Scientific Papers. Series B, Horticulture. Vol. LXX, No. 1, 2026
Print ISSN 2285-5653, CD-ROM ISSN 2285-5661, Online ISSN 2286-1580, ISSN-L 2285-5653

IMPACT ASSESSMENT OF PASSIVE ELECTROMAGNETIC DEVICES ON THE GROWTH PERFORMANCE OF SELECTED LETTUCE VARIETIES

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Abstract

The study was conducted at the Faculty of Horticulture in Bucharest under greenhouse conditions with LED lighting on two Lollo-type lettuce cultivars, aiming to evaluate the effect of electromagnetic frequencies (5-30 MHz) on morphological, productive, and quality parameters. The results highlighted differentiated responses depending on frequency compared with the control variant. Vegetative growth parameters, such as plant height and rosette diameter, showed small variations, suggesting low sensitivity to the applied treatments. The number of leaves remained relatively constant, with slight increases at 7 and 30 MHz, indicating a moderate influence on leaf development. In contrast, productive parameters were significantly influenced. The highest total plant weight values were recorded at 28 MHz and 30 MHz. At the same time, root system development was stimulated, with maximum values of root weight and root volume observed at 28 MHz. Root length was greater at lower frequencies and reduced at higher frequencies, suggesting a redistribution of resources toward volumetric growth. Frequencies of 28-30 MHz demonstrated a stimulatory effect on biomass accumulation and root system development, indicating potential applicability in optimizing production.

Key words*: Lettuce, LED Light, Electromagnetic Fields, Nutrient Film Technique, Bio Stimulation, Frequency-Dependent Effects.*

INTRODUCTION

In the context of sustainable agricultural development and the imperative to reduce chemical inputs in crop production, research into alternative plant growth stimulation methods has become increasingly vital. Among these approaches, the application of passive electromagnetic devices and electromagnetic fields represents a prominent physical factor capable of influencing the biological processes of plant organisms.

In studies conducted in recent years, Abdel Latef et al. (2020) highlighted that exposing plants to magnetic or electromagnetic fields can alter processes such as seed germination, water and nutrient uptake, enzymatic activity, photosynthesis, and biomass development. Concurrently, Tran et al. (2023) demonstrated that exposing lettuce plants to radiofrequency electromagnetic fields (Wi-Fi and DECT) reduced photosynthetic efficiency and stress tolerance, negatively impacting plant development and physiological responses, particularly under field conditions. "

De Souza et al. (2008) demonstrated that applying magnetic treatments to lettuce seeds prior to sowing enhanced plant development across all growth stages, stimulating root length, plant height, leaf area, and ultimately, crop yield and fresh biomass. Similarly, Abdel Latef et al. (2020) showed that exposing lettuce seeds to a static magnetic field led to an increase in vegetative parameters and antioxidant system activity, contributing to a yield enhancement of up to 50% compared to the control group.

Shabrangi and Majd (2009) highlighted that magnetic pretreatment of lentil seeds stimulated the growth of roots and shoots, increased biomass and the activity of antioxidant enzymes (APX and SOD), and also contributed to enhanced plant tolerance to water stress.

Putti et al. (2023) highlighted that utilizing magnetically treated water for lettuce crop irrigation improved nutrient uptake, plant development, and yield, while also contributing to enhanced water-use efficiency and the optimization of irrigation management under water stress conditions.

El-Ssawy et al. (2020) evaluated the effect of utilizing magnetized water across different hydroponic systems for lettuce cultivation, finding that higher magnetic field intensities improved the properties of the irrigation water, reduced water consumption, and increased water productivity. The best results regarding lettuce yield and quality were obtained by combining the NFT system with the maximum water magnetization level (6300 Gauss), thereby highlighting the potential of utilizing magnetized water to enhance water-use efficiency and crop yield in hydroponics.

El-Sayed (2022) demonstrated that treating wheat seeds with synchronized electro-magnetization and microwave radiation significantly improved their germination parameters, vigour, and physiological characteristics compared with the control, highlighting the efficiency of this method as a sustainable alternative for seed priming.

Kim and Oh (2024) reported that applying electric fields to lettuce plants stimulated growth, mineral uptake, and physiological processes. Furthermore, the direction of the electric field differentially influenced leaf development and plant physiological responses, suggesting the potential of utilizing these fields to enhance crop productivity.

Ramalingam (2019) highlighted that the application of magnetic fields represents a promising strategy for stimulating plant growth and enhancing resistance to both biotic and abiotic stresses, while simultaneously underscoring the need for further research to elucidate the underlying mechanisms of action. Similarly, Nyakane Neo et al. (2019) showed that utilizing magnetic fields in agriculture has the potential to contribute to increased crop productivity and improved water-use efficiency; however, they highlighted the necessity of additional studies to establish optimal application parameters and clarify the contradictory results reported in the literature.

The utilization of electromagnetic fields (EMFs) across various frequencies represents an innovative approach in modern agrotechnology, aiming to stimulate germination, accelerate growth rates, and enhance the vegetative vigor of agricultural crops. The present study analyzes the effects of exposing the 'Lollo Bionda' lettuce cultivar (*Lactuca sativa* L. var. *crispa*) to different electromagnetic frequencies ranging from 5 MHz to 30 MHz, compared with an untreated control group. The primary objective of this research is to identify the optimal frequency that maximizes the development of both the shoot and root systems, as well as fresh biomass accumulation.

Tong et al. (2013) and Cai et al. (2024) highlighted that optimizing lighting and HVAC systems, alongside integrating renewable energy sources, represents essential pathways for reducing energy consumption and enhancing the sustainability of plant factory with artificial light (PFAL) systems.

This study aims to evaluate the impact of passive electromagnetic devices operating at different frequencies on the growth performance, biomass accumulation, and quality of selected lettuce cultivars grown in an NFT system under LED lighting.

To this end, relevant morphological and biochemical parameters were analyzed to determine the efficacy of these devices in enhancing crop yield and nutritional quality.

MATERIALS AND METHODS

Experimental Site and Growth Conditions

The study was conducted at the Faculty of Horticulture within the University of Agronomic Sciences and Veterinary Medicine of Bucharest, inside an experimental 'plant factory' greenhouse.

The facility was equipped with a hydroponic Nutrient Film Technique (NFT) system and controlled LED lighting.

Environmental conditions within the experimental greenhouse (air temperature, relative humidity, photoperiod, and light intensity) were continuously monitored and maintained at constant parameters throughout the research to ensure the uniformity of growth factors and to eliminate experimental errors.

Biological Material

The biological material consisted of two lettuce (*Lactuca sativa* L.) cultivars evaluated to determine the impact of passive electromagnetic treatments on their growth and development. The selected varieties were Aleppo (a Lollo Bionda type with green, wrinkled leaves) and Carmesi (a Lollo Rossa type with reddish, wrinkled leaves).

Experimental Layout

The study incorporated nine experimental treatments based on the varying operational frequencies of the tested passive electromagnetic devices, organized as follows: V1 - 5.0 MHz; V2 - 7 MHz; V3 - 10 MHz; V4 - 14 MHz; V5 - 21 MHz; V6 - 25 MHz; V7 - 28 MHz; V8 - 30 MHz și V9 - Control (plants cultivated under identical conditions, but without exposure to electromagnetic devices).

Biometric Determinations and Statistical Analysis

At the end of each cultivation cycle, upon reaching commercial maturity, plants were harvested for biometric analysis. The evaluated morphological traits included shoot parameters (plant height, rosette diameter, and total leaf count per plant), fresh biomass (mean plant weight), and root system characteristics (root length, total root weight, and root volume). Arithmetic means were calculated across three replicates for each treatment over both crop cycles. Data were statistically analyzed to evaluate the significance of differences between the treated groups and the untreated control (V9).

RESULTS AND DISCUSSIONS

The results regarding average plant height revealed differential responses between the two analyzed cultivars depending on the frequency of the applied devices, compared with the control variant (V9), which recorded 18.50 cm for the Aleppo cultivar and 18.00 cm for Carmesi.

For the Aleppo cultivar, the highest values were recorded in treatment V7 - 28 MHz (20.50 cm), representing an increase of +10.8% compared with the control, followed by V4 - 14 MHz (20.30 cm; +9.7%) and V8 - 30 MHz (20.25 cm; +9.5%). Treatment V1 - 5 MHz resulted in a moderate increase (19.30 cm; +4.3%), whereas V2 - 7 MHz showed a slight reduction (18.25 cm; −1.4%) relative to the control. Overall, the Aleppo cultivar exhibited a positive response to medium and high frequencies, with the most pronounced effect observed at 28 MHz.

For the Carmasi cultivar, the response was more variable. The highest value was also recorded in treatment V7 - 28 MHz (20.0 cm), corresponding to an increase of +11.1% compared with the control, followed by V4 - 14 MHz and V5 - 21 MHz (19.0 cm; +5.6%). Treatment V6 - 25 MHz resulted in a decrease relative to the control (16.5 cm; −8.3%), whereas V3 - 10 MHz exhibited values similar to those of the control (18.0 cm). In comparison between cultivars, Aleppo demonstrated greater stability and slightly higher values across most treatments, suggesting a more consistent adaptation to the applied treatments (Figure 1).

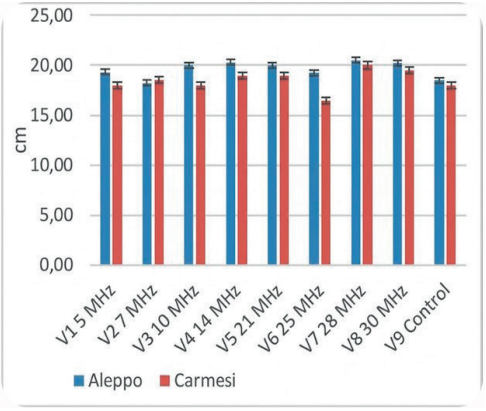


Figure 1. Average plant height of lettuce plants

Regarding rosette diameter, the experimental treatments exhibited moderate differences across both frequencies and cultivars when compared to the control groups-which measured 30.50 cm for Aleppo and 29.50 cm for Carmesi (Figure 2).

For the Aleppo cultivar, the largest rosette diameters were obtained in treatments V4 - 14 MHz and V7 - 28 MHz (33.50 cm), corresponding to an increase of +9.8% compared with the control. Treatment V2 - 7 MHz also produced a favorable effect (32.50 cm; +6.6%), while V8 - 30 MHz resulted in an increase of +7.4%. Treatments V1 - 5 MHz and V6 - 25 MHz showed only slight increases (+1.6% and +3.3%, respectively), whereas V5 - 21 MHz recorded a value lower than that of the control (30.00 cm; −1.6%).

For the Carmesi cultivar, the most favorable response was observed in treatments V4 - 14 MHz and V8 - 30 MHz (34.0 cm), representing an increase of +15.3% compared with the control.

Treatment V7 - 28 MHz also showed a positive effect (+10.2%), while treatments V2 - 7 MHz and V6 - 25 MHz resulted in moderate increases

(+5.1% and +6.8%, respectively). Treatments V1 - 5 MHz and V5 - 21 MHz exhibited values close to those of the control (+1.7%), whereas V3 - 10 MHz showed a relatively small increase (+5.1%).

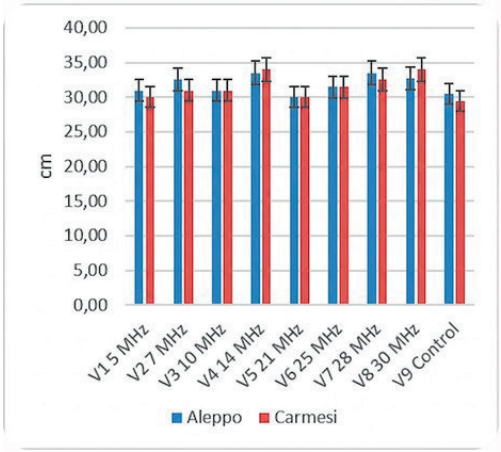


Figure 2. Rosette Diameter

Compared with the control group (27.00 leaves for Aleppo and 24.00 leaves for Carmesi, the experimental treatments induced distinct responses depending on both the cultivar and the applied frequency.

Regarding the Aleppo cultivar, the highest values were recorded in treatments V7 (28 MHz) and V8 (30 MHz), both yielding 30 leaves, which corresponds to an 11.1% increase relative to the control. These were followed by treatment V2 (7 MHz), with 29 leaves (+7.4%), V5 (21 MHz), with 28.50 leaves (+5.6%), and V3 (10 MHz), with 28.00 leaves (+3.7%). In contrast, treatments V1 (5 MHz) and V6 (25 MHz) fell below the control baseline, both recording 26.00 leaves (-3.7%), while V4 (14 MHz) exhibited only a minor increase (+1.9%).

In the case of Carmesi, the variations were more constrained, with values remaining close to the control baseline in most instances. Certain treatments induced slight reductions, indicating a higher sensitivity of this cultivar to the applied treatments. The most favorable outcomes were achieved in treatments V2 (7 MHz) and V8 (30 MHz), both yielding 24.0 leaves, matching the control exactly. Conversely, treatments V1 (5 MHz), V6 (25 MHz), and V7 (28 MHz) recorded moderate declines (22.0 leaves; –8.3%), while the lowest values were observed in V3 (10 MHz) with 21.0 leaves (12.5% below the control). Furthermore, treatment V4 (14 MHz) resulted in an average of 20.0 leaves, representing a decrease of 16.7% relative to the control baseline. Comparative analysis between the two cultivars revealed that Aleppo responded more favorably to the frequency applications, particularly within the 28-30 MHz range. In contrast, Carmesi exhibited higher sensitivity, with the majority of the treatments leading to a reduction in leaf number compared to the control (Figure 3).

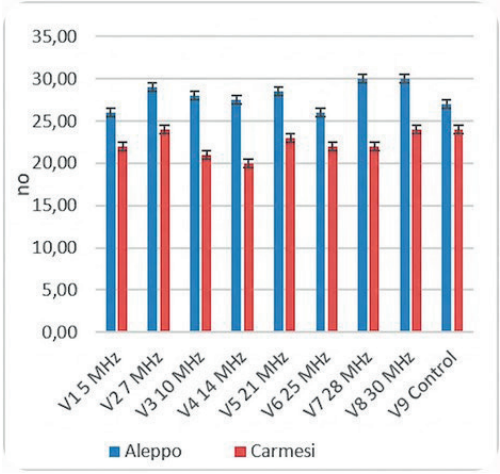


Figure 3. Number of leaves on plants

Root length analysis revealed that the response of the lettuce plants varied depending on both the cultivar and the applied frequency. For Aleppo, root length ranged between 22.50 and 33.25 cm. The highest value was recorded in treatment V1 (5 MHz), yielding 33.25 cm, which represents a +41.5% increase compared with the control group (23.50 cm). Relatively high values were also observed in treatments V2 (7 MHz) and V8 (30 MHz), with averages of 27.75 cm and 25.75 cm, respectively. Conversely, the lowest values were recorded in treatments V6 (25 MHz) and V7 (28 MHz), where root lengths reached only 23.00 cm and 22.50 cm - levels that were close to or even below the control baseline. In the case of Carmesi, the recorded values were generally higher, ranging from 28.0 to 36.0 cm, with the maximum achieved in treatment V2 (7 MHz), which reached 36.0 cm (a +38.5% increase relative to the control). Overall, low frequencies

(5-7 MHz) promoted root development in both cultivars.

In the case of the Carmesi cultivar, the development of the root system was more pronounced compared with the Aleppo cultivar. The maximum root length was recorded in treatment V2 (7 MHz), which achieved an average value of 36.0 cm, representing an increase of approximately 38.5% relative to the control group (26.0 cm). Furthermore, treatments V1 (5 MHz) and V4 (14 MHz) also induced high values for this parameter, reaching 35.5 cm and 32.0 cm, respectively. The lowest value was observed in treatment V7 (28 MHz), where root length was measured at 28.0 cm; however, this value remained superior to that of the control baseline.

Comparative analysis between the cultivars established that Carmesi exhibited higher root length values across the majority of the experimental treatments than Aleppo. This indicates both a higher capacity for root system development and greater sensitivity to the applied treatments. Concurrently, the results demonstrate that low frequencies, particularly within the 5-7 MHz range, promoted root growth in both cultivars. Conversely, frequencies ranging between 21 and 28 MHz exerted a more limited effect on this morphological trait (Figure 4).

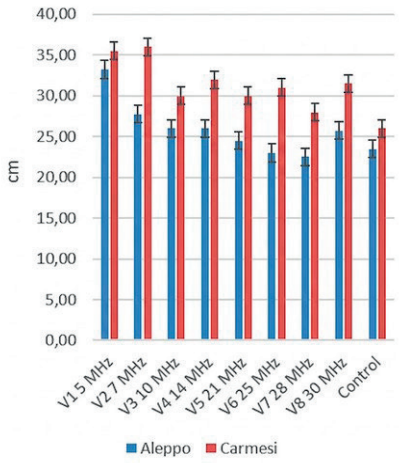


Figure 4. Root length

Regarding fresh biomass accumulation, the data presented in Tables 1 and 2 reveal a general increase in lettuce plant mass across all treated variants compared with the control, thereby indicating a favorable effect of the applied treatments on vegetative biomass accumulation. Concurrently, the intensity of this response varied according to both the cultivar and the applied frequency.

In the case of the Aleppo cultivar (Lollo Bionda type), the average plant mass of the control group was 95.4 g, whereas all experimental variants recorded higher values, ranging between 106.4 g and 121.3 g. The highest value was observed in variant V2 (7 MHz), where the average mass reached 121.3 g, representing an increase of 25.9 g (+27.1%) relative to the control. Furthermore, variants V3 (10 MHz) and V4 (14 MHz) exhibited substantial biomass increases of 23.7% and 21.7%, respectively, compared to the control group. These differences were highly statistically significant, demonstrating the high efficiency of frequencies between 7 and 14 MHz in stimulating plant growth.

Variants corresponding to higher frequencies - specifically 25 MHz, 28 MHz, and 30 MHz - recorded gains of 19.1%, 16.4%, and 15.4% over the control, with these differences being distinctly statistically significant. In contrast, at frequencies of 5 MHz and 21 MHz, growth enhancements were more limited, reaching 11.5% and 12.1%, respectively, and lacked statistical significance (ns). Overall, these results suggest the existence of an optimal frequency window for stimulating biomass accumulation in the Aleppo cultivar, situated between 7 and 14 MHz, where the highest average mass values and the greatest increases relative to the control were achieved.

For the Carmesi cultivar (Lollo Rosa type), the average plant mass in the control group was 106.91 g. In comparison, all treated variants displayed superior values, fluctuating between 115.50 g and 142.17 g.

The maximum average mass was recorded in variant V8 (30 MHz; 142.17 g), followed closely by V7 (28 MHz; 136.70 g). These values corresponded to increases of 35.26 g (32.98%) and 29.79 g (27.86%), respectively, compared with the control, with the differences being highly statistically significant.

These findings indicate that high frequencies exerted the strongest stimulatory effect on biomass accumulation for this specific cultivar.

Variants V5 (21 MHz), V6 (25 MHz), V4 (14 MHz), and V3 (10 MHz) induced increases ranging between 11.93% and 16.28% relative to the control; all of these were statistically significant. At frequencies of 5 MHz and 7 MHz, the gains were more modest (8.03% and 10.78%, respectively), yet they remained statistically significant.

These outcomes suggest that the Carmesi cultivar responds favorably across the entire tested frequency range, although the maximum effect is observed at high frequencies, particularly between 28 and 30 MHz.

A comparative analysis of the two cultivars highlights clear discrepancies in their response mechanisms to the treatments. The Aleppo cultivar exhibited the most robust biomass development at intermediate frequencies (between 7 and 14 MHz), whereas Carmesi manifested a superior response to high frequencies (28-30 MHz).

The maximum mass increase was 27.1% for Aleppo and 32.98% for Carmesi, indicating a higher sensitivity of the Carmesi cultivar to high-frequency stimulation. These differences suggest the presence of distinct genetic and physiological traits that influence each cultivar's specific capacity of each cultivar to respond to the applied treatments.

Table 1. Average fresh weight of lettuce plants

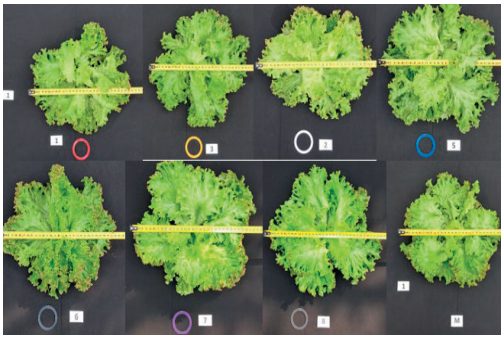
Variant	Weight (g)	Difference from Control (g)	Percentage Difference (%)	Significance
V1 - 5 MHz	106.4	11	11.5	ns
V2 - 7 MHz	121.3	25.9	27.1	***
V3 - 10 MHz	118	22.6	23.7	***
V4 - 14 MHz	116.1	20.7	21.7	***
V5 - 21 MHz	106.9	11.5	12.1	ns
V6 - 25 MHz	113.6	18.2	19.1	**
V7 - 28 MHz	111	15.6	16.4	**
V8 - 30 MHz	110.1	14.7	15.4	**
V9 - Control	95.4	0	0	Ct.

Table 2. Average fresh biomass and statistical significance for the Carmesi lettuce cultivar (Lollo Rosa type) under different frequency treatments

Variant	Weigh t (g)	Difference from Control (g)	Percentage Difference (%)	Signifi cance
V1 - 5 MHz	115.50	8.59	108.03	*
V2 - 7 MHz	118.44	11.53	110.78	*
V3 - 10 MHz	119.66	12.75	111.93	**
V4 - 14 MHz	122.25	15.34	114.35	**
V5 - 21 MHz	124.31	17.40	116.28	**
V6 - 25 MHz	121.48	14.57	113.63	**
V7 - 28 MHz	136.70	29.79	127.86	***
V8 - 30 MHz	142.17	35.26	132.98	***
V9 - Control	**106.91**	**0.00**	**100.00%**	**control**



a



b

Figure 5. The appearance of lettuce plants in the Aleppo (a) and Carmasi (b) cultivars



Figure 6. Appearance of plants grown under LED lighting

Analysis of Root System Parameters

In the Aleppo variety, root length ranged between 22.50 and 33.25 cm (Figure 7).

The highest value was recorded for V1 - 5 MHz (33.25 cm), followed by V2 - 7 MHz (27.75 cm). Compared with the control (23.50 cm), most variants showed superior values, indicating a favorable effect of low frequencies on root system development. The lowest value was observed for V7 - 28 MHz (22.50 cm), slightly lower than the control.

In the Carmesi variety, root length was greater across all variants compared with the Aleppo, with values ranging between 28.0 and 36.0 cm. The maximum value was recorded for V2 - 7 MHz (36.0 cm), followed by V1 - 5 MHz (35.5 cm) and V4 - 14 MHz (32.0 cm). Compthered with the control (26.0 cm), all treatments led to increases in root length, highlighting a superior capacity of the Carmesi variety to respond to the applied stimuli.

It was noted that low frequencies (5-14 MHz) favored the development of root length in both varieties.

In the Aleppo variety, root mass ranged between 3.91 g and 7.83 g. The highest value was obtafored in V7 - 28 MHz (7.83 g), significantly exceeding the control (4.74 g). Additionally, variants V5 - 21 MHz (5.54 g), V6 – 25 MHz (5.22 g), and V8 - 30 MHz (5.70 g) presented high values. These results suggest that high frequencies stimulated root thickening.

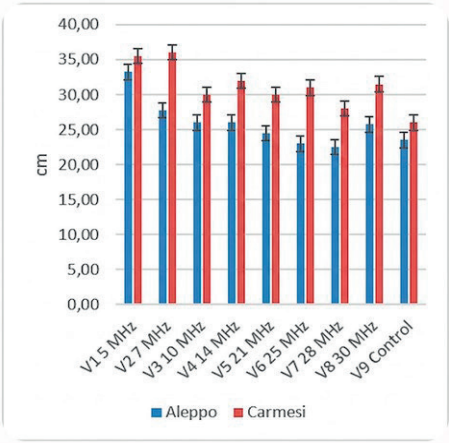


Figure 7. Root length in the analyzed cultivars

In the Carmesi variety, root mass ranged between 4.1 g and 8.9 g. The maximum value was also recorded for V7 - 28 MHz (8.9 g), followed by V6 - 25 MHz (6.5 g) and V8 - 30 MHz (6.2 g) (Figure 8).

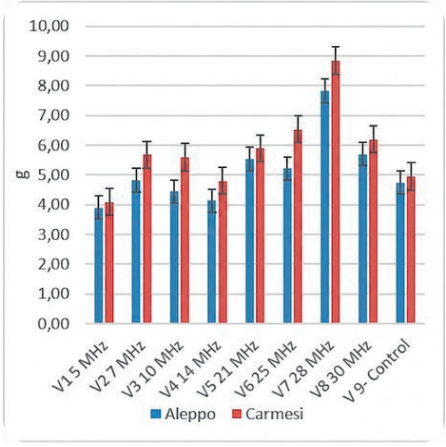


Figure 8. Root mass of lettuce plants

For the Aleppo variety, root volume ranged between 4.50 and 8.25 cm^3. The maximum value was observed in V7 - 28 MHz (8.25 cm^3, followed by V5 - 21 MHz (6.00 cm^3 and V8 - 30 MHz (6.00 cm^3). The control presented a value of 5.40 cm^3.In the Carmasi variety, the values were higher, ranging between 5.0 and 9.0 cm^3. The highest value was recorded in V7 - 28 MHz

(9.0 cm^3), followed by V6 – 25 MHz and V5 - 21 MHz (6.8-6.5 cm^3). The control had a value of 5.8 cm^3.

These results show that the frequency of 28 MHz stimulated root volume most strongly in both varieties (Figure 9).

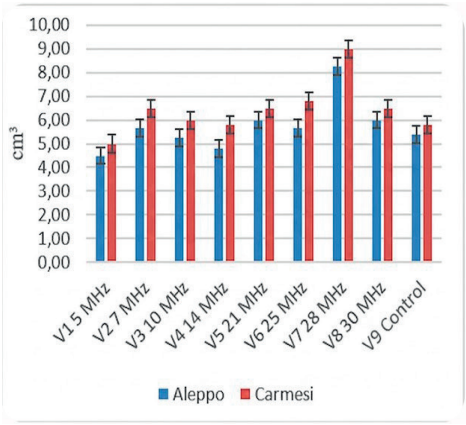


Figure 9. Root volume in the analyzed varieties

Nitrate content

The nitrate content in the Aleppo lettuce variety was influenced by the applied frequencies, with the determined values ranging between 1010.0 and 1730.0 mg/kg. The control variant (V9) recorded the highest nitrate content of 1730.0 mg/kg, while all treated variants exhibited lower values, highlighting a favorable effect of the treatments on reducing nitrate accumulation in the leaves. According to European regulations regarding maximum residue limits for nitrates in lettuce, the values obtained in this experiment are below the maximum allowable limits. This indicates that the resulting yield is safe for consumption and complies with food quality requirements. Compared to the control, the greatest reduction in nitrate content was recorded in variant V7 (28 MHz), where the concentration was 1010.0 mg/kg, representing a 41.6% decrease. Additionally, variant V3 (10 MHz) led to a major reduction of 38.0%, with a recorded value of 1073.3 mg/kg. Significant reductions were also observed in variants V8 (30 MHz), V2 (7 MHz), V4 (14 MHz), and V1 (5 MHz), where the nitrate content was 27.7-36.4% lower than in the control. In contrast, variants V5 (21 MHz) and V6 (25 MHz) presented values closer to the control, namely 1500.0 and 1,600.0 mg/kg, indicating a lower efficiency of these frequencies in limiting nitrate accumulation. These results suggest that the application of specific frequencies, particularly 28 MHz and 10 MHz, favored a more efficient utilization of nitrogen in the plant's metabolic processes, thereby reducing nitrate accumulation in plant tissues. From a product quality standpoint, these variants are highly valuable, as reduced nitrate content is an important indicator of food safety and the nutritional value of lettuce (Figure 10).

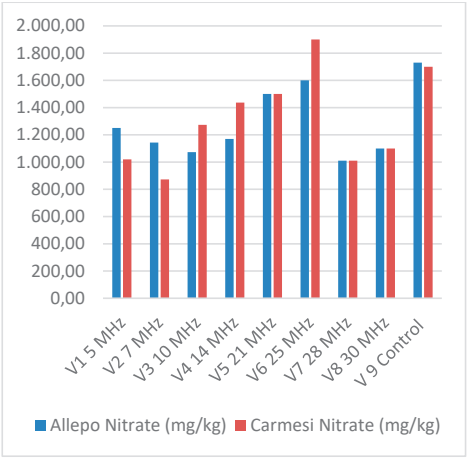


Figure 10. Nitrate content in lettuce leaves

Carbohydrate Content

The carbohydrate content showed less variation compared to nitrates, with values ranging between 2.80% and 3.50%. The control variant (V9) recorded a content of 3.00%, and most treated variants showed equal or superior values. Thus, variants V1 (5 MHz), V2 (7 MHz), and V4 (14 MHz) presented the same carbohydrate level as the control (2.80%). The highest values were determined in variants V6 (25 MHz) and V5 (21 MHz), where the carbohydrate content reached 3.50% and 3.40%, respectively, representing increases of 16.7% and 13.3% compared to the control. Similarly, variants V7 (28 MHz) and V8 (30 MHz) recorded a content of 3.20%, which is 6.7% higher than the untreated variant. The only reduction was observed in variant V3 (10 MHz), where the value of 2.80% was 6.7% lower than that of the control. The increase in carbohydrate content across most treated variants may indicate an intensification of the photosynthetic process and a higher accumulation of storage substances in the leaves. From a food quality

perspective, a higher carbohydrate level contributes to improving the nutritional value and organoleptic characteristics of the product. Variant V6 (25 MHz) stood out particularly, recording the highest carbohydrate content, which suggests that this frequency favored the accumulation of organic compounds resulting from photosynthesis. Overall, the results demonstrate that the applied treatments had a favorable effect on carbohydrate content while simultaneously contributing, in most cases, to a reduction in nitrate content compared to the control variant. Cambria variety (Lollo Rossa Type) - Nitrate Content. In the Lollo Rossa type lettuce, the Cambria variety, the nitrate content ranged between 873 and 1900 mg/kg, depending on the applied frequency. The control variant (V9) recorded a content of 1700 mg/kg, a value that falls within the maximum limits allowed by European legislation for lettuce. Furthermore, all experimental variants presented values below the maximum allowable thresholds for human consumption, confirming the quality and safety of the obtained product. Compared to the control, the greatest reduction in nitrate content was observed in variant V2 (7 MHz), where the value of 873 mg/kg represents a decrease of approximately 48.6%. Major reductions were also recorded in variants V7 (28 MHz), at 1010 mg/kg, and V1 (5 MHz), at 1020 mg/kg, corresponding to decreases of 40.6% and 40.0% compared to the control, respectively. Variant V8 (30 MHz) also led to a significant reduction in nitrate accumulation, with its value of 1100 mg/kg being 35.3% lower than the control. In the case of variant V3 (10 MHz), the nitrate content was 1273 mg/kg, representing a 25.1% reduction, while variant V4 (14 MHz) recorded 1437 mg/kg, which is 15.5% less than the control. Variant V5 (21 MHz) presented a value close to the control, namely 1500 mg/kg, corresponding to an 11.8% reduction. The only variant that exceeded the control value was V6 (25 MHz), where the nitrate concentration reached 1900 mg/kg, representing an increase of approximately 11.8% compared to V9. This result suggests that the 25 MHz frequency favored nitrate accumulation in plant tissues, unlike the other experimental variants. Overall, the results indicate that frequencies of 7 MHz, 28 MHz, and 5 MHz had the most pronounced effect on reducing nitrate accumulation in Cambria lettuce, contributing to improved product quality and yielding values considerably lower than the control variant (Figure 11).

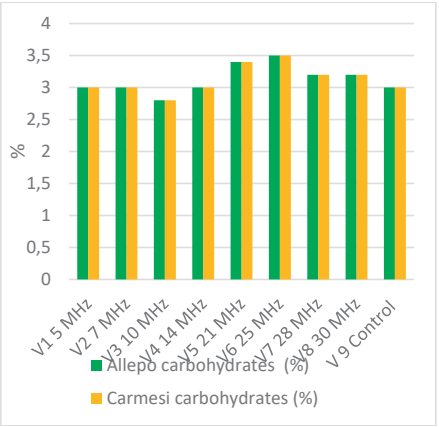


Figure 11. Carbohydrate Content

CONCLUSIONS

The application of treatments using passive electromagnetic devices exerted a general stimulatory effect on biomass accumulation and morphological parameters in lettuce. The biological response is strictly dependent on the genotype (cultivar) and the applied frequency.

The Aleppo variety shows an affinity for medium frequencies (7-14 MHz), optimizing its biomass at 7 MHz.

Conversely, the Carmesi variety exhibits higher sensitivity to high frequencies (28-30 MHz), achieving a biomass increase of +32.98% at 30 MHz. Root system development follows a dual pattern: low frequencies (5.0-7 MHz) stimulate root elongation, whereas high frequencies (especially 28 MHz) stimulate root density, mass, and volume, generating a more vigorous anchoring and absorption system.

Passive electromagnetic technology represents a sustainable and promising alternative for optimizing horticultural production in Plant Factory-type systems.

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