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Magnetic and electromagnetic treatment of the nutrient solution in arugula hydroponic cultivation[1]

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ABSTRACT

Hydroponic cultivation is relevant in vegetable production due to the efficient use of resources, plant growth control, high yields and good quality of harvested products. This study aimed to assess the effects of magnetic and electromagnetic treatments of the nutrient solution on the hydroponic arugula production. The treatments comprised the exposition of the nutrient solution to magnetism, electromagnetism and conventional cultivation (control) monitored during four periods (7, 14, 21 and 28 days after transplanting), with four replicates for each treatment. The experiment followed a completely randomized factorial design. The magnetic treatment led to gains in plant growth and yield, in addition to reducing the presence of algae in roots, as well as increasing the concentrations of magnesium, manganese and iron in the development of the arugula crop under hydroponic cultivation, but with no direct effect on plant growth.

KEYWORDS: *Eruca sativa*, hydroponic cultivation, plant nutrition.

RESUMO

Tratamento magnético e eletromagnético da solução nutritiva na produção hidropônica de rúcula

O cultivo hidropônico é relevante na produção de hortaliças devido ao uso eficiente de recursos, controle do desenvolvimento das plantas, elevada produtividade e boa qualidade dos produtos colhidos. Objetivou-se quantificar os efeitos de tratamentos magnético e eletromagnético na solução nutritiva sobre a produção de rúcula hidropônica. Os tratamentos incluíram exposição da solução nutritiva a magnetismo, eletromagnetismo e cultivo convencional (controle), com monitoramento ao longo de quatro períodos (7, 14, 21 e 28 dias após o transplante), e quatro repetições para cada tratamento. Utilizou-se delineamento inteiramente ao acaso, em esquema fatorial. O tratamento magnético proporciona ganhos no desenvolvimento e produtividade e reduz a presença de algas na raiz, bem como aumenta a concentração de magnésio, manganês e ferro no desenvolvimento da cultura de rúcula hidropônica, embora sem implicações diretas no desenvolvimento das plantas.

PALAVRAS-CHAVE: *Eruca sativa*, cultivo hidropônico, nutrição vegetal.

INTRODUCTION

The demand for high-quality food has benefited leafy vegetables like arugula (*Eruca sativa* Miller) (Fernandes et al. 2015). This plant can be grown in diverse environments and consumed fresh, requiring a steady supply. Over 39,000 hectares of vegetables are cultivated annually in Brazil, significantly boosting the farmers' income (Vilela & Luengo 2022). Arugula, recognized for its medicinal properties (digestive, diuretic, stimulant, laxative and anti-inflammatory), as well as a source of vitamin C and iron, has seen a rise in demand (Porto et al. 2013).

Hydroponic techniques are gaining prominence for achieving high yields, reducing production areas and cutting the water use by up to 70 %, as well as agricultural labor, resulting in yields that meet or may exceed the conventional soil farming. These advantages have spurred their implementation, even in urban centers (Jardina et al. 2017, Al-Tawaha et al. 2018). Such technologies align with the United Nations Sustainable Development Goals (SDG) for the 2030 Agenda, particularly the SDG 2, which aims to end hunger, achieve food security and improved nutrition, as well as to promote a sustainable agriculture. They also support the efficient water

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use (SDG 6) and ensure a sustainable production and consumption (SDG 12) by reducing the need for land, water resources and pesticides (United Nations 2024).

The nutrient film technique (NFT) has been highly recommended for growing leafy greens like lettuce and arugula (Jardina et al. 2017). Moreover, researchers have explored other techniques to maximize the genetic potential of crops with lower costs, such as exposing them to low-frequency electric pulses, as well as magnetic and electromagnetic irrigation water treatments (Dastorani et al. 2022, Putti et al. 2023a, Tellez et al. 2023). Studies by Putti et al. (2022) and Khaskhoussy et al. (2023) indicate that magnetizing the irrigation water can alter its physical and chemical properties, benefiting the plant development. The advantages of magnetic and electromagnetic treatments have been observed in seed germination, plant growth and development, and reduction of adverse effects from saline and water stresses, potentially due to biochemical changes that enhance nutrient uptake and water absorption by roots (Liu et al. 2019, Dastorani et al. 2022, Putti et al. 2023b).

Lemos et al. (2021) reported an improved water-use efficiency in agricultural production, with benefits observed in the germination (Massah et al. 2019) and development (Selim et al. 2019) of wheat, eggplant (Souza et al. 2019) and sunflower (Dastorani et al. 2022). The exposition to magnetic fields of barley decreased potential cell damages, chlorophyll fluorescence and contents of Ca, Mg, P and K derived from saline and water stresses (Ercan et al. 2022). Studies with lettuce (Lemos et al. 2021, Putti et al. 2023b), barley (Ercan et al. 2022), cotton (Zhang et al. 2022) and wheat (Massah et al. 2019) have shown improvements in growth, yield, nutrient uptake and even biofilm formation (Gosselin et al. 2018).

Other effects may be related to the dipolar movement of water molecules and oxygen content, forming small clusters of water molecules, and influencing characteristics such as solubility and reaction rate (Khoshravesh et al. 2011, Esmaeilnezhad et al. 2017). The effects of treating water with magnetic and electromagnetic fields can last for up to 15 hours after exposure (Mghaiouini et al. 2021). Polarized water molecules tend to align in the same direction, reducing ion concentrations and hydrogen bonding within and between clusters (Gaafar et al. 2015, Chibowski & Szczes 2018).

Mghaiouini et al. (2021) reported that magnetic and electromagnetic treatments cause changes in magnetic fields (B) from a maximum (B_{max}) of 0.023 mT to a minimum (B_{min}) of 0.008 mT, averaging (B_{avg}) 0.0155 mT in the magnetic water. On the other hand, it fluctuates from a B_{max} of 0.0185 mT to a B_{min} of 0.005 mT, averaging 0.01175 mT in the non-magnetic water. Such changes may raise the water pH, electrical conductivity, diffusion and permeability, besides reducing its viscosity and surface tension, thereby increasing fluidity and permeability, when compared to non-treated water (Szczes et al. 2020, Zhao et al. 2021).

Chibowski & Szczes (2018) and Sarraf et al. (2020) tried to understand the potential benefits of using magnetically-treated water and observed that the magnetic field gradient is more important than the magnetic field strength. Therefore, a better understanding of the interaction between magnetic fields and plant responses could revolutionize the crop production, as it may increase the plant resistance to diseases and stress conditions, as well as its nutrition and water-use efficiency, thus improving crop yields.

Public policies and increasingly demanding consumers are steering research toward environmentally friendly techniques aligned with the SDG, such as magnetic and electromagnetic treatments, to understand their interactions within the soil-water-plant system, a relatively unexplored field (Yu & Wu 2018, Zhang et al. 2022).

Given the benefits of hydroponic systems in greenhouses for controlling factors that interfere with crop development, this study aimed to assess the effects of magnetic and electromagnetic treatment of nutrient solutions on hydroponic arugula production.

MATERIAL AND METHODS

The study was conducted with arugula cv. Antonella, in 2023, at the experimental field of the Universidade Estadual Paulista "Júlio de Mesquita Filho", in Botucatu, São Paulo state, Brazil (22º51'03''S and 48º25'37''W), where the climate is classified as Cfa (humid subtropical), according to Köppen, with average temperatures above 22 ºC in the hottest month, annual rainfall averaging 945.15 mm, and altitude of 780 m (Cunha & Martins 2009).

A completely randomized design was used, in a 3 x 4 factorial scheme, including three nutrient solutions (magnetic, electromagnetic and conventional) and four monitoring periods (7, 14, 21 and 28 days after transplanting - DAT), with four replicates consisting of four bunches of arugula each.

The hydroponic system was implemented in a greenhouse equipped with temperature and light control. A ridge vent was used to regulate temperatures exceeding 25 ºC, while a 50 % shade cloth provided light management. The nutrient film technique featured a 5 % slope and a capacity for 24 bunches per PVC hydroponic channel.

Nutrient solutions were stored in 500-L tanks, each equipped with a 0.5 HP FERRARI centrifugal pump. An electromechanical timer was used to control irrigation, activating pumps every 15 min from 6:00 a.m. to 6:00 p.m., and every 5 min from 6:00 p. m. to 6:00 a.m. The flow rate was maintained between 1.5 and 2.0 L min^{-1}, with uniformity monitored. The nutrient solutions adhered to the guidelines of Furlani et al. (1999) and were replaced weekly, with daily pH and electric conductivity checks.

The nutrient solution treatments comprised: A) magnetism using the Sylocymol device (Timol Group), which is capable of magnetizing 5 m^3 h^{-1}, installed vertically in the middle of the tank, maintaining a magnetic field over the nutrient solution throughout the experimental period; B) electromagnetic treatments employing the AQUA4D device, which used a pre-programmed electronic panel to generate electromagnetic signals. The device was installed in the pipeline connecting the tank to the hydroponic system, subjecting the nutrient solution to these signals during irrigation cycles; C) conventional system, consisting of nutrient solution without any additional treatment.

The arugula seedlings were cultivated in plastic germination trays containing substrate within cells holding 5 to 10 seeds, under protected conditions, for 20 days. Once plants exhibited 3 to 5 true leaves and displayed an uniform growth within each bunch, they were carefully transferred to the hydroponic system. At 6 days after transplanting (DAT), thinning was conducted to reduce the plant count to six per experimental unit (bunch). Buffer rows of bunches were placed at the beginning and end of each bench to minimize edge effects.

At 7, 14, 21 and 28 DAT, four bunches per replicate were collected from each treatment, following the planting order and properly identifying them. To ensure an even sampling, the end of the bench was alternated with each new collection. Each collection involved counting the number of leaves and measuring fresh and dry masses of shoots and roots using a precision scale (0.01 g). The dry weights were assessed after drying the samples in a forced air circulation oven at 65 ºC, until reaching a constant weight.

The chlorophyll content was monitored on the day of each harvest between 7 and 10 a.m. on a fully developed apical leaf with the highest photosynthetic activity. Four measurements were taken on a selected leaf from each bunch using a portable electronic green plant color intensity meter (SPAD), model Digital SPAD 502 (Minolta Camera Co. Ltd.), with two measurements on the left and two on the right side of the leaf blade.

At 28 DAT, four bunches of plants were collected from each replication for each treatment, transported in plastic trays to the laboratory, and divided into shoot and root. The shoot parts were washed three times with distilled water individually and dried using a manual food centrifuge. The material was placed in individual paper bags and dried in a forced air circulation oven at 65 ºC, until constant weight. The dried material was ground using a Willey-type mill and processed to determine the concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn), following the methods of Malavolta et al. (1997).

During the experimental period, the presence or absence of algae on the roots of all arugula bunches was monitored at each collection and throughout the cycle, with climatic conditions inside the greenhouse being recorded. Moreover, pH and electric conductivity were measured and corrected daily as needed, with the aid of a pre-calibrated HORIBA LAQUAtwin portable meter kit.

The meteorological variables were monitored with the help of a portable humidity and temperature meter, and a thermometer was installed inside the greenhouse next to the arugula production area.

The data were subjected to Anderson-Darling normality tests and Hartley's homoscedasticity tests (homogeneity of variances), followed by an analysis of variance (Anova), with significance levels set at a 5 % probability of error. When significant, the averages were subjected to the Tukey test at 5 % of significance, and regression studies using the R statistical software (version 4.1.2) and SigmaPlot (version 14.0) for graphing.

RESULTS AND DISCUSSION

At the beginning of the cycle, temperatures exceeded 30 ºC, while the relative humidity dipped below 70 % (Figure 1A). Initial electric conductivity readings surpassed 1.5 dS m^{-1} (Figure 1B), requiring a reduction to 1.2 dS m^{-1} to accommodate the prevailing climatic conditions. However, the pH remained within the optimal range of 5.8-6.3 throughout the experimental period. Notably, the hydroponic system exhibited a distribution uniformity coefficient exceeding 95 %.

Throughout the experiment, the temperature and relative humidity averaged 24.85 ºC and 73.3 %, respectively. As noted by Filgueira (2013), temperature and light intensity can be limiting factors, as certain cultivars exhibit varying adaptability to abrupt temperature fluctuations well below or above 30 ºC. To reduce these effects, shading screens should be installed in protected growing environments (Neves et al. 2016).

Monitoring the electric conductivity enables correcting it and maintaining it at 2.5 dS m^{-1}, decreasing plant stress, particularly on elevated temperature days (Jardina et al. 2017). The organoleptic quality of arugula, such as the intensity of spicy flavor, is affected by environmental conditions (Di Gioia et al. 2018, Matev et al. 2018).

Significant differences were observed among the nutrient solution treatments, monitoring times and their interactions for the number of leaves, SPAD readings, root dry mass, shoot dry and fresh masses, and macro and micronutrients. The root and shoot dry masses and fresh masses showed significant differences among the magnetic, electromagnetic and conventional treatments. However, the number of leaves, root fresh mass and SPAD readings did not respond to these treatments (Figure 2).

Compared to the conventional treatment, the root dry mass increased by 20.8 % with magnetism, while the shoot fresh and dry masses rose by 36 and 25 %, respectively (Figures 2C, 2D and 2E). Electromagnetic treatments positively influenced the shoot fresh mass (6 % increase), but had a minimal effect on shoot dry mass. These findings highlight the distinct impact of magnetism on mass accumulation, demonstrating its potential for optimizing plant growth.

Our findings highlight that arugula exhibits growth gains under magnetic treatment. A previous research suggests that magnetism can influence plant metabolism (Liu et al. 2019), mitigating stress and enhancing water and nutrient uptakes, chlorophyll levels, and thus nitrate reductase activity (Zhou et al. 2022, Khaskhoussy et al. 2023). Iron absorption increases the production of growth hormones in arugula plants, regulating the root development and accumulation of shoot fresh mass (Di Gioia 2019).

Abade (2021) noted that a greater light intensity enhances the production of photoassimilates and dry mass. Changes in the water surface tension, increased nutrient solubility, enhanced root development and nutrient absorption can be attributed to the magnetism use. This also reduces the effects caused by stress from temperature and electrical conductivity (Liu et al. 2019, Zhao et al. 2021, Dastorani et al. 2022, Khaskhoussy et al. 2023). Changes in biometric parameters have been reported in tomatoes and

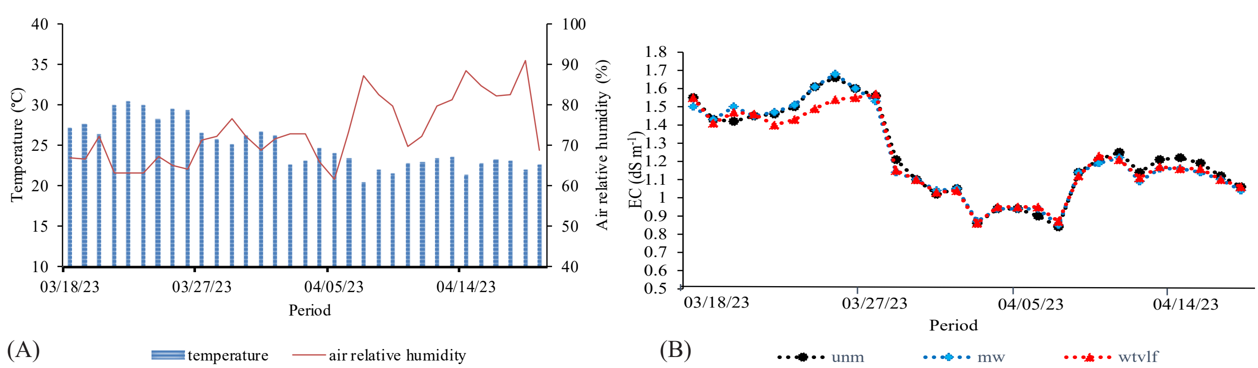

Figure 1. Monitoring of the climate conditions (air relative humidity and temperature) within the greenhouse (A) and electric conductivity (EC) in the nutrient solution (B) during the experimental period. unw: untreated water; mw: magnetic water; wtvlf: water treated with very low-frequency electromagnetic resonance fields.

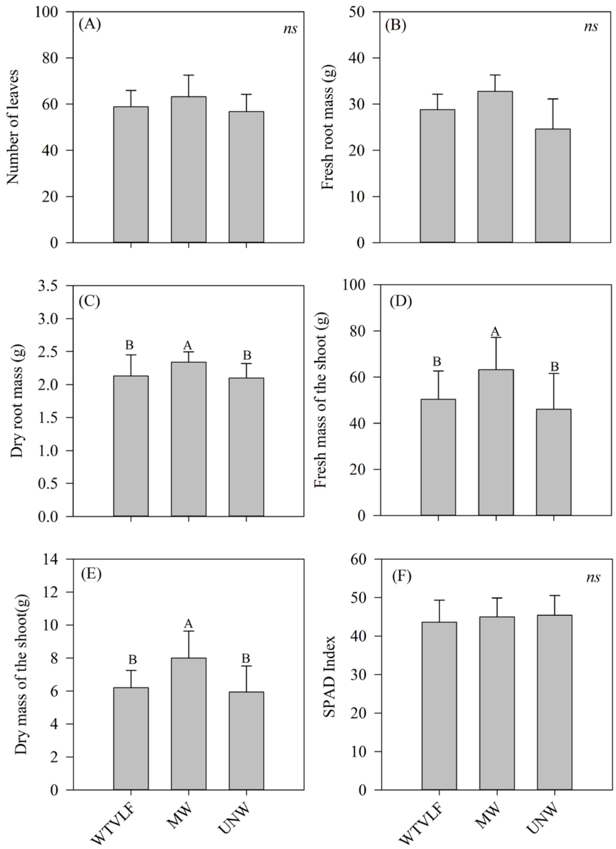

Figure 2. Responses of biometric parameters in hydroponic arugula plants. Distinct uppercase letters indicate statistical differences among the treatments with significance of 5 %, while similar letters indicate lack of statistical difference (ns). UNW: untreated water; MW: magnetic water; WTVLF: water treated with very low-frequency electromagnetic resonance fields.

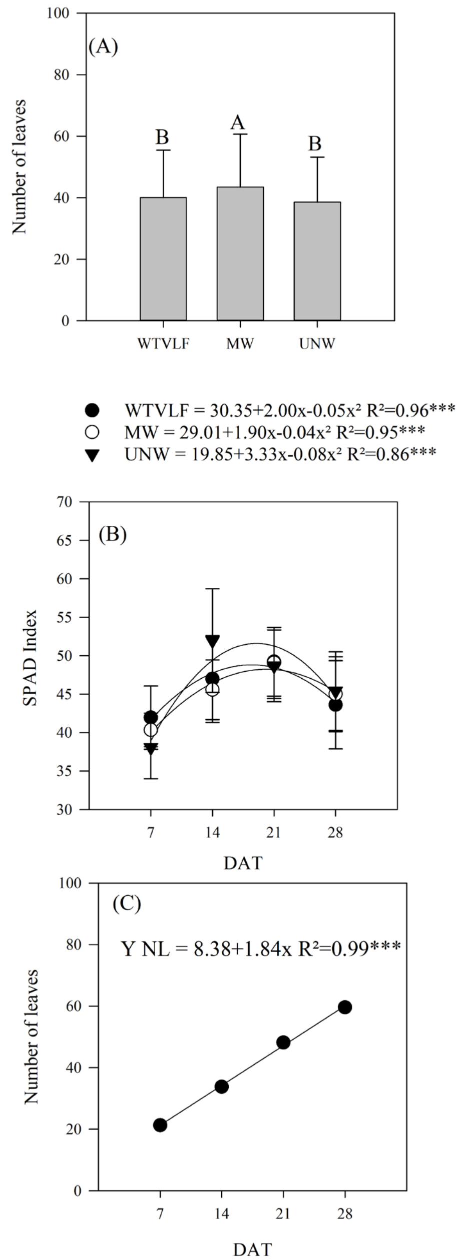

Figure 3. Number of leaves and SPAD readings throughout the cultivation cycle of hydroponic arugula. Distinct uppercase letters indicate statistical differences among the treatments with significance of 5 %, while similar letters indicate lack of statistical difference. *** Linear regression significant at < 1 %. UNW: untreated water; MW: magnetic water; WTVLF: water treated with very low-frequency electromagnetic resonance fields; DAT: days after transplanting.

lettuce (Putti et al. 2023a and 2023b), wheat (Selim et al. 2019), eggplant (Souza et al. 2019) and sunflower (Dastorani et al. 2022).

The number of leaves (Figures 3A and 3C) showed a linear variation pattern, regardless of the treatments, with a coefficient of determination (R^2) of 99 %, and highlighted a 16 % greater difference, when compared to the electromagnetic treatment and 19 % over the conventional one. The SPAD readings (Figure 3B) displayed a quadratic pattern, with R^2 values of 96, 95 and 86 %, respectively for the magnetic, electromagnetic and conventional treatments. The peak SPAD value was 50.35 units at 20 DAT under the conventional system, but without difference when compared to the other treatments at the end of the cycle.

Arugula, a fresh-consumption crop, responds to the environmental conditions and demands cultivation practices that preserve its organoleptic characteristics (Di Gioia et al. 2018, Matev et al.

2018). Crop management and plant population density interfere with the number of leaves, which directly compete for light (Sousa Filho et al. 2021). Production systems like the nutrient film technique (NFT) optimize the plant spatial distribution and quality per bunch (Pinheiro et al. 2021). External factors, such as magnetism, improve biometric parameters potentially related to molecular-level changes in water structure within the nutrient solution (Szczes et al. 2020).

The dry and fresh shoot masses (Figures 4A and 4B) followed a linear variation ($R^2 \approx 98$ %) in all treatments, peaking at 28 DAT (7.61 g and 63.12 g, respectively) under the magnetic treatment. The root dry mass (Figure 4C) increased linearly in all treatments ($R^2 = 99$ %), peaking at 28 DAT (2.28 g) under the magnetic treatment, averaging 7 % every 7 days. Electromagnetism and magnetism boosted the shoot dry mass by averages of 26 and 33 %, respectively, every 7 days.

Pang & Deng (2008) proposed that magnetic fields enhance hydrogen bonding within water molecules, facilitating the formation of closed chains. This, in turn, promotes a molecular electric current due to the Lorentz force from the magnetic field. These magnetic interactions can reduce surface tension and increase mineral dissolution, leading to improved nutrient absorption and plant growth (Szczes et al. 2020, Zhao et al. 2021).

Low iron concentrations can limit the arugula growth (Di Gioia 2019), and environmental fluctuations can also significantly impact plant responses (Carvalho 2021). In this sense, magnetically- or electromagnetically-treated water can mitigate the impacts of adverse production conditions on plant development. Dastorani et al. (2022) and Putti et al. (2023a) observed gains in biometric parameters in tomato and sunflower crops irrigated with magnetic water under water and saline stresses. The authors linked this to improvements in assimilate transport, nutrient absorption and efficient water use.

Electromagnetic treatments increased the magnesium levels, when compared to magnetism and conventional methods (Figure 5E). Similarly, micronutrient concentrations (iron and manganese) were elevated under the electromagnetic treatment (Figures 6C and 6D, respectively).

The electromagnetic treatment influences the nutrient uptake, particularly magnesium, manganese and iron, which play crucial roles in plant processes

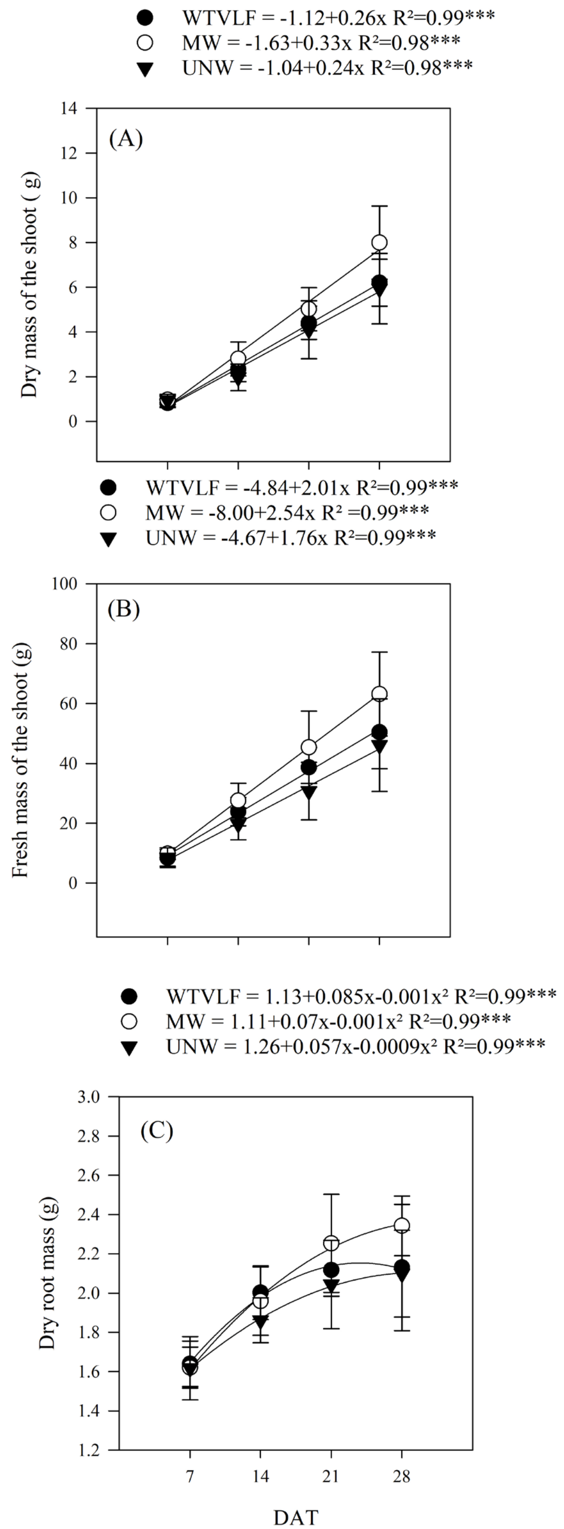

Figure 4. Root dry mass and shoot fresh and dry masses throughout the cycle of hydroponic arugula cultivation. UNW: untreated water; MW: magnetic water; WTVLF: water treated with very low-frequency electromagnetic resonance fields; DAT: days after transplanting. *** Linear regression significant at < 1 %.

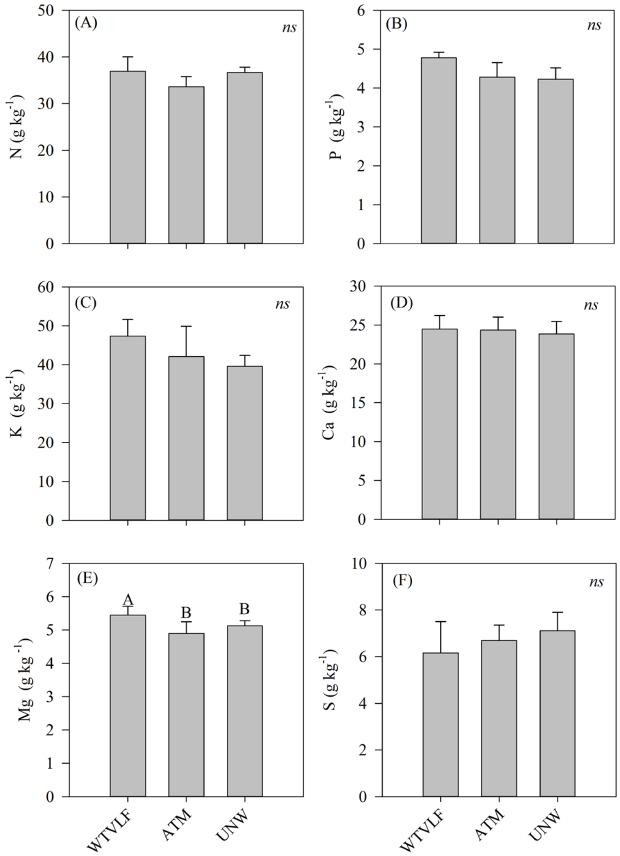

Figure 5. Concentrations of macronutrients in arugula crop under hydroponic system. Distinct uppercase letters indicate statistical differences among the treatments with significance of 5 %, while similar letters indicate lack of statistical difference (ns). UNW: untreated water; MW: magnetic water; WTVLF: water treated with very low-frequency electromagnetic resonance fields.

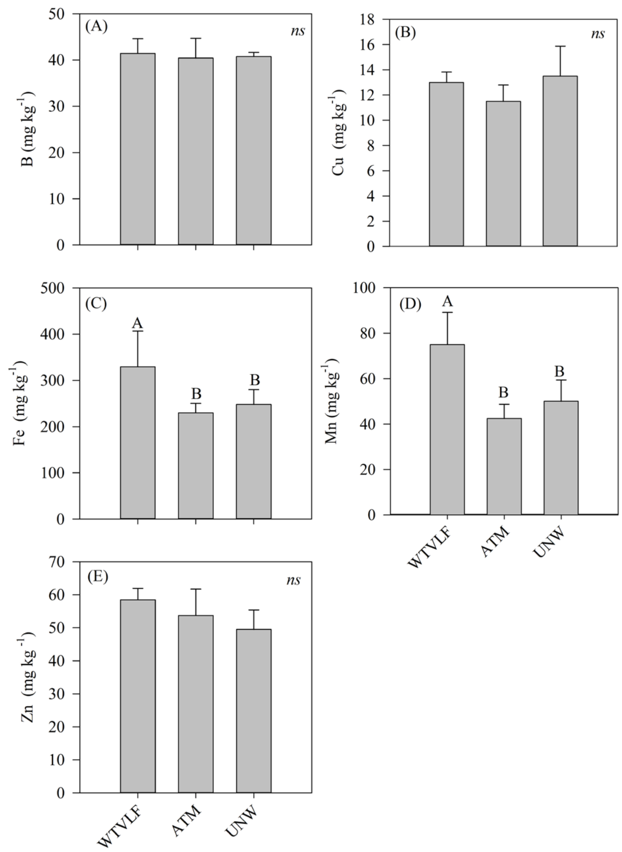

Figure 6. Concentrations of micronutrients in arugula crop under hydroponic system. Distinct uppercase letters indicate statistical differences among the treatments with significance of 5 %, while similar letters indicate lack of statistical difference (ns).UNW: untreated water; MW: magnetic water; WTVLF: water treated with very low-frequency electromagnetic resonance fields.

like chlorophyll formation, enzyme activation, DNA synthesis and hormone production (Taiz et al. 2017). These findings suggest that biometric variables may not always directly correlate with nutrient concentrations.

Optimizing the nutrient levels is essential for preserving the leafy green quality. Yuan et al. (2017) noted that iron supplementation can enhance plant nutrition, while Di Gioia (2019) noted a lower dry mass production at lower iron concentrations. Although the electromagnetic treatment increased the magnesium, manganese and iron uptake, it did not directly translate to a higher number of leaves and root or shoot masses, which differed under the magnetic treatment.

The electromagnetic treatment increased the iron and manganese levels, but did not affect nitrogen or phosphorus, contrasting with lettuce studies by Putti et al. (2023b). While the electromagnetic treatment increased the concentrations of some nutrients, it did not significantly affect the arugula growth, as it responds to environmental conditions (Di Gioia et al. 2018). Conversely, magnetism positively influenced the arugula growth, likely by stimulating the phytohormone production (Turker et al. 2007). From an enzymatic perspective, the magnetically-treated plants showed better growth responses, optimizing the nutrient use (Maheshwari & Grewal 2009).

The algal incidence on plant bunches was lower under the electromagnetic and magnetic treatments (22 and 34 %) than under the conventional treatment (56 %) (Figure 7). This reduction suggests potential benefits for maintaining hydroponic systems. Mercier et al. (2016) and Gosselin et al. (2018) reported

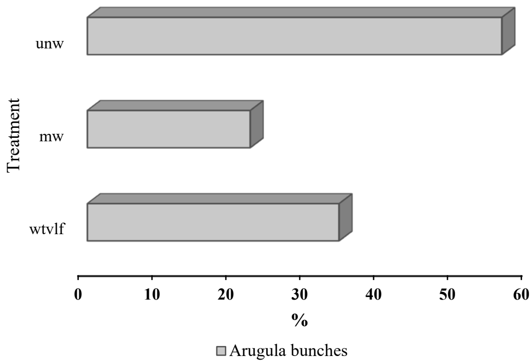

Figure 7. Presence of algae in roots of arugula bunches. unw: untreated water; mw: magnetic water; wtvlf: water treated with very low-frequency electromagnetic resonance fields.

changes in biofilm development associated with algal incidence in magnetically- and electromagnetically-treated water.

Literature reports (Liu et al. 2019, Dastorani et al. 2022, Putti et al. 2023b) have shown numerous benefits of magnetically-treated water, including the induction of biochemical changes, yielding positive outcomes like those noted in the present study. Specifically, hydroponic arugula treated with magnetic systems exhibited enhanced growth.

CONCLUSIONS

1. Implementing magnetism in hydroponic arugula cultivation enhances its development and yield, besides reducing the presence of algae on roots;
2. The electromagnetic treatment increased the concentrations of magnesium, manganese and iron in arugula plants under hydroponic cultivation.

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