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Mornea (Petrache) Alina Maria

SUMMARY OF THE DOCTORAL THESIS

Adaptability of *Fragaria* species to climate change: Efficiency of Schüessler Salts and Fertirigation

SCIENTIFIC LEADER
Prof. univ. dr. Emil LUCA

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INTRODUCTION

The climate is undergoing continuous transformation, with the speed of these changes being unprecedented. Plants, by their nature, have much slower biological adaptation mechanisms and are profoundly affected by the accelerated pace of climate change. Thus, there arises a necessity for research, experiments, and studies, as well as the rapid implementation of protocols with efficient and practical solutions to cope with climate change. Sustainable agriculture is a key point for protecting natural resources, ensuring food security, and optimizing the use of the planet's natural resources (Altieri, 2018; Luca *et al*., 2004; Puia & Soran, 2001).

In this context, it is important to explore innovative, adaptive, efficient, and easily implementable agricultural practices by studying in detail the two species of *Fragaria*: *Fragaria vesca* 'Alexandria' and *Fragaria viridis*. These species have demonstrated high adaptability to stress factors imposed by environmental changes (Rugienius *et al*., 2015; Sammarco *et al*., 2023; Terry, 2007). The study presented in this paper focuses on the impact of various irrigation and fertilization methods, exploring the use of Schüessler salts, mulching, and hydrogel utilization, and their effects on development and production growth. Thus, the mentioned *Fragaria* species have shown notable resilience to environmental variations, highlighting their potential for sustainable agricultural practices (Ahokas, 2000; Rugienius *et al*., 2015; Sammarco *et al*., 2023; Terry, 2007).

The effects of Schüessler Salts on seed germination were also tested, showing a significant improvement in germination rates, vigor, and resistance of young plants. These results are particularly important for sustainable agriculture, as rapid and uniform germination, combined with a simple application protocol, can ensure robust early crop development, reducing risks associated with unfavorable climatic conditions.

This paper is thus part of a global effort to develop innovative and sustainable solutions for agriculture, with the main objective of adapting to climate change and ensuring a sustainable future for food security and sustainable agriculture.

Chapter I
SUSTAINABLE AGRICULTURE

Sustainable agriculture is based on ecological principles that promote the efficient use of natural resources, reduce dependence on chemical inputs, and improve biodiversity. Climate change profoundly affects agriculture, causing climatic variability, droughts, floods, and other extreme events that threaten global food security. Thus, sustainable agriculture becomes a necessity, capable of reducing negative environmental impacts and ensuring stable agricultural production (Altieri, 2018; Luca *et al*., 2004; Puia & Soran, 2001). Identifying and cultivating new adaptable plants becomes urgent in this context. Plants that can withstand difficult environmental conditions such as drought, extreme temperatures, and nutrient-poor soils are essential for ensuring food security and maintaining agricultural sustainability.

1.1. Irrigation

One of the most effective methods to address climatic challenges is the use of efficient irrigation. Modern irrigation methods, such as drip irrigation and sensor-controlled irrigation, allow precise application of water, reducing losses and ensuring efficient resource use. These techniques not only save water but also reduce water stress on plants, thus improving agricultural productivity under climatic variability (Velasco *et al.*, 2019). Water conservation through efficient irrigation methods is essential to maintain agricultural productivity and protect limited natural resources. Additionally, water conservation plays a crucial role in agriculture, especially in drought-prone regions (Luca *et al.*, 2003; Velasco *et al.*, 2019).

Techniques such as rainwater harvesting and storage, mulching to reduce evaporation, and implementing efficient irrigation systems are essential to ensure water availability during critical periods (Luca *et al.*, 2003). Moreover, the use of cover crops and crop rotation can improve soil structure and water conservation in the soil (Meena *et al.*, 2017). Healthy soils have a higher water retention capacity, making them more resistant to drought and erosion (Luca *et al.*, 2004; Meena *et al.*, 2017). Thus, by adopting these techniques and principles, farmers can contribute to creating a more sustainable and resilient agricultural system capable of facing current and future challenges.

1.2. Fertirigation

Applying amendments to plants through irrigation systems is an innovative and efficient method of delivering nutrients and other essential substances directly to plant roots. This process, known as fertirigation, combines irrigation and fertilization, allowing precise application of nutrients, which can lead to improved yields and efficient resource use. Fertirigation is particularly useful under water stress conditions, where available water must be optimally used. This process allows for precise and controlled application of nutrients, reducing losses through volatilization and runoff (Kafkaif & Tarchitzky, 2011; Kapoor *et al.*, 2022).

Besides economic advantages, efficient irrigation systems contribute to the ecological sustainability of agriculture. By reducing water consumption and improving water resource management, these systems help protect ecosystems and maintain biodiversity. Water conservation through efficient irrigation methods is crucial for maintaining agricultural productivity under climatic variability and ensuring the long-term sustainability of agricultural systems (Kassam *et al.*, 2009, 2014; Luca *et al.*, 2004). Fertirigation can be used not only for applying chemical fertilizers but also for biological amendments, such as beneficial microorganisms, plant extracts, and Schüessler salts. These amendments can stimulate plant growth and improve soil health by increasing microbial activity and nutrient availability. The use of fertirigation can have a significant impact on the quality and quantity of agricultural products (Kafkaif & Tarchitzky, 2011; Kapoor *et al.*, 2022). Thus, by the integrated use of these technologies and principles, an agricultural system capable of facing current and future challenges can be developed (Velasco *et al.*, 2019).

1.3. Schüessler Salts

Schüessler Salts played an essential role in this experiment, demonstrating their efficiency in improving the growth and production parameters of *Fragaria vesca* 'Alexandria' and *Fragaria viridis*. These Schüessler salts, also called tissue or cell salts, are used in complementary medicine to stimulate the body's self-healing processes. In the agricultural context, Schüessler salts were applied through fertirigation to evaluate their impact on plant development and productivity.

1.4. *Fragaria* Species

Berries and aromatic plants play a crucial role in sustainable agriculture due to their multiple benefits (Altieri, 2018; Luca *et al*., 2004; Puia & Soran, 2001). They play an important role in crop diversification, soil quality improvement, and biodiversity promotion.

These fruits are rich in essential nutrients and antioxidants, contributing to human health and preventing chronic diseases. Wild strawberries (*Fragaria spp*.) are particularly valuable in sustainable agriculture due to their ability to adapt to various environmental conditions, their distinct aroma, and significant nutritional and medicinal value (Fierascu *et al*., 2020; Giampieri *et al*., 2012). These plants can thrive under drought conditions and nutrient-poor soils, making them ideal for cultivation in resource-limited areas (Ahokas, 2000; Sammarco *et al*., 2023).

The use of these fruits in intercropping systems can improve soil structure and reduce soil losses caused by wind and water erosion (Meena *et al*., 2017).

Strawberry species (*Fragaria spp*.) are an example of adaptable plants, recognized for their resistance to harsh environmental conditions and their nutritional, pharmacological, and medicinal benefits (Fierascu et al., 2020; Sammarco *et al*., 2023). Wild strawberries are high in antioxidants, vitamins, minerals, and trace elements, being considered a superfood (Fierascu *et al*., 2020; Giampieri *et al*., 2012). Integrating *Fragaria spp*. into agricultural systems can offer farmers a resilient and valuable crop, both nutritionally and economically (Sammarco *et al*., 2023). Wild strawberries can contribute to diet diversification and population health improvement, while ongoing research on these plants can open new opportunities for agricultural innovations and the development of more resilient and sustainable agricultural systems (Fierascu *et al*., 2020; Giampieri *et al*., 2012).

1.5. Hydrogel

Hydrogel represents a significant innovation in modern agricultural technology, with the ability to retain and gradually release water, thereby improving the efficiency of water resource utilization (Nirmala *et al*., 2019; Palanivelu *et al*., 2022). Composed of super-absorbent polymers, this material can retain up to 400 times its dry weight in water and gradually release it, reducing the frequency of irrigation and improving soil quality (Palanivelu *et al*., 2022).

Chapter II
MATERIAL AND METHODS

2.1. Research Objectives

The main aim of the research was to evaluate and analyze the cultivation of *Fragaria spp*., focusing on the influence of environmental factors and agricultural practices on fruit production and quality for optimizing sustainable agriculture. Specific objectives:

- Evaluate the influence of irrigation and fertilization on fruit production and quality.
- Determine the efficiency of bio-amendments and Schüessler salts.
- Collect data on the properties of *Fragaria viridis* species.
- Identify factors influencing water consumption and plant productivity.
- Analyze electron spin resonance (ESR) data for two *Fragaria* species.

- Establish the optimal irrigation regime for *Fragaria*.
- Evaluate the economic efficiency of irrigation.
- Identify useful patterns in the development of large-scale cultivation technologies.

2.2. Experimental Location

The experiments were conducted in Bociu village, Cluj County, in a semi-wild orchard in Mărgău commune, with predominant cambisols. This location offers varied soil and climate conditions, ideal for complex agricultural studies on berries.

2.3. Climatic Conditions

The climate of Mărgău commune is continental-moderate with subalpine influences, with cool summers and cold winters. The average annual temperature is between 8-10°C, and the average annual precipitation is about 1000 mm. Climatic data were provided by the Huedin meteorological station (15 km northeast of the site) and include monthly average temperature and precipitation.

2.4. In-situm Experiments Description

The experiments evaluated two species of *Fragaria* (*Fragaria viridis* and *Fragaria vesca* 'Alexandria') under sustainable agricultural conditions. Raised beds and planters were used, and the irrigation water source was a local spring. The planting material was sourced locally and from authorized nurseries.

2.5. Experimental Plots

Seven plots were established, each containing between 45 and 50 plants. The plots were monitored bi-monthly, and data collected included physical measurements and visual assessments. Five main factors were analyzed: irrigation, fertilization, varieties, cultivation conditions, and light exposure, each with multiple experimental combinations.

2.6. Field Monitoring and Data Collection

Over three years, from 2018 to 2020, plants of *Fragaria vesca* 'Alexandria' and *Fragaria viridis* were analyzed bi-monthly. For fruits, only the fruiting period was analyzed, and for flowers, the period in which the inflorescences were produced. Measurements were taken in the field for each plot and each analyzed factor.

Chapter III
EXPERIMENTAL RESULTS

3.1. *Fragaria vesca* 'Alexandria'

Plant Height: The best results were obtained in the irrigated and Schüessler salt-fertilized and mixed treatment plots, where the average plant height reached maximum values.

Plant Width: Plant width was significantly greater in the hydrogel and mixed fertilization (hydrogel-mixed fertilization) treatment plots.

Number of flowers: The most flowers were observed in the organic treatment and sun exposure plots (organic only fertilisation- in the sun).

Number of Fruits: Fruit production was highest in the irrigated and Schüessler salt-fertilized plots, with an approximately 30% increase compared to the control plot.

ESR Results: Electron Spin Resonance (ESR) analyses for *Fragaria vesca* 'Alexandria' showed significant differences between various fertilization and irrigation regimes. The spectra for manganese ions indicated that Schüessler salt treatments had a positive impact on plant bioactivity, indicating the presence of intense and efficient biochemical processes. Antioxidant levels measured by the ESR method were also significantly higher in plants fertilized with Schüessler salts compared to those in control plots. These results suggest that the use of Schüessler salts not only improves plant growth and production, but also the nutritional quality of the fruits, making them more valuable from a food and medicinal point of view.

In **the germination experiment** related to *Fragaria vesca* 'Alexandria' seeds under the influence of Schüessler salts, the results showed that the use of these salts had a significant impact on germination rate and survival to fungal infections. For instance, the survival rate to fungal infections was higher in the treated plots compared to the untreated plots. These data suggest that Schüessler salts can play an important role in improving plant health from the germination stage.

In the **experiment regarding the inhibitory effect of extracts** from *Fragaria vesca* 'Alexandria' on the development of human cancer cells, conducted at the University of Medicine and Pharmacy in Cluj-Napoca, the results showed that extracts of *Fragaria* with Schüessler salts had a greater capacity to inhibit tumor cell proliferation compared to extracts from untreated plants. These observations highlight the potential use of Schüessler salts not only in agriculture but also in the medical field for developing anticancer treatments.

3.2. *Fragaria viridis*

Plant Height: *Fragaria viridis* had maximum height in the irrigated and Schüessler salt-fertilized plots, but the value was approximately 20% lower than that observed for *Fragaria vesca* ‘Alexandria’.

Plant Width: Plant width was highest in the hydrogel and mixed fertilization (hydrogel-mixed) treatment plots, similar to the results for *Fragaria vesca*.

Number of flowers: The number of flowers was significantly higher in the organic treatment and sun exposure plots.

Number of Fruits: *Fragaria viridis* produced fruits only over two months, with the best results in the irrigated and Schüessler salt-fertilized plots. ESR analyses for *Fragaria viridis* revealed a resolved spectrum for manganese ions in the Schüessler salt-treated plots, indicating increased bioactivity compared to the control plots. Antioxidant levels were also higher in these plots, suggesting that Schüessler salt treatments not only support plant growth but also improve fruit quality. Additionally, the use of hydrogel in combination with Schüessler salts was effective in maintaining an optimal balance of moisture and nutrients, contributing to healthy plant development even under water stress conditions.

Table 3.1.

Comparative Analysis of Minimum/Maximum Values for the Two Species

Parameter	*Fragaria vesca* 'Alexandria'	*Fragaria viridis*
Maximum plant height (cm)	37 cm	24 cm
Minimum plant height (cm)	12 cm	4 cm
Maximum plant width (cm)	44 cm	27 cm
Minimum plant width (cm)	15 cm	8 cm
Maximum number of flowers	17	18
Minimum number of flowers	2	3
Maximum number of fruits	16	12
Minimum number of fruits	2	1
Maximum fruit size (cm)	3 cm	2 cm
Minimum fruit size (cm)	0.32 cm	0.30 cm
Maximum fruit weight (g)	420 g	240 g
Minimum fruit weight (g)	6.4 g	5 g

3.3. Comparison with Control Plots

Compared to control plots (non-irrigated and non-fertilized), the use of Schüessler salts showed significant improvements in all evaluated parameters. Plants treated with Schüessler salts had up to 25% growth increase and 30% higher fruit production than control plots. These results underscore the importance of adopting innovative and efficient fertilization practices to maximize agricultural production and improve fruit quality.

3.4. Fertirigation Results

The fertirigation method demonstrated remarkable positive effects on the studied *Fragaria* species as follows:

For *Fragaria vesca* 'Alexandria', fertirigation led to an 18% increase in plant height and a 22% increase in total fruit weight compared to traditional fertilization methods.

In the case of *Fragaria viridis*, fertirigation had a positive but more moderate impact than on *Fragaria vesca* 'Alexandria'. Plants showed a 15% increase in height and a 20% increase in total fruit weight compared to traditional methods. Fertirigation also demonstrated more efficient use of water and nutrients, essential in the context of climate change, contributing to reducing nutrient losses and improving sustainability.

3.5. General ESR Results

General results from the ESR (electron spin resonance) analysis revealed significant differences between the two *Fragaria* species, *Fragaria vesca* 'Alexandria' and *Fragaria viridis*, in relation to the control plot and different applied treatments. Spectra for manganese ions showed resolved presence in 85% of Schüessler salt-treated plots for *Fragaria vesca* 'Alexandria', indicating intense biochemical activity. In contrast, *Fragaria viridis* showed resolved spectra in only 10% of the treated plots, suggesting a lower biochemical activity and a more pronounced natural biodiversity.

Antioxidant levels were significantly higher in Schüessler salt and hydrogel-treated plots compared to control plots. *Fragaria vesca* 'Alexandria' recorded a 45% increase in antioxidant capacity in Schüessler salt-treated plots, while *Fragaria viridis* had a 30% increase under the same conditions.

In conclusion, ESR (electron spin resonance) analysis demonstrated that the use of Schüessler salts and hydrogel can significantly optimize the biochemical activity and antioxidant capacity of plants, with more pronounced benefits for *Fragaria vesca* 'Alexandria'. These results underline the potential of these treatments in improving crop performance, offering a viable and sustainable solution in the context of modern agriculture.

Chapter IV
CONCLUSIONS

This paper demonstrates the importance of using sustainable and adaptive agricultural practices to address the challenges posed by climate change. In the context of rising global average temperatures and increasingly unpredictable rainfall patterns, it is essential for farmers to adopt methods that not only maintain productivity but also conserve natural resources and protect ecosystems. The studies conducted have shown that the implementation of techniques such as fertirigation and the use of Schüessler salts can significantly improve crop performance while reducing dependence on traditional chemical inputs that negatively impact the environment. Moreover, these practices contribute to increasing crop resilience to abiotic stresses, such as drought and extreme temperature variations.

The species *Fragaria vesca* 'Alexandria' and *Fragaria viridis* proved to be particularly adaptable and resilient in the experiments conducted. These species demonstrated the ability to optimally develop under various environmental conditions and different fertilization and irrigation regimes. The use of Schüessler salts, in particular, showed remarkable results in terms of plant growth and production. These Schüessler salts not only improved the size and weight of fruits but also increased antioxidant levels, thus contributing to better nutritional quality of the final products. Additionally, the analyzed irrigation methods, including hydrogel utilization, demonstrated increased efficiency in water resource management, essential for agriculture in drought-affected areas.

Academic studies in this field are essential for developing sustainable agricultural practices and protecting natural resources, thereby ensuring food security and the future of agriculture. By deepening research on the interaction between different fertilization and irrigation methods and crop adaptability to climate change, we can develop more efficient and sustainable strategies. These strategies will not only improve agricultural productivity but also reduce the negative impact on the environment, promoting agriculture that meets current needs without compromising the ability of future generations to meet their own needs.

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