer period which happened three times during the irrigation season on the months of May, June and September with a cumulative rainfall of 45.7 *mm*, 47.3 *mm* and 86.5 *mm*, respectively. Air temperatures and Air Humidity values followed the naturally expected tendencies.

Through the irrigation season there were some considerable heat peaks. At a heat peak, average air temperatures rise, and there is a natural drop on average air humidity percentage values, as shown in Figure 47. Thus, and because of the self and natural water flow regulation that the SLECI elements provide, an above average water consumption and water flow should be expected for this time periods. On the other hand, on the time periods with more cumulative rainfall, less water and less water flow should be registered in the smart water meters.

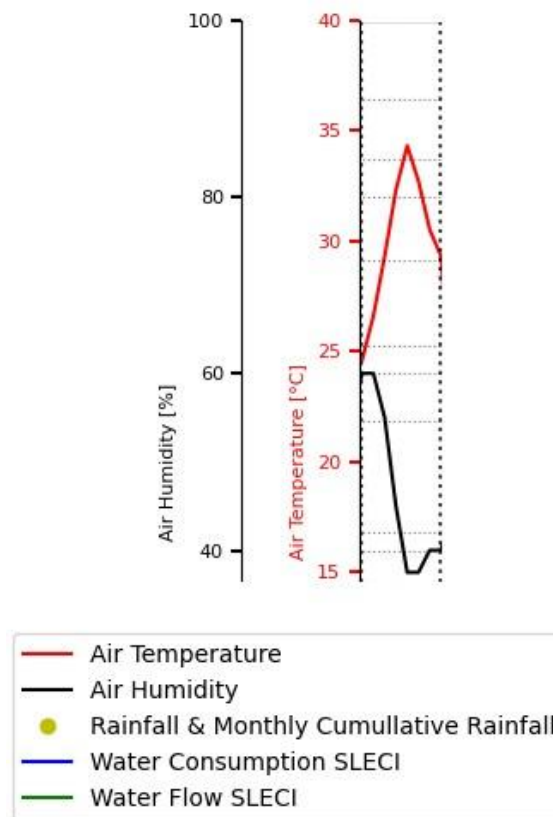


Figure 47. Typical values for average air temperature and average air humidity during a heat peak

In light of this weather information, there are some main events that must be analyzed more carefully and compared with the irrigation technical data provided by the water meters, namely the rainfalls at irrigation weeks number 3, 5 and 17/18 for the cherries crop but only week 12/13 for the peach crop, and then the heat waves at weeks 7, 13 and 16 for the cherries and then at weeks 2, 8 and 10 of the peach crop.

4.2. Cherry Trees field tests

For the Cherries Trees test field, the irrigation period extended from the 10th May to the 2nd October 2023. Once irrigation started at the Cherry Trees, a spike represented by point A) in Figure 48 at the SLECI's water flows values is registered. The system needed an amount of 0.005 m³ to completely fill the main irrigation line, and once that happened, the SLECI elements started dripping into the fine sand underground. Also in this irrigation week, there was a heat peak, to which the SLECI elements responded properly as point B) in Figure 48 shows, with an average water flow of 0.009 m³/h.

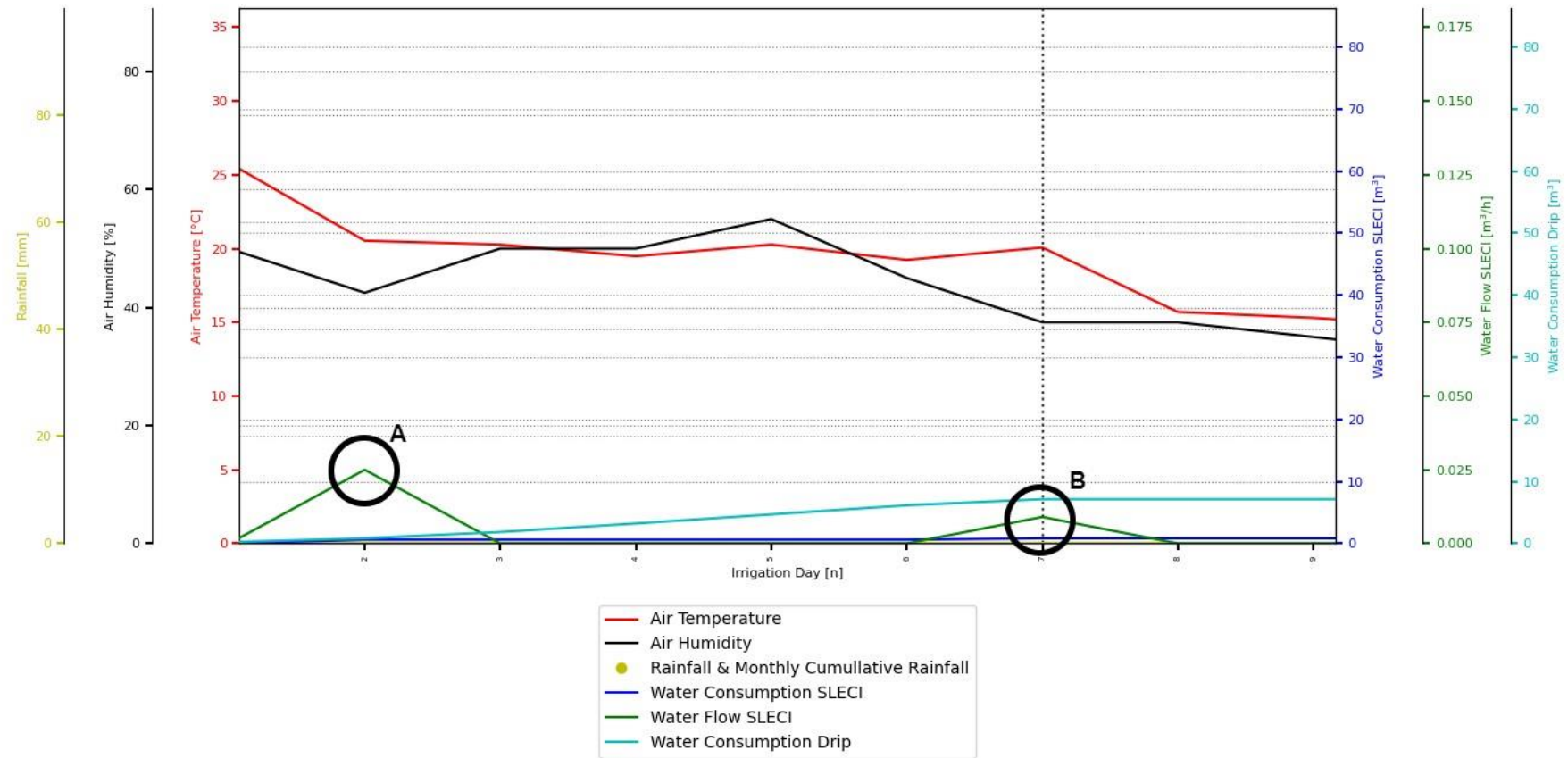


Figure 48. SLECI behaviour under different conditions. Point A) represents the initial water flow to fill the the main irrigation line and point B) shows the SLECI response to a rise of air temperature and drop on air humidity.

By the 2nd irrigation week (19th to the 26th May 2023), when analysing the weekly water consumption on the SLECI, it could be concluded that something was wrong with the system because there was no water consumption for 10 days straight, when the weather reports would not predict so. Thus, tests started being conducted for the following weeks to solve the problem. Then, the 3rd irrigation week (27th May to the 2nd June 2023) irrigation week was characterized by the occurrence of the first out of season rainfall as mentioned before. Theoretically, Figure 49 would show an irresponsive SLECI, that sensed that the soil was moisturized enough to dismiss any kind of irrigation, while the SDIs kept consuming water and energy for expendable irrigation. Meanwhile, in this case the SLECI was irresponsive due to not known yet phenomenon, so further tests had to be conducted when evaluating the system self-regulation reaction to this kind of meteorological events.

Following the contact with the international project partners, on the 5th irrigation week (10th to the 16th June 2023) the decision was made to double the SLECI elements on both irrigation lines with this system actuation. The suggested problems on the system could be the low water flow rate, not being properly detected by the water meter, consistently creating air bubbles inside the system and causing faulty readings at the water meter ultrasonic sensor. The installation process and final result of the technical intervention are shown in Figure 50.A and Figure 50.B, respectively.

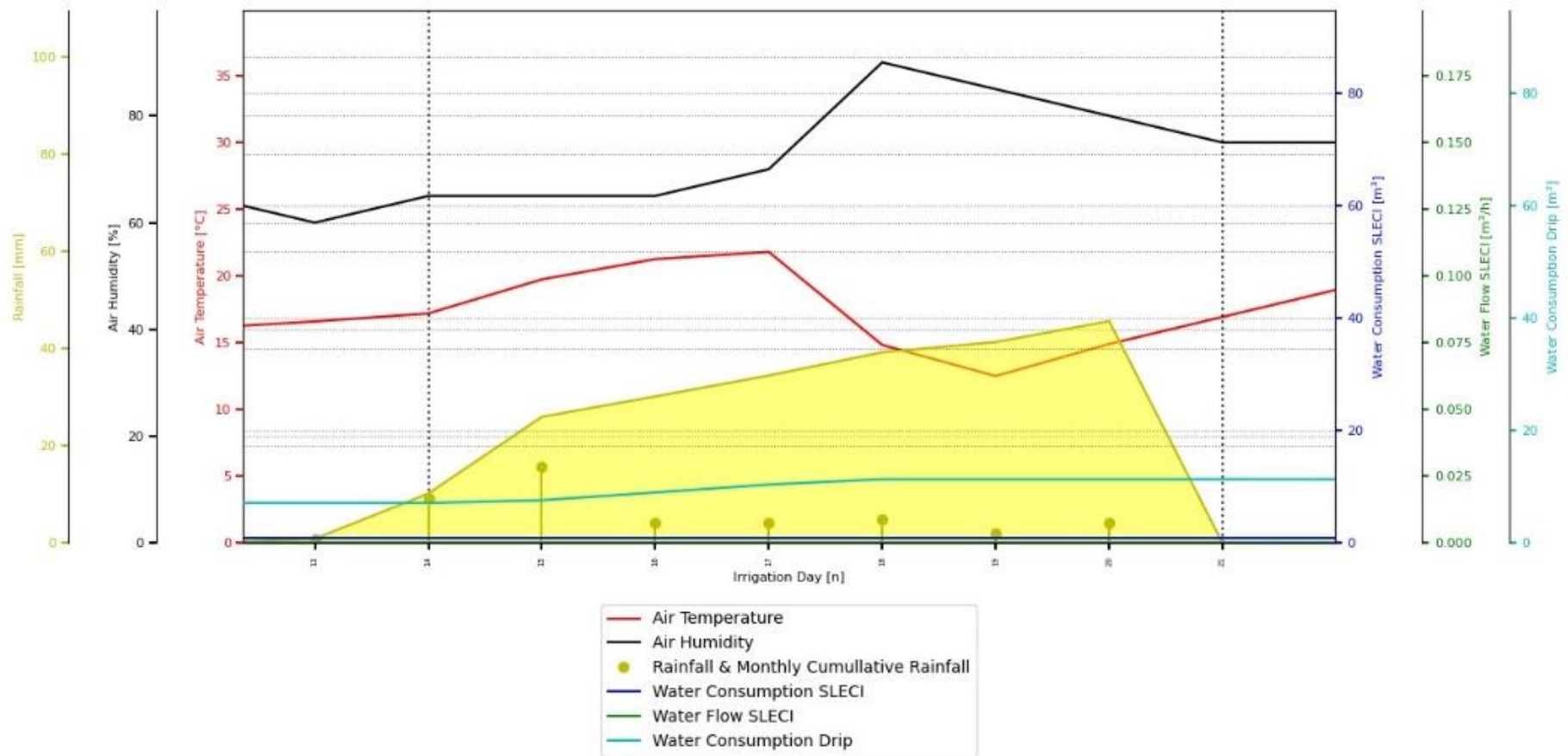


Figure 49. SLECI irresponsible system during a rainfall period, due to the clogging of the filtration system.



a) Drilling process of the bore hole for the doubling of the SLECI elements



b) Final result of the technical intervention

Figure 50 - Installation and final result of the technical intervention at the Cherrie Trees test field

The foliage from both systems was registered as shown Figure 51, and even though the SLECI's showed no water consumption, the cherry trees irrigated by this system showed no sign of drying or being in a state of hydric stress.

Thus, the SLECI's irrigated plants were without any water for 6 weeks, while the SDI's kept irrigating daily, which does not make sense when we analyse both foliage's, so in light of this information we could presume that the SLECI's was watering the trees, just not at a measurable flow rate for the smart water meter, which have a minimum flow rate of $1 L/h$ to provide measurements within the maximum permissible error of the device.



a) SLECI irrigation system



b) Drip irrigation system.

Figure 51 - Foliage comparison between irrigation systems, registered at the 7th irrigation week (24th to the 30th June 2023)

Still concerning the SLECI's smart water meter readings, at the 8th irrigation week (1st to the 7th July 2023) it was decided to remove some faulty SLECI's elements for further testing as shown in Figure 53. The holes left by the removed elements in the main line were then covered with electrical tape, just as shown in Figure 53.B, so that there would be no water or pressure loss in the system. Figure 52 shows a working SLECI element and a broken one.



a) SLECI element irrigating properly



b) Broken SLECI element

Figure 52. Demonstration of a working SLECI element and a broken one



- a) Removal of one SLECI element from each irrigation line b) Covering of the SLECI element hole, left by its removal

Figure 53. SLECI elements removal and covering process.

Figure 55 also represents the effects of the filter replacement shown in Figure 54, and even though there was no irrigation or rainfall for 4 weeks straight, the SLECI's water flow did not go over $0.01 \text{ m}^3/h$ on the next few days, as point A demonstrates.



Figure 54. Clogged 50 µm water filter.

The figure also displays results regarding the SLECI's elements response to average air temperatures between 25°C and 30°C, to which they start dripping at a flow rate between 0.009 m³/h and 0.01 m³/h. This response happened 2 days after the heat peak, with an exception for point C where the response took place on the day after due to a streak of days with high average air temperatures and high evapotranspiration values (the last 8 days registered an average daily value of 6.34 mm/day).

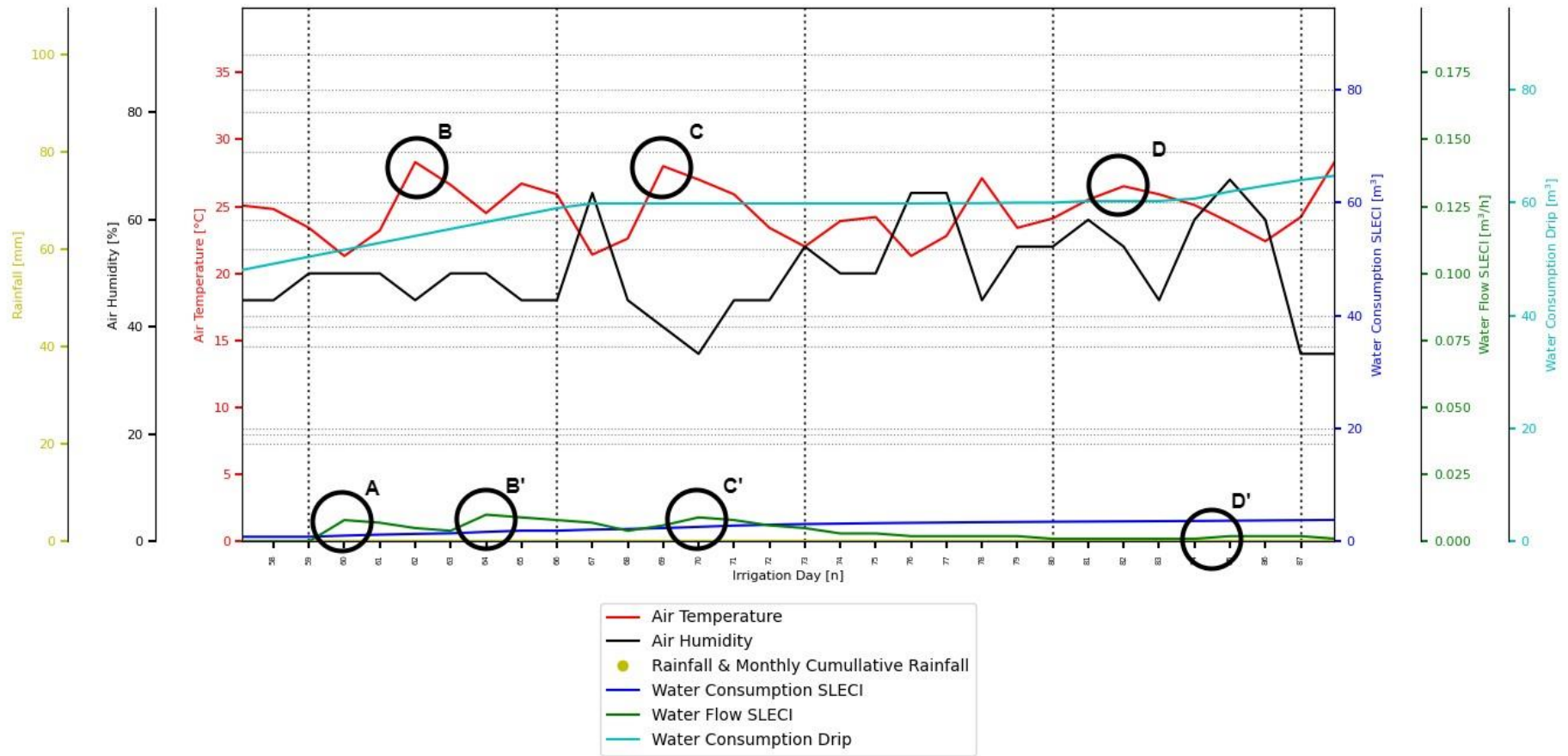


Figure 55. SLECI response to replacing the filtering system, and to average air temperature around 30°C.

At the past 3rd and 5th irrigation weeks (from the 27th May to the 16th June), the 2nd and 3rd rainfalls occurred. The SLECI displayed no water consumption as Figure 56 shows, due to the clogging of the filtration system, so no conclusions could be taken about the SLECI behaviour and further tests must be conducted to get to an assessment on the clay elements' self-regulation properties and their efficiency under these weather conditions.

At the 9th irrigation week (8th to the 14th July 2023) there was a 1 µm filter replacement due to the clogging of the previous one, which indicates the high values of residues and sustained particles on this water source. Once we proceeded with the filter replacement, there must be extra care to the formation of air sockets inside the main irrigation line. These air sockets can lead to faulty readings on the water meters and to the damage or malfunctioning of the SLECI elements. Figure 57.A shows one of the effects of air sockets, keeping the water from flowing naturally to the second filter cage. Another concern was about another broken SLECI element that was to be registered (Figure 57.B), which makes a total account of 8 broken SLECI elements out of 53. Regarding this issue, the possibility of ants damaging the SLECI had to be taken into consideration (Figure 57.C).

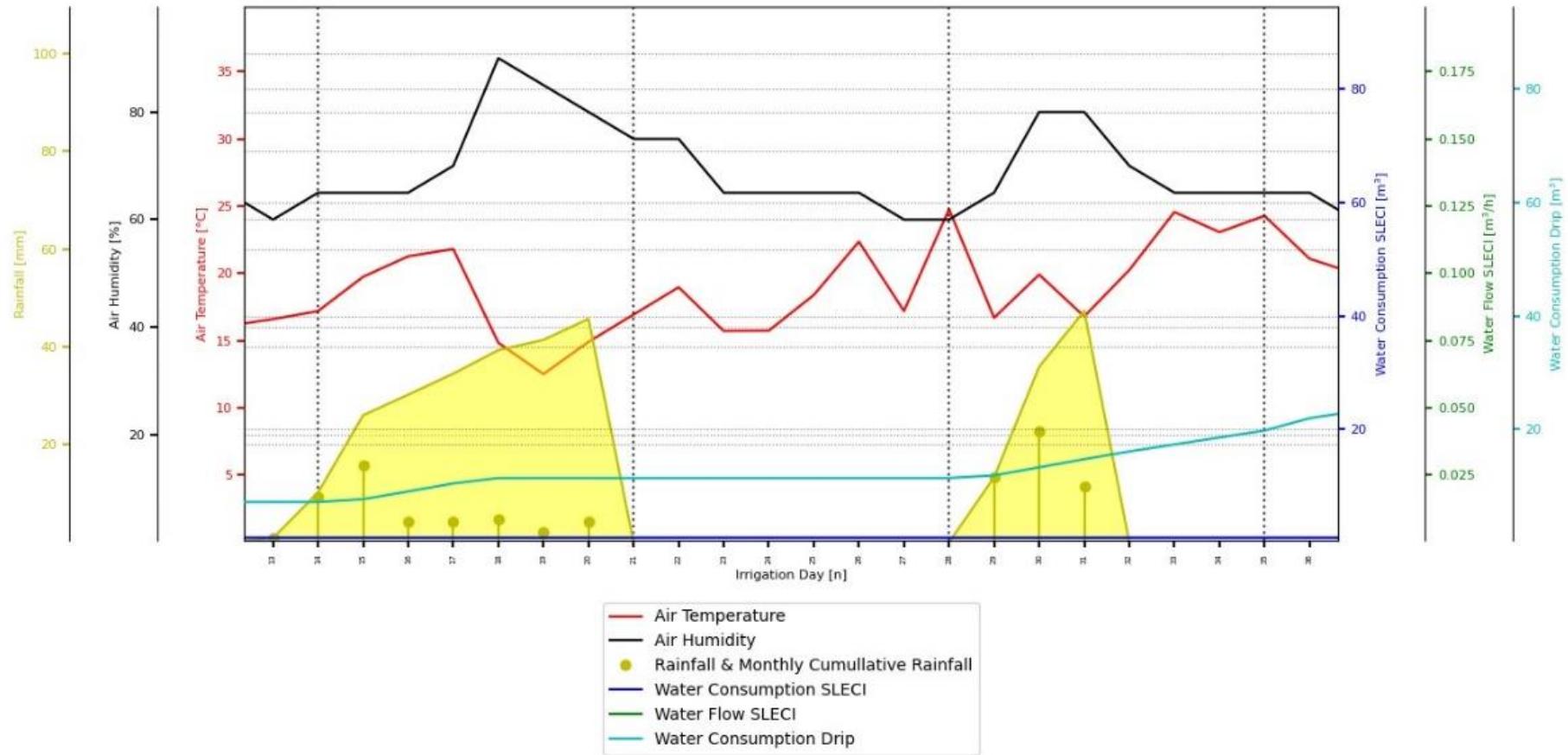
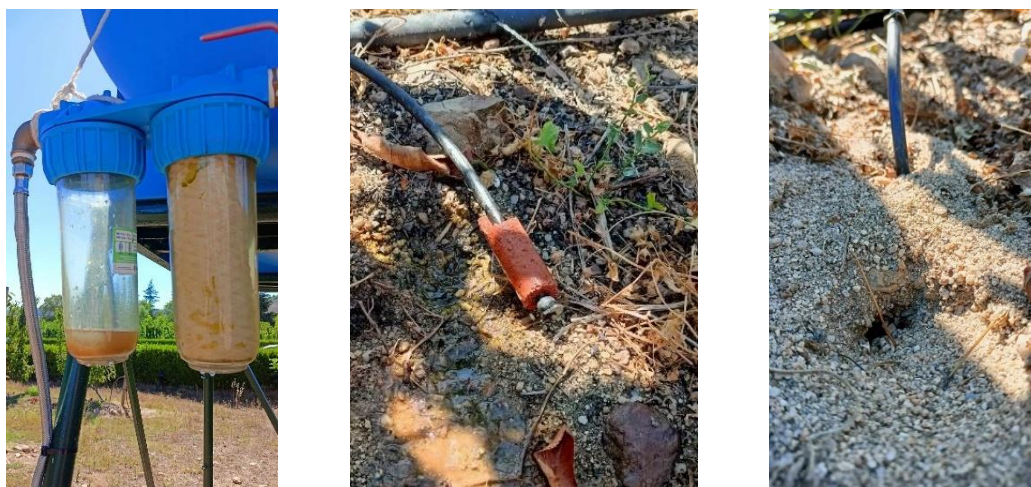


Figure 56. SLECI behaviour on the 3rd and 5th irrigation weeks when there was the occurrence of rainfalls.



- a) Formation of air socket in the SLECI water filtering system b) Broken SLECI element c) Ant colony entrance hole near the clay element.

Figure 57. Report of different problems registered at irrigation week number 9.

Then, tackling the possible problem of the high-water pressure inside the SLECI's main irrigation lines, a water pressure monitoring was conducted, as shown in Table 5. Additional information was gathered concerning the cherry trees irrigated with the SLECI's and the SDI's, shown in Figure 58 and Figure 59 respectively.

Table 5. Water pressure monitoring.

| <i>Irrigation Line</i> | Pressure |
|-----------------------------------|-----------------|
| Line 1 – 27 SLECI elements | 0.354 bar |
| Line 2 – 26 SLECI elements | 0.265 bar |



a) Close look to the SLECI irrigation foliage



b) General SLECI irrigation line 1

Figure 58. Foliage monitoring for the SLECI, registered at the 15th irrigation week (19th to the 25th July 2023).



a) Close look to the SDIS irrigated foliage



b) General SDIS irrigation line 1

Figure 59. Foliage monitoring for the SDIs, registered at the 15th irrigation week (19th to the 25th July 2023).

Also, during this irrigation week, another heat peak took place at the 105th irrigation day (22nd August), the hottest day of 2023 with an average air temperature of 34.3°C

and average air humidity of 37.5%, and the SLECI responded promptly to this extreme event on the next day, as shown in Figure 60, with an average flow rate of $0.057 \text{ m}^3/\text{h}$. The average air temperatures kept in the 25°C to 30°C interval until the 108th irrigation day (25th August) and given that weather condition, from the 106th (23rd August) to the 109th irrigation day (26th August) the SLECI assured the crop with an average daily water flow rate of $0,033\text{m}^3/\text{h}/\text{day}$.

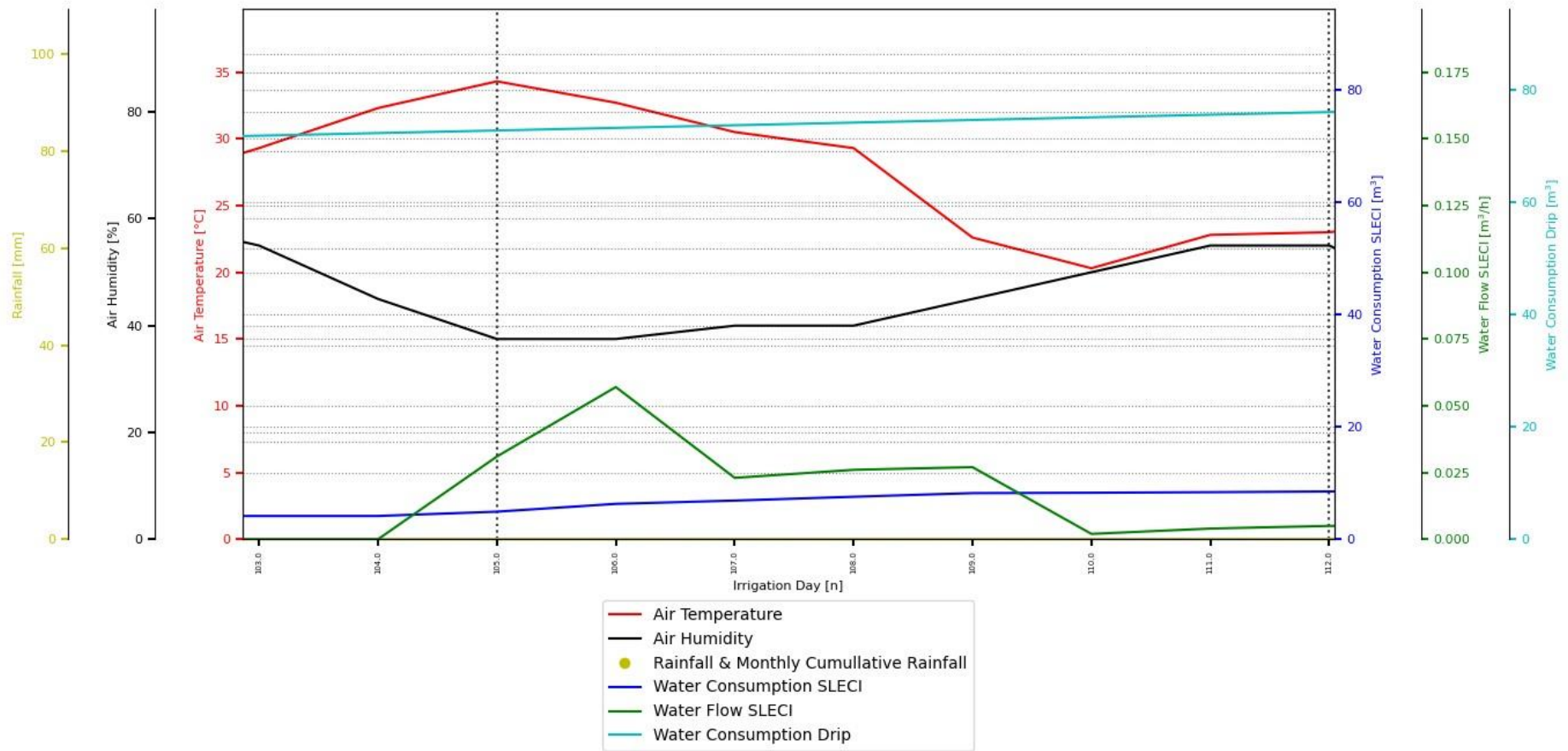


Figure 60. SLECI behaviour for temperatures on the 25°C to 30°C range

Bringing the irrigation season to a close at the cherry trees, there was a 3rd and final rainfall period. As Figure 61 shows, from the 116th irrigation day (2nd September) to the 126th (22nd September) the last rainfall of the irrigation season took place. Naturally, at a rainy period the average air temperatures drops, and average air humidity rises, so this would make us foretell that the SLECI's water consumption would drop. In the time being, a cumulative rainfall value of 86.5 mm was registered and the average air temperature and air humidity values were at 17.5°C and 71.8% respectively. In response to this information, the SLECI's triggered a reaction at the 117th irrigation day (4th September), when cumulative rainfall value was at 41.3mm and the system's flow rate started decreasing at a daily rate of 8.61% until it reached no flow rate at the 122nd irrigation day (14th September). Meanwhile the SDI's kept consuming water during a heavy rainfall period.

Besides water pumping to the 1 m³ water deposit, another expense inherent to the SLECI's is the water filtration system. Filter replacement monitoring for the cherry trees field tests is presented in Table 6.

Table 6. Filter change monitoring through the irrigation season on the cherry trees.

| Filter [<i>xx</i>µm] | Change number | Change date | Days working |
|-----------------------------|----------------------|--------------------|---------------------|
| 50 µm | 1 | 7/Jul | 58 |
| 1 µm | 1 | 7/Jul | 58 |
| 1 µm | 2 | 14/Jul | 7 |
| 1 µm | 3 | 11/Ago | 28 |

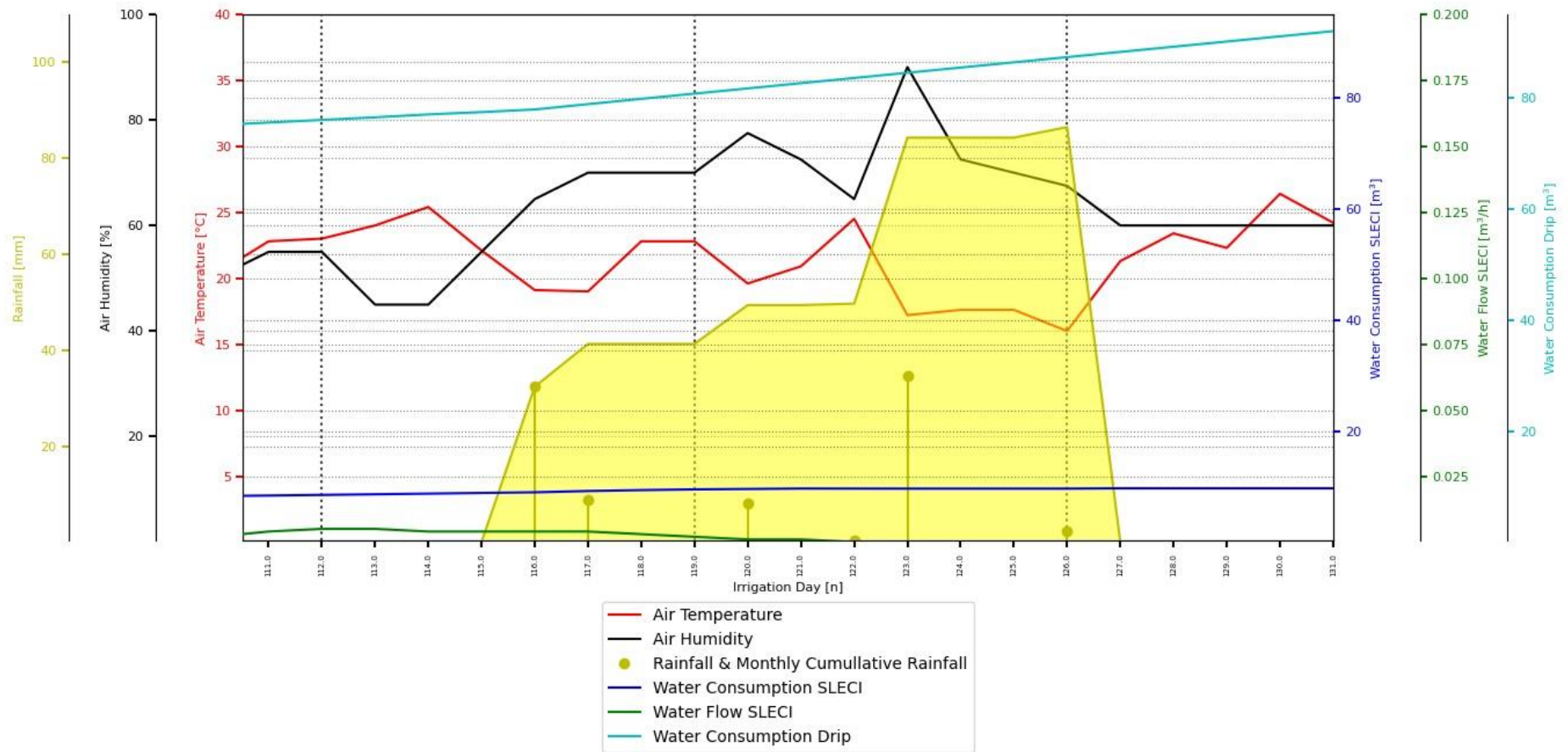


Figure 61. SLECI behaviour during a heavy rainfall period

4.3. Peach Trees field tests

For the Peach Trees test field, the irrigation period extended from the 17th June to the 2nd October 2023. As Figure 62 shows, once irrigation started at the 17th June 2023, unlike the cherries crop there was no water consumption at the SLECI. This is due to the fact that the thin-walled DN-16 main irrigation hose for the SLECI was already filled with water and ready to initiate irrigation, but between the 8th and the 10th irrigation days (7th to the 9th June) rainfalls were registered, with a cumulative value of 47.3 mm, which is considerable for this region and this time of the year. This fact, together with the loamy clay soil hydric dynamics triggered no reaction on the SLECI elements until the 8th irrigation day (24th June), when the system provided an average daily water flow of 0.005 m³/h/day for 2 days until the elements self-regulation mechanism intervened. In light of this information, it can be assumed that when the SDI was actioned, the soil and trees were still draining the water from the previous rainfalls. According to the weather data provided by IPMA (Figure 63), by the time the SDI was triggered, soil water content values were still at 41 to 60% θ_{fc} and kept in that interval for a couple days, until they started dropping at the 5th irrigation day (21st June) due to high air temperatures (average air temperature of 27 to 29°C since the 1st irrigation day). The system provided irrigation water flow at the 8th irrigation day (24th June), responding to a decrease in the soil water content, which has dropped to the interval 21 to 40% θ_{fc} ever since the 5th irrigation day (21st June). Thus, the SLECI only actuated after a streak of 3 days with this kind of evapotranspiration and water concentrations on the soil. Girona *et al.* (2002), based in long-term experiments conducted in fruit trees, suggests that these trees (where peach trees are included) water threshold levels for irrigation scheduling should not be very different from those determined for herbaceous crops. So, the θ_{fc} value to which the SLECI was triggered match the conclusions of Theerawitaya *et al.* (2023) and Zotarelli *et al.* (2021), regarding herbaceous crops and peach trees water demands. When the conclusions from both studies are cross-checked, it can be defined that the ideal value for this parameter when applying DI strategies, should be registered at the 25% θ_{fc} , and even though the studies were conducted on different kinds of soils: garden soil and sandy soil respectively.

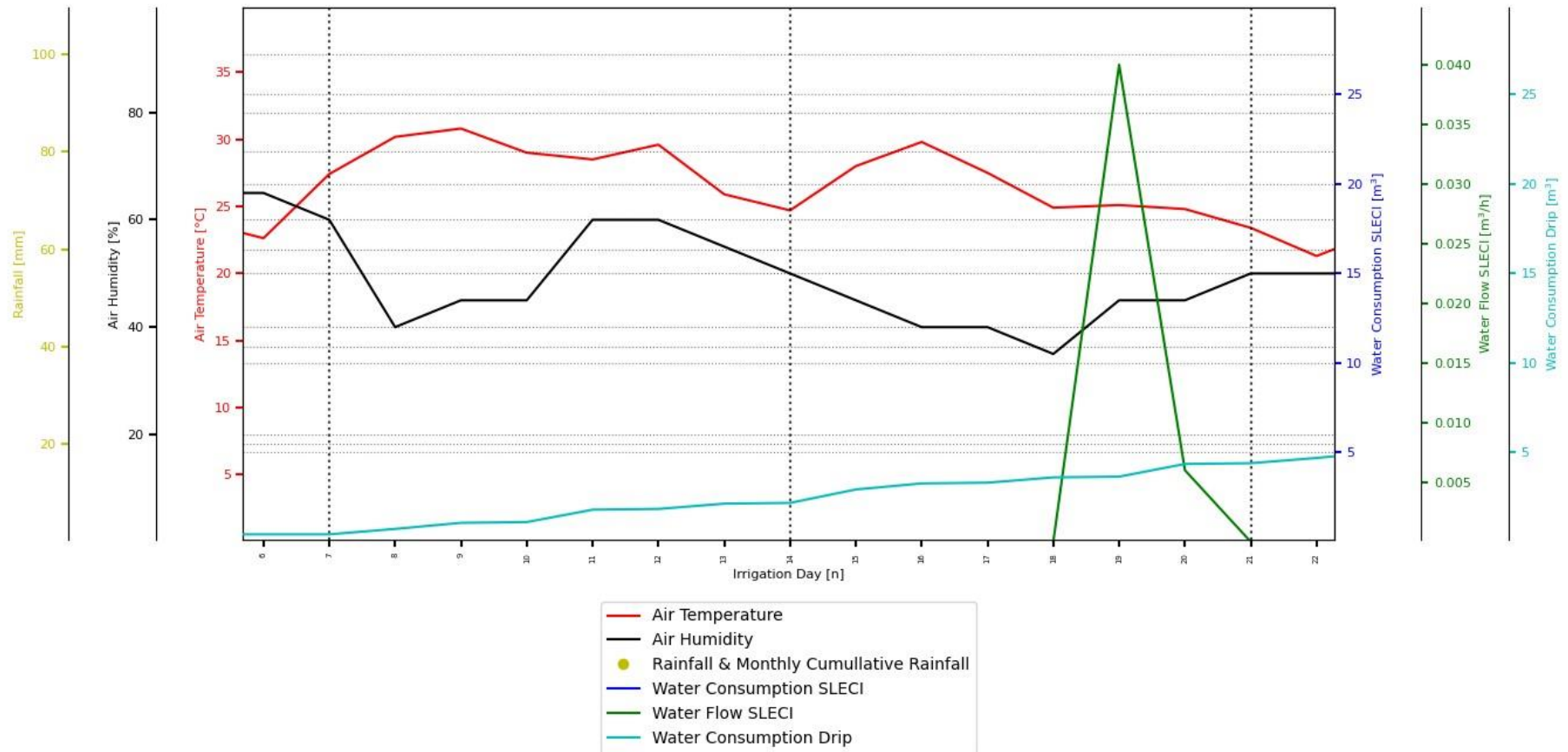
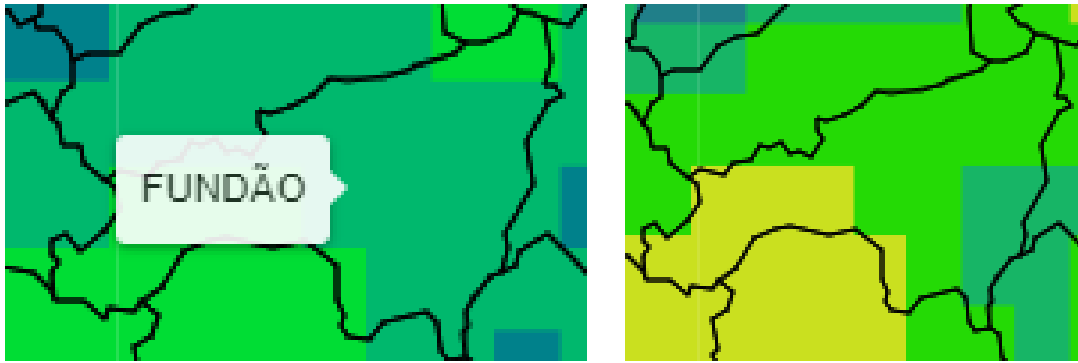


Figure 62. SLECI system initial water flow, at the 3rd irrigation week



a) Field capacity values at the 17th June
(begin of the SDIs at the peach trees)

b) Field capacity values at the
24th June (begin of the SLECI
at the peach trees)

Figure 63. Difference between field capacity values at the begin of the SDIs and SLECI at the peach trees field test

One of the usual concerns when dealing with subsurface micro-irrigation systems is the risk of hydric stress amongst the crops, because the producers have no direct visual way to ascertain if the system is properly watering or not. So, just like in the cherry tree field tests, and in a way to access this situation, a foliage monitoring was performed at the Peach Trees test field, as Figure 64 and Figure 65 shows for *SLECI* technology system and for the SDIs, respectively. The foliage's from both systems indicates the same health status from both irrigation lines, so assuming that the SDIs is causing no hydric stress, the SLECI also not conducting the trees into this undesirable situation.



a) Close look to the SDIs irrigated foliage.



b) Overall outlook SDIs irrigation line 1.

Figure 65. SDIs peach trees foliage, registered at the 4th irrigation week (8th to the 14th July 2023).



a) Close look to the SLECI irrigation foliage.



b) Overall outlook at the SLECI irrigation line 1.

Figure 64. SLECI peach trees foliage, registered at the 4th irrigation week (8th to the 14th July 2023).

Figure 66 shows that the *SLECI*S provided no kind of water flow for a full week, until at the 28th irrigation day, it provided the crops with an average water flow of 0.001 m³/h in response to a week that registered a daily average air temperature of 25°C. Then, at the 6th irrigation week (22nd to the 28th July 2023), a water pressure monitoring was conducted, which results are shown in Table 7.

Table 7. Water pressure monitoring at the *SLECI* lines.

| Irrigation Line | Pressure |
|--|-----------------|
| Line 1 – 23 <i>SLECI</i> elements | 0.53 bar |
| Line 2 – 26 <i>SLECI</i> elements | 0.57 bar |

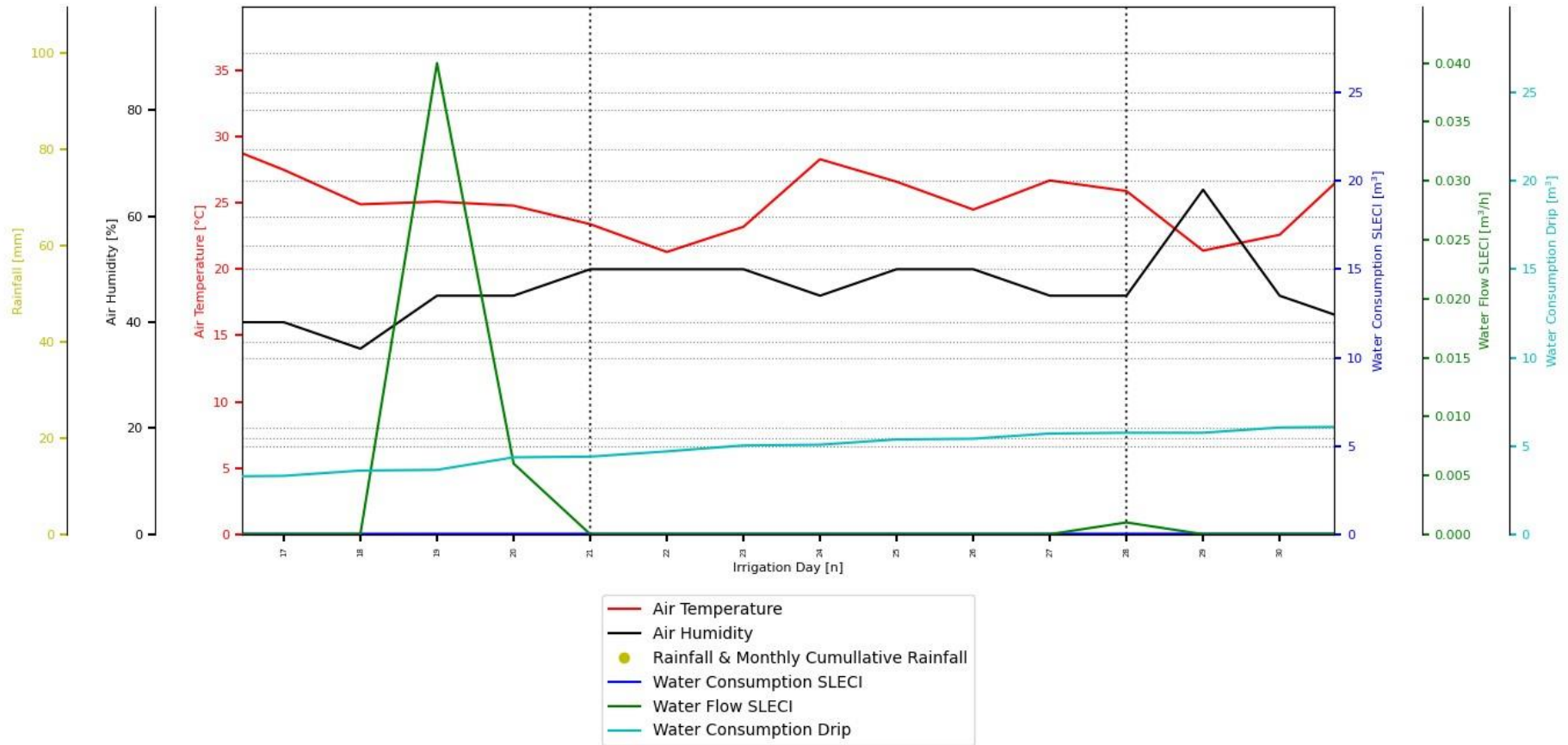


Figure 66. SLECI behaviour at the early 5th irrigation week.

Figure 67 concerns the 7th irrigation week, when after two and a half weeks with no irrigation, in a time period that registered daily average air temperatures of 25.67°C and the lowest daily average air humidity among the irrigation season (25% at the 52nd irrigation day, the 7th August). The SLECI system was again triggered at the 44th irrigation day (30th July). By that time, the system kept providing the plants for the next 16 irrigation days, with a daily average flow rate of 0.0014 m³/h/day. On this situation, the SLECI water flow curve followed the average air humidity, which had a drop from the 49th irrigation day to the 55th irrigation day (4th August to the 10th August) and the SLECI irrigation water flow went from 0.001 m³/h to 0.002 m³/h for the time being and then back to 0.001 m³/h until the 60th irrigation day, when it once again interpreted that the soil and trees had no more need of water.

After 8 weeks of irrigation, new monitoring metrics were introduced: the “peach counting” in units and the average “fruit caliber” in millimeters, at the 4th and 24th trees of both SLECI irrigation lines, and then at the 4th, 24th and 48th trees of the SDI line. Results are presented in Table 8, and on the following week, another foliage monitoring was conducted, as Figure 68 and Figure 69 shows.

Table 8. Week 8 data - Fruit Counting (units) and Fruit Caliber (mm).

| Tree Number (<i>units</i>) | Fruit Count (<i>units</i>) | Caliber (<i>mm</i>) |
|------------------------------|------------------------------|-----------------------|
| 4 th tree | 114 | 58.07 |
| 24 th tree | 232 | 49.84 |
| 4 th tree | 30 | 54.58 |
| 24 th tree | 89 | 45.02 |
| 4 th tree | 147 | 46.71 |
| 24 th tree | 86 | 47.36 |
| 48 th tree | 132 | 62.36 |
| | Line 1 <i>SLECI</i> s | |
| | Line 2 <i>SLECI</i> s | |
| | Line 1 <i>SDI</i> s | |

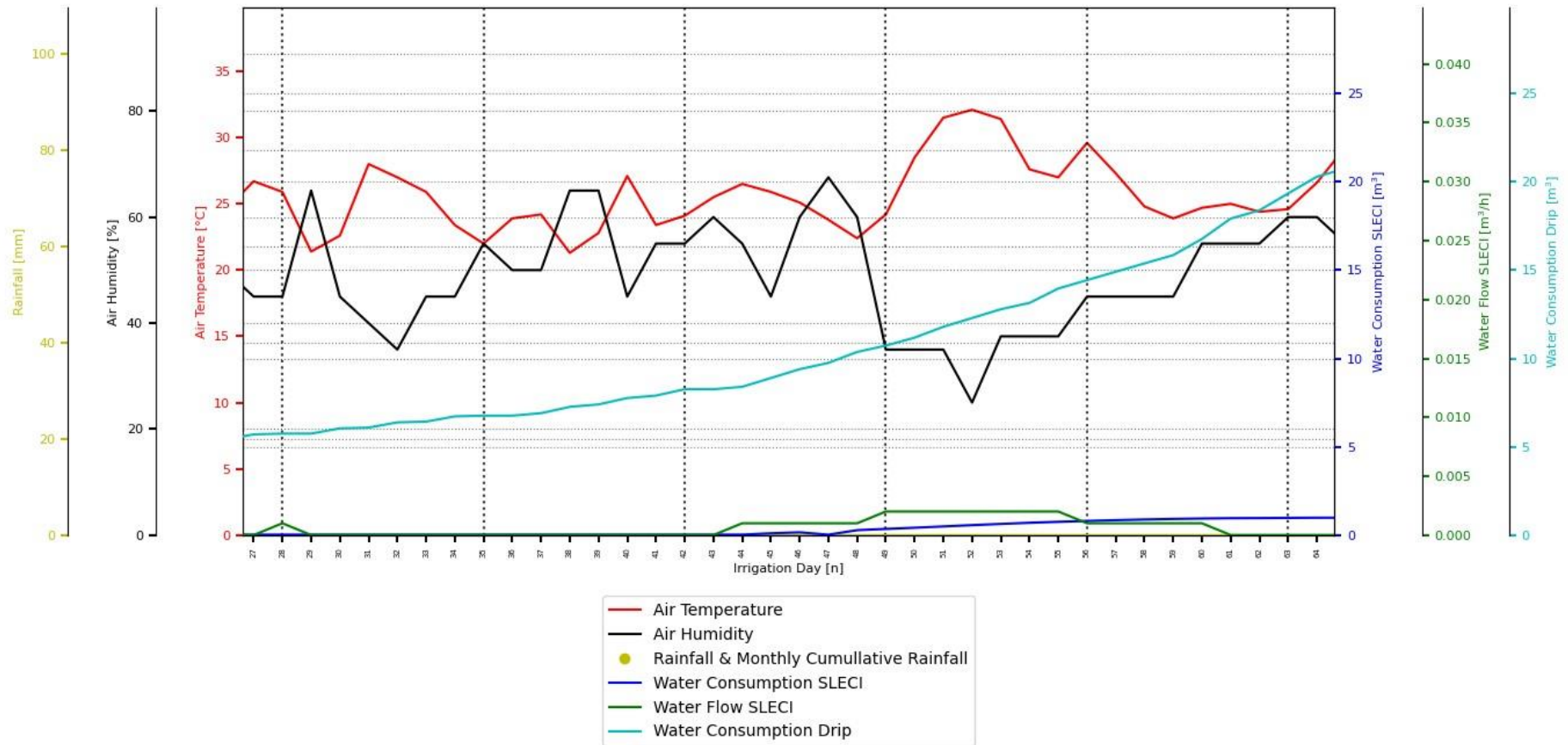


Figure 67. SLECI's response to a significant drop in average air humidity values.



a) Close look to the SDIs irrigated foliage.



b) General outlook SDIs irrigation line.

Figure 68. Foliage monitoring for the SDIs at the 9th irrigation week (12th to the 18th August 2023).



a) Close look to the SLECI irrigation foliage.



b) General SLECI irrigation line 1.

Figure 69. Foliage monitoring for the SLECI irrigation at the 9th irrigation week (12th to the 18th August 2023).

Figure 70 targets the time period between the 78th and the 88th irrigation day (1st and 24th September), when the 3rd and heaviest rainfall period occurred with a registered cumulative value of 86.5 mm. The SDIs was suspended by the 79th irrigation day, so it was watering during the 78th irrigation day with no need, because that day had a daily rainfall value of 34.4 mm, and the SLECI's showed no consumption on this specific weather situation. Not until the 86th irrigation day (18th September) when it provided the crop with an average water flow of 0.003 m³/h. This SLECI's response happened during a heavy rainfall period, with a cumulative rainfall value of 84.3 mm at that time period, so more studies need to be conducted to understand this behaviour, because the natural weather conditions do not justify this behavior.

Finally, at the 31th August, 1st and 2nd September the peach harvest occurred for this field, and so the data collected concerning the fruit count and caliber was collected at the 30th September 2023, and is displayed in Table 9.

Table 9. Week 11 data - Fruit Counting (units) and Fruit Caliber (mm).

| Tree Number (units) | Fruit Count (units) | Caliber (mm) |
|----------------------------|----------------------------|---------------------|
| 4 th tree | 114 | 58.13 |
| 24 th tree | 232 | 50.01 |
| 4 th tree | 30 | 54.73 |
| 24 th tree | 89 | 45.56 |
| 4 th tree | 147 | 46.69 |
| 24 th tree | 86 | 47.57 |
| 48 th tree | 132 | 62.64 |
| | Line 1 SLECI's | |
| | Line 2 SLECI's | |
| | Line 1 SDI's | |

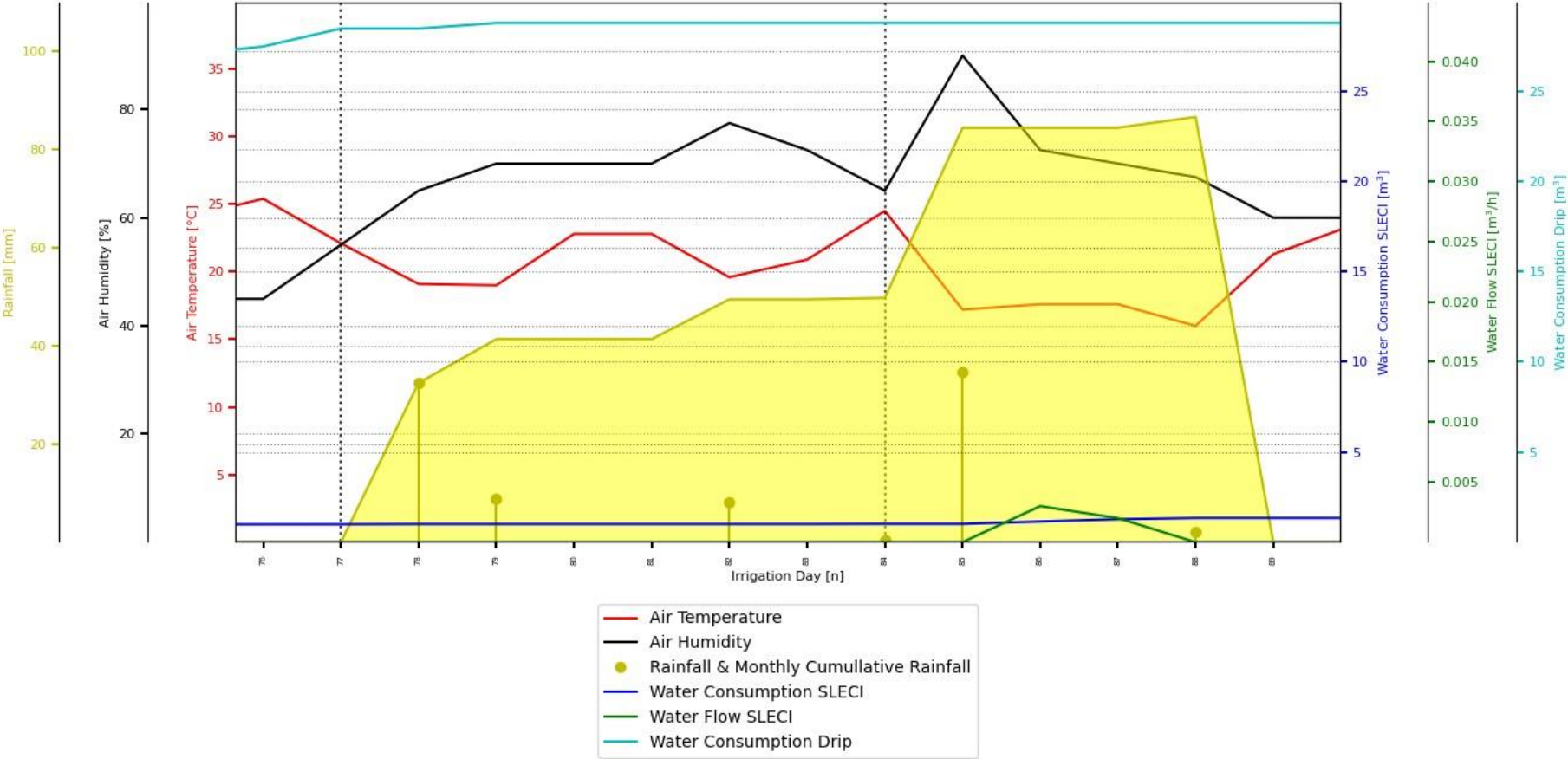


Figure 70. SLECI behaviour for the 3rd and heaviest rainfall period on the peach trees test field.

Just like in the cherry trees field test, water pumping to the 1 m^3 water tank is not the only expense concerning the SLECI. The water filtration system must be taken into account too, and so Table 10 presents the filter replacement monitoring for the peach tree field test.

Table 10. Filter change monitoring through the irrigation season on the cherry trees field test.

| Filter [$xx\mu\text{m}$] | Change number | Change date | Days |
|--|----------------------|--------------------|-------------|
| 50 μm | 1 | 7/Jul | 58 |
| 1 μm | 1 | 7/Jul | 58 |

For both field tests, the maintenance, replacement and technical work on the water filtration system are always pending on the water quality of the irrigation source being used, in this case both basin water source on each test field.

4.4. Yields and Water User Efficiencies

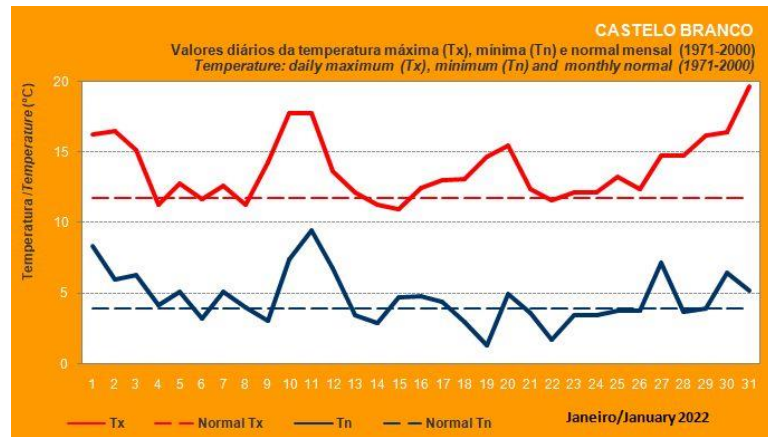
On this sub-chapter, the cherry and peach trees field tests yield are evaluated and discussed.

4.4.1. Cherry Trees

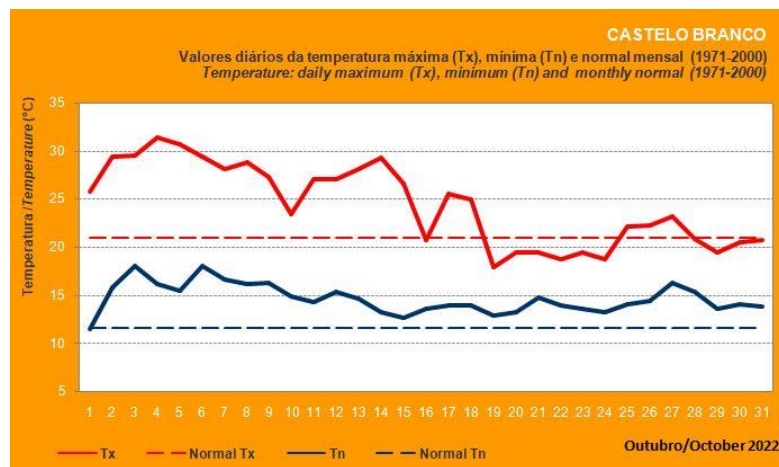
Unfortunately, 2023 was a year with low cherry trees yield, and on the field tests of Seminário do Fundão, the 40 cherry trees yield was not considerable for this year.

According to Sønsteby *et al.* (2019), who conducted a yield data and air temperature analysis for cherry trees over a period of 40 years, these trees have better performance in colder weather. In the year following the data acquisition of air temperature, there was no flowering in trees grown at 23°C , a few flowers in trees from 20°C and an increasing abundance of flowering at the trees grown at even lower temperatures. Thus, an air temperature analysis about the colder month's weather must be conducted. Figure 71 shows the air temperature monitoring for 2022 on the chiller months that registered the most abnormal daily air temperatures when compared to the monthly normal between 1971-2000. As depicted in the graphic information, the months of January, October and December registered above average maximum air temperature values when compared to the monthly normal in the period 1971-2000. Additionally, these months also registered minimum air temperature above the monthly normal, with a special note to the months

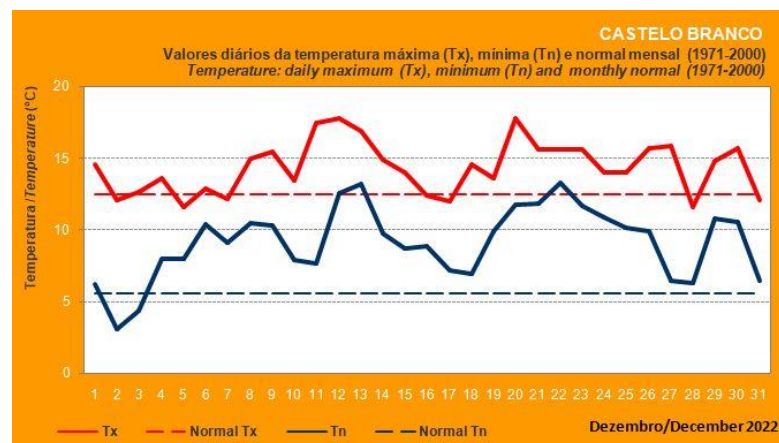
of October and December where the minimum air temperature on most days is above the monthly normal temperatures line. On the second and last third of December, the daily minimum temperatures were even above the normal line of the maximum air temperature. Considering this information, it can be predicted that 2023 would not provide such great yields when it comes to cherry trees at the region of Castelo Branco, which includes Fundão, especially for such small sized fields such as the one at Seminário do Fundão.



a) Air temperature monitoring for January 2022.



b) Air temperature monitoring for October 2022.



c) Air temperature monitoring for December 2022.

Figure 71 – Air temperature monitoring for the 2022 chiller months, with the daily maximum, minimum and monthly normal (1971-2000) (retrieved from <https://www.ipma.pt/pt/oclima/monitorizacao/index.jsp?selTipo=g&selVar=tx&selAna=me&selAno=2022#>, available at 29 January 2024).

4.4.2. Peach Trees

Unlike the cherry trees field tests, the peach trees presented a significant yield, so that the production study could be conducted and performance metrics could be estimated, such as an approximate fruit count (*units/tree*), fruit caliber (*mm/tree*), fruit weight (*g/peach*), fruit yield (*kg*), rainfall and irrigation applied water (m^3) and Water Use Efficiency (WUE) (kg/m^3). This way, by the end of the agricultural season, it could be concluded that under direct comparison of the SLECI and the SDIs fruit counts were technically the same (approximately 116 *units/tree* in the SLECI against 121 *units/tree* in the SDI), and so did fruit caliber (approximately 52.1 *mm/tree* in the SLECI against 52.3 *mm/tree* in the SDI), fruit weight (66.4 *g/peach* in the SLECI against 66.65 *g/peach* in the SDI) and fruit yield (377.398 *kg* in the SLECI against 387.143 *kg* in the SDI). The main differences between systems arise when we analyse the water applied (through rain and irrigation) and the Water Use Efficiency (WUE). For both this metrics the SLECI performed outstandingly when compared to the SDI, with a total of 13.195 m^3 of water applied against 41.143 m^3 and with a WUE of 28.601 kg/m^3 against 9.4 kg/m^3 . Table 11 summarizes these results and as it can be seen, the SLECI system was able to achieve the same amount and quality of yield while almost consuming less 30 m^3 of water, which translates in a 32.07% reduction on water consumption between the SLECI and the SDI systems.

Table 11. Peach Tree yield information.

| Irrigation Tech | ≈ Fruit count [units/tree] | ≈ Fruit caliber [mm/tree] | ≈ Fruit weight [g/peach] | ≈ Fruit yield [kg] | Rainfall + Irrigation [m^3] | WUE [kg/m^3] |
|------------------------|-----------------------------------|----------------------------------|---------------------------------|---------------------------|---|----------------------------------|
| SLECI | 116 | 52.1 | 66.4 | 377.398 | 13.195 | 28.601 |
| SDI | 121 | 52.3 | 66.65 | 387.143 | 41.143 | 9.4 |

Analysing these performance metrics of both systems applied to peach trees, the WUE results of the SDIs match the results assembled by Wang *et al.* (2020) during a 10-year period. As for the SLECI, there are no similar values as the ones registered for the WUE metric in literature till this date.

4.5. Conclusive Remarks

This chapter presented the experimental results from the field tests, highlighting the performance of the SLECI system under various climatic conditions. The SLECI system demonstrated superior water use efficiency and adaptability to environmental changes, particularly during heat peaks and rainfall periods. The results showed that the SLECI system could self-regulate water flow based on soil moisture and weather conditions, reducing water consumption when compared to the SDIs. The chapter also discussed the challenges encountered, such as filtration system clogging and the need for technical adjustments. These findings highlighted the potential of the SLECI system to enhance sustainable agricultural practices, especially in water scarce regions. The next chapter, Chapter 5, will provide general conclusions and suggest future research directions.

5. Conclusions

5.1. General Conclusions

The 2023 irrigation season was characterized by its weather dynamism and constant change, abnormal to most periods regarding the late part of spring and summer season, with three out of season rainfall periods that presented a significant cumulative rainfall value. Thus, it was possible to access and get interesting results about the SLECI's behaviour under different kinds of weather condition in a short period of time and compare this new irrigation system with the SDIs applied to cherry and peach trees. The SDIs presented a constant water consumption (approximately $0.04 \text{ m}^3/h$ and $0.015 \text{ m}^3/h$ for the cherry and peach tree field test respectively) for the full irrigation period, no matter the average air temperatures, average air humidity, soil water content (θ_{fc}) or evapotranspiration registered, while on the other hand, the SLECI's unveiled its self-regulating properties in different occasions and under different conditions on both field tests, through managing and adapting water flows (in a range of $[0, 0.57] \text{ m}^3/h$ and $[0, 0.15] \text{ m}^3/h$), according to weather conditions and soil water dynamics interpretation, triggering the system under several occasions where usually fruit trees tend to enter a situation of hydric stress under average air temperatures in the $[25, 30]^\circ\text{C}$ interval and different heat peaks, average air humidity values in the $[30, 40]\%$, soil water contents in the $[21, 40]\%$ and also delivering more water flow when high evapotranspiration values are registered for a series of days. The SLECI's was also able to naturally block the system when the opposite conditions are registered, and the irrigated soil has no need of water. The final two weeks of irrigation illustrate this clearly, particularly in the cherry trees field test. The SLECI gradually reduced the irrigation water supplied until the soil was fully moisturized, while the SDI system maintained a constant water flow. During this period, despite rainfall, the SLECI system operated for only 6 out of 11 days, whereas the SDI system continuously supplied water. Consequently, the SDI system used $9,439 \text{ m}^3$ of water, compared to 664 m^3 by the SLECI system.

On other topic, unlike the SDIs energy requirements and besides water savings comparison, the new micro-irrigation system has no need of additional electronics, controllers, or even electrical energy once the water is pumped to the tank and flow is assured in the irrigation lines. According to Shahabuddin *et al.* (2023) e-waste generation is increasing globally, with over 53.6 million tonnes produced in 2019 alone and only a small portion (17%) is collected and properly recycled, while the rest is often burnt openly or dumped illegally, posing threats to both humans and the surrounding

environment biodiversity. In the end, no doubt the SLECI is a technology to have in mind for the future of irrigation and sustainability in the agricultural sector in a global paradigm of water scarcity.

5.2. Suggested Future Works

The results only regard one year of implementation and irrigation, and besides SLECI is promising when the micro-irrigation technology is applied to cherry and peach trees, so that a proper assessment can be made further tests must be conducted from 4 to 10 years, as other literature such as Wang *et al.* (2020), Tong *et al.* (2022) or Pascual *et al.* (2016) suggest. Also, the fruit trees being monitored on this particular study were 4 and >3 years old, regarding the cherry and peach trees respectively, so the dimension differences on the trees were not considerable and it would be scientific interest to compare the tree growth rhythms from different irrigation methods along the years. Other metrics like yield information and WUE should also be monitored along the years and irrigation seasons. Concerning the monitoring of leaf and tree health and the existence of stress conditions (either by drought or disease), many studies such as Ramírez-Cuesta *et al.* (2022), Martínez *et al.* (2017) or Qin *et al.* (2023) devolve into the use of infrared canopy imaging cross-checked the data together with the weather station data. It would be interesting to also introduce this kind of techniques and methods to get an even more detailed assessment concerning the trees' reaction to this new micro-irrigation technology and then integrate this kind of new technologies on a single remotely managed monitoring platform. Lastly, regarding the smart water meters used, they reported a daily average water flow of $0\text{ m}^3/h$ for 61 and 74 irrigation days on peach and cherry trees respectively. Thus, and because the SLECI tree leaves presented no visual sign of hydric stress when compared to the SDIs, it can be assumed that the micro-irrigation clay elements were watering the trees with a lower rate than the smart water meter could read ($1\text{ m}^3/h$).

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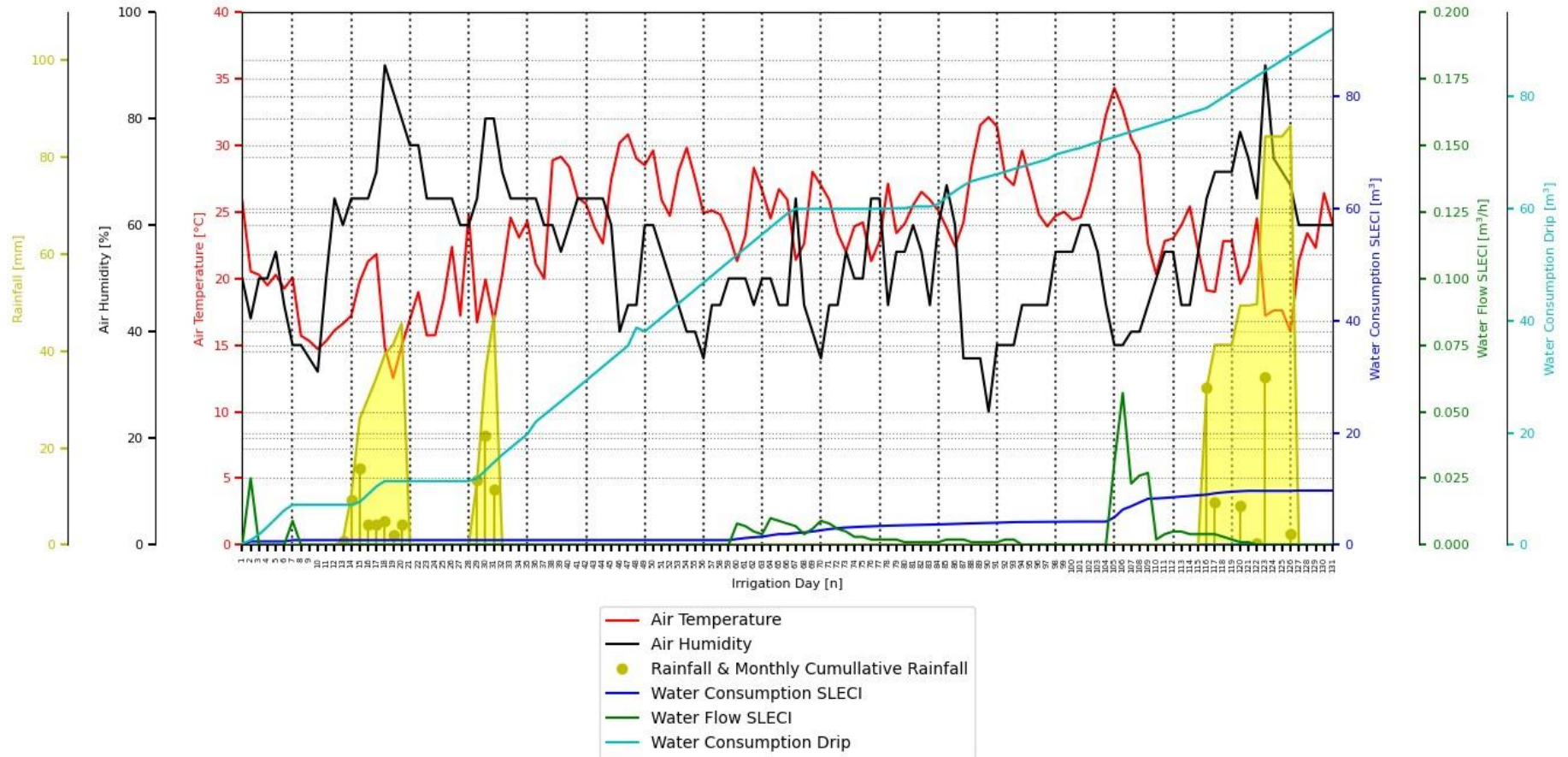
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Appendix A



Appendix B

