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Effect of Pulsed Electromagnetic Field on Growth, Physiology and Postharvest Quality of Kale (*Brassica oleracea*), Wheat (*Triticum durum*) and Spinach (*Spinacia oleracea*) Microgreens

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Abstract: Microgreens' popularity is increasing worldwide, and many efforts are focused on novel techniques that could increase fresh production without affecting the quality and the shelf life of the young plants. Three species of microgreens (kale, durum wheat, and spinach) were cultivated in a greenhouse experiment in November–December 2020. Pulsed electromagnetic field (PEMF) was applied at three different growth stages (seed, newly developed plant, and before harvest) and three different times of exposure at each stage, while untreated seeds were used as control. According to the results, certain PEMF treatments increased fresh weight for all three plant species, while dry weight was higher in the treated plants for wheat and spinach, compared to the control. As for the color parameters L*, a*, and b*, at the harvest and postharvest, PEMF treatments had no negative effects, either at harvest or at green color retention, during storage. Moreover, PEMF treatments improved green color in wheat, and restricted yellow color in spinach. An important finding regarding respiration was that PEMF treatments increased both O_2 consumption and CO_2 production for durum wheat and CO_2 production for spinach.

Keywords: microgreen; wheat; kale; spinach; PEMF; postharvest

1. Introduction

Microgreens are new specialty food products that are constantly attracting increasing attention from consumers worldwide as they have high concentrations of bioactive substances [1] and mineral nutrients [2]. Microgreens have gained popularity among consumers due to their crispy textures, vibrant colors, and intense flavors [3]. They are considered as a new category of edible vegetables and they are used as an edible garnish or as a salad ingredient [4]. Studies have shown that microgreens are important sources of nutrients (ascorbic acid, tocopherols, carotenoids, phenolics, and trace elements) in concentrations higher than the corresponding conventional mature products [3,5,6].

Microgreens are tiny versions of ordinary plants produced from the seeds of vegetables, herbs, or cereals, and their final edible form contains two fully developed cotyledons with the first pair of true leaves that emerged. Unlike sprouts and baby leaf, whose specifications

are described in detail in relevant regulations, microgreens is a marketing term to describe plants that are more developed than sprouts (4–10 days) and less developed than baby leaf (20–40 days), namely 7–28 days [1] or, more strictly, plants harvested 10 to 20 days after seed emergence [7]. This novel type of plant cultivation focuses on the production of young plant leaves with high nutritional value for the human diet that, at the same time, are sought after in gastronomy [6].

Pre-sowing treatments of the seeds that are used to produce microgreens are gaining the interest of researchers, in order to regulate the production cycle, as well as to increase yield and quality [6]. Seed treatment techniques have been used to improve the establishment of beet and chard microgreens [7]. Cold plasma treatments at 21 and 23 kV for 5 min in mustard green seeds increased germination and plant growth of microgreens [8]. Cold plasma in combination with elicitors has been used to investigate plant growth and antioxidant activity of rat-tailed radish [9]. Preharvest and postharvest treatments with $CaCl_2$ have been used in broccoli microgreens to increase yield, shelf life, and postharvest quality [10]. Even etiolation has been used as a treatment on barley and wheat microgreens in order to increase pigments and equivalent antioxidant capacities [11]. To the best of our knowledge, there is no published research on the use of pulsed electromagnetic field (PEMF) as a treatment for the cultivation of microgreens. However, PEMF has been extensively investigated as a novel organic priming method on germination and early growth stages [12]. Different types of devices [13,14] that produce magnetic fields, with a wide range of intensities and duration of exposure, have been used [15,16], providing significant results for the role of magnetic fields on plant growth.

The treatment with magnetic field at the early stages of plant growth is practically impossible, especially for field crops, due to the large areas that are cultivated and the small coverage of the magnetic field devices. This is the reason why the research is focused mainly on pre-sowing treatments. Conversely, in the case of microgreen cultivation, the treatment of seedlings is feasible, as the method of production allows such handling. Various priming methods have been used on microgreen experiments. Seeds of beet and chard germinated in a shallow layer of vermiculite had increased early seedling growth compared to control seeds [7]. Seeds of mustard green treated with cold plasma had higher germination and dry weight compared to control [8]. The use of NaCl elicitor increased germination of rat-tailed radish, while the treatments of NaCl and $CaCl_2$ led to the highest fresh weight of microgreens [9].

As microgreens are highly perishable, their postharvest performance has been investigated in many experiments, in order to preserve, as far as possible, their high nutritional value and organoleptic traits [2]. Storage temperature, modified atmosphere packaging, and washing treatments have been used to identify differences in postharvest quality and shelf life of different species of microgreens [17,18]. Pre-sowing seed treatments and preharvest and postharvest treatments are major areas of investigation that could contribute to the optimization of microgreen cultivation [19].

The aim of this study was to investigate the effect of pulsed electromagnetic field on kale (*Brassica oleracea*), wheat (*Triticum durum*), and spinach (*Spinacia oleracea*) microgreens. Treatments at three different growth stages (seed, newly developed plant, and before harvest) and three different times of exposure at each stage were used in an attempt to identify the most suitable technique for this innovative type of cultivation. Plant growth, physiology, and quality parameters at the harvest and postharvest were measured in order to obtain valuable information regarding the quantity and the quality of the production, as well as the postharvest behavior of the microgreens.

2. Materials and Methods

2.1. Microgreen Cultivation and Experimental Design

Three species of microgreens were cultivated in a greenhouse experiment in November–December 2020. Seeds of kale (*Brassica oleracea*) variety Darkibor (Bejo Zaden B.V., Warmenhuizen, Netherlands), wheat (*Triticum durum*) variety SY Atlante (Syngenta Hellas S.A.),

and spinach (*Spinacia oleracea*) variety Revere (Bejo Zaden B.V.) were used. The cultivation of microgreens was conducted in trays with dimensions 13 × 10.5 cm and 6 cm height. The substrate was a mixture of perlite, peat, and vermiculite (1:1:1). Fifty seeds were used at each tray.

The three experiments followed a completely randomized design, with ten treatments of exposure in pulsed electromagnetic field with three replications. The magnetic field was applied at three different growth stages (seed, newly developed plant, and before harvest) and three different times of exposure at each stage (15, 30, and 45 min as pre-sowing, 5, 10, and 15 min at seedlings, and 10, 20, and 30 min at microgreens just before harvest), making nine treatments. Untreated seeds were used as control. The choice to use these times of exposure as a pre-sowing treatment was based on our previously published work and preliminary studies, while the choice of the exposure times in the newly developed plants and before harvest application was based on our unpublished data and preliminary experiments.

The exposure of the seeds and the young microgreens in pulsed electromagnetic field was conducted with PAPIMI device. This device is a pulsed electromagnetic field (PEMF) generator (PAPIMI model 600, Pulse Dynamics, Athens, Greece. Manufacturer characteristics: 35–80 J/pulse energy, 1×10^{-6} s wave duration, 35–80 $\times$ 10^6 W wave power, amplitude of the order of 12.5 mT, rise time 0.1 ms, fall time 10 ms, and repetitive frequency of 3 Hz).

For all three species, the microgreens were harvested at BBCH 12 [20], corresponding to the stage of two fully developed cotyledons with the first pair of true leaves unfolded for kale and spinach, and to the stage of two leaves unfolded for wheat. The microgreens were harvested by cutting the whole plant at a height of about 4–5 mm above substrate level and transporting to the laboratory within 10 min. From each replicate tray, half the portion of microgreens were used for the measurements at harvest and the remaining microgreens (about 2–3 g) were packaged for postharvest experiments. The packaging material was a polypropylene (PP) cylindrical container (120 mL, 70 mm height × 50 mm i.d.) sealed with a polyethylene (PE) modified atmosphere film of 9 μm thickness (FOX-45, VAM, Greece). Packaged microgreens were stored for 7 d at 4 °C and 90% RH.

2.2. Measurements and Observations

The physiology measurements of photosynthetic rate (μmol CO_2 m^{-2} s^{-1}), transpiration rate (mmol H_2O m^{-2} s^{-1}), and stomatal conductance (mol m^{-2} s^{-1}) took place 29 days after sowing (DAS), using an LCi Leaf Chamber Analysis System (ADC, Bioscientific, Hoddesdon, UK). For the measurement of plant fresh weight, a precision balance with accuracy of two digits was used. For the measurement of plant dry wight, the measurement was conducted with a precision balance after the samples were oven-dried at 70 °C for three days.

The respiration rates were measured by a static system method using a portable gas analyzer (Dansensor CheckPoint 3, Mocon, Denmark) equipped with both ceramic solid-state and infrared single beam sensors for O_2 and CO_2 measurement, respectively. About 1 g of whole microgreens were incubated in a 60 mL sealed jar for 60–90 min (depending on species) at 20 °C, and a headspace gas sample of 5 mL was used for the analysis. Tissue temperature was equilibrated at 20 °C before sealing the jar. Results were expressed in mL/kg/h O_2 consumption or CO_2 production.

The leaf (cotyledon for kale and spinach, and first leaf for wheat) color of the microgreens was measured using a Minolta Colorimeter (CR-300, Minolta Company, Chuo-Ku, Osaka, Japan). The lightness or brightness of the samples was indicated by the L* value, where 0–100 represents dark to light color. The index a* indicates the redness or greenness of the microgreens, with a negative a* value representing more green color. The index b* value represents the degree of the yellow–blue color, with a positive b value illustrating more yellow color. For each replication, the color was recorded in five leaves from five different microgreens.

The texture analysis was carried out by an HD-Plus texture analyzer (Stable Micro Systems Ltd., Godalming, UK) and the Texture Expert Exceed Software for the data analysis. The determination of the textural characteristics of microgreen leaf was performed by a cylindrical probe of 2 mm diameter. Probe speeds of 1 mm/s during the test, 5 mm/s for the pretest, and 10 mm/s for the post-test were used throughout the study. All the measurements were performed at 20 ± 1 °C and the perforation force of the leaf was determined and expressed in g. For each replication, the texture was recorded in five leaves (cotyledon for kale and spinach, and first leaf for wheat) from five different microgreens.

2.3. Statistical Analysis

The experimental data were analyzed using IBM SPSS software ver. 27 (IBM Corp., Armonk, NY, USA). The evaluation of the effect of the treatments at three different growth stages and three different times of exposure at each stage was calculated via one-way analysis of variance (ANOVA). The comparisons of means were calculated using Duncan's test at the 5% level of significance ($p < 0.05$).

3. Results and Discussion

The application of pulsed electromagnetic field at three different growth stages and three different times of exposure at each stage affected the physiology (Table 1) and the fresh and dry weight of the kale, wheat, and spinach microgreens. Regarding the quality of the microgreens, the three species that were cultivated presented diverse results for the different treatments used. The treatments of PEMF in some cases were found to have statistically significant differences, while for others it did not affect color parameters (Table 2), texture (Table 2), and respiration as O_2 and CO_2 consumption at harvest and postharvest (Table 3) of the microgreens.

3.1. Physiology Measurements

Regarding the measurement of photosynthetic rate of kale microgreens, the treatments of S-30 (9.11 μmol CO_2 m^{-2} s^{-1}), H-30 (8.95 μmol CO_2 m^{-2} s^{-1}), and H-20 (8.77 μmol CO_2 m^{-2} s^{-1}) resulted in the highest values with statistically significant differences compared to control (7.17 μmol CO_2 m^{-2} s^{-1}). Regarding the wheat microgreens, the treatment of P-10 (14.68 μmol CO_2 m^{-2} s^{-1}) had the highest value, although most treatments (S-30, S-45, P-5, P-15, H-10, and H-20) had statistically significant differences compared to control (10.70 μmol CO_2 m^{-2} s^{-1}). As for the spinach microgreens, all three treatments (H-10, H-20, and H-30) with PEMF before harvest (19.08, 19.24, and 18.50 μmol CO_2 m^{-2} s^{-1}, respectively) had statistically significant differences compared to control (14.68 μmol CO_2 m^{-2} s^{-1}).

Transpiration rate of kale microgreens treated with S-30 (1.31 mmol H_2O m^{-2} s^{-1}) was statistically significantly higher compared to all other treatments. All H- and S-treatments had statistically significant differences compared to the treatments of P- and control. In contrast to kale, wheat transpiration rate was found to be higher for the treatments of H-30 (2.92 mmol H_2O m^{-2} s^{-1}) and H-20 (2.84 mmol H_2O m^{-2} s^{-1}). Moreover, all PEMF treatments had statistically significant differences compared to control (1.62 mmol H_2O m^{-2} s^{-1}). Similar to wheat, the transpiration rate of spinach microgreens treated with PEMF was statistically significantly higher than control. The H- treatments (10, 20, and 30) with PEMF before harvest (2.28, 2.30, and 2.30 mmol H_2O m^{-2} s^{-1}, respectively) resulted in the highest values with statistically significant differences compared to control (14.68 mmol H_2O m^{-2} s^{-1}).

Regarding the measurement of stomatal conductance, all PEMF treatments had statistically significant differences compared to control in the case of kale and wheat microgreens. As for the spinach, the treatments of H-20 (0.38 mol m^{-2} s^{-1}) and H-30 (0.36 mol m^{-2} s^{-1}) gave the highest values with statistically significant differences compared to control.

The exact mechanism of action by which pulsed electromagnetic field affects the physiology of plants remains under investigation. However, there is similar research with

results that are in accordance with our findings. The use of magnetic field as a pre-sowing method on two cultivars of durum wheat seeds had a positive impact on dry weight, photosynthetic rate, transpiration rate, stomatal conductance, and yield [21]. In a study focused on 1 month seedlings, it was found that stationary magnetic fields of 150 and 200 mT for 60 min enhanced the photosynthetic efficiency of the young plants [22].

Table 1. Influence of pulsed electromagnetic field treatments, at three different growth stages and three different times of exposure at each stage, on photosynthetic rate, transpiration rate, and stomatal conductance of kale (*Brassica oleracea*), wheat (*Triticum durum*), and spinach (*Spinacia oleracea*) microgreens.

	Photosynthetic Rate (μmol CO_2 m^{-2} s^{-1})	**Transpiration Rate (mmol H_2O m^{-2} s^{-1})**	**Stomatal Conductance (mol m^{-2} s^{-1})**
Kale			
Control	7.17 ^{d}	0.92 ^{d}	0.04 ^{b}
S-15	8.58 ^{bc}	1.15 ^{b}	0.08 ^{a}
S-30	9.11 ^{a}	1.31 ^{a}	0.08 ^{a}
S-45	8.38 ^{c}	1.03 ^{c}	0.09 ^{a}
P-5	6.75 ^{de}	0.90 ^{d}	0.08 ^{a}
P-10	6.62 ^{e}	0.88 ^{d}	0.08 ^{a}
P-15	6.86 ^{de}	0.89 ^{d}	0.07 ^{a}
H-10	8.58 ^{bc}	1.20 ^{b}	0.09 ^{a}
H-20	8.77 ^{abc}	1.17 ^{b}	0.09 ^{a}
H-30	8.95 ^{ab}	1.21 ^{b}	0.09 ^{a}
F_{treat}	47.456 ***	29.273 ***	3.870 **
Wheat			
Control	10.70 ^{d}	1.62 ^{c}	0.22 ^{b}
S-15	13.12 ^{c}	2.30 ^{b}	0.28 ^{a}
S-30	14.56 ^{ab}	2.28 ^{b}	0.30 ^{a}
S-45	14.02 ^{abc}	2.34 ^{b}	0.30 ^{a}
P-5	13.90 ^{abc}	2.44 ^{b}	0.32 ^{a}
P-10	14.68 ^{a}	2.26 ^{b}	0.32 ^{a}
P-15	14.04 ^{abc}	2.30 ^{b}	0.34^{a}
H-10	14.08 ^{abc}	2.36 ^{b}	0.32 ^{a}
H-20	13.78 ^{abc}	2.84 ^{a}	0.34 ^{a}
H-30	13.62 ^{bc}	2.92 ^{a}	0.34 ^{a}
F_{treat}	14.763 ***	23.967 ***	4.222 **
Spinach			
Control	14.68 ^{c}	1.66 ^{d}	0.18 ^{d}
S-15	15.12 ^{bc}	1.82 ^{c}	0.30 ^{c}
S-30	15.78 ^{b}	1.80 ^{c}	0.30 ^{c}
S-45	15.22 ^{bc}	1.92 ^{b}	0.30 ^{c}
P-5	15.40 ^{bc}	1.94 ^{b}	0.28 ^{c}
P-10	15.82 ^{b}	1.94 ^{b}	0.30 ^{c}
P-15	15.14 ^{bc}	2.00 ^{b}	0.30 ^{c}
H-10	19.08 ^{a}	2.28 ^{a}	0.32 ^{bc}
H-20	19.24 ^{a}	2.30 ^{a}	0.38 ^{a}
H-30	18.50 ^{a}	2.30 ^{a}	0.36 ^{ab}
F_{treat}	33.086 ***	67.228 ***	11.648 ***

S: treatment with PEMF on seeds for 15, 30, and 45 min. P: treatment with PEMF on newly developed plants for 5, 10, and 15 min. H: treatment with PEMF on microgreens before harvest. Means followed by the same letter for treatments are not significantly different according to Duncan's test ($p < 0.05$). Values presented are mean values of three replicates. Significance levels: ** $p < 0.01$; *** $p < 0.001$.

Table 2. Influence of pulsed electromagnetic field treatments, at three different growth stages and three different times of exposure at each stage, on color parameters and texture of kale (*Brassica oleracea*), wheat (*Triticum durum*), and spinach (*Spinacia oleracea*) microgreens at harvest and postharvest.

	At Harvest				Postharvest (8 DAH)			
	L*	**a***	**a***	**Texture (g)**	**L***	**a***	**b***	**Texture (g)**
Kale								
Control	44.04	−16.53	20.69	73.25	45.51	−17.27	23.26	75.22
S-15	44.41	−16.50	20.79	86.29	45.77	−17.07	23.26	89.67
S-30	44.69	−16.01	20.81	80.69	44.71	−16.42	21.71	90.92
S-45	44.09	−16.20	20.62	88.08	45.90	−17.08	23.25	84.76
P-5	45.21	−16.29	20.84	86.29	45.44	−15.63	22.49	84.40
P-10	44.87	−16.43	21.08	80.69	45.21	−16.77	22.90	86.62
P-15	44.97	−16.31	20.41	84.54	44.44	−16.45	21.65	81.34
H-10	45.26	−16.54	20.83	84.42	45.39	−16.99	23.15	79.20
H-20	44.48	−15.99	20.08	86.56	44.90	−16.53	22.08	80.39
H-30	44.49	−15.88	20.11	81.59	45.07	−16.70	21.87	89.59
F_{treat}	1.253 ^{ns}	1.432 ^{ns}	1.038 ^{ns}	1.135 ^{ns}	0.466 ^{ns}	1.005 ^{ns}	1.200 ^{ns}	1.876 ^{ns}
Wheat								
Control	43.11^{a}	−18.78 ^{ab}	22.66	163.28	42.21	−17.66^{ab}	23.38	164.61
S-15	43.25^{a}	−19.13 ^{bcd}	22.82	172.36	43.55	−18.03^{abc}	24.32	177.17
S-30	43.08^{a}	−19.20 ^{bcd}	22.59	173.63	43.95	−18.89^{abc}	24.70	170.28
S-45	42.85^{a}	−19.26 ^{cd}	23.06	174.94	44.57	−19.49^{c}	25.71	176.60
P-5	42.70^{a}	−18.90 ^{abcd}	22.70	172.13	44.61	−19.46^{c}	25.20	167.92
P-10	42.05^{ab}	−19.21 ^{bcd}	22.95	151.97	44.93	−18.91^{abc}	25.39	172.71
P-15	42.43^{a}	−19.32 ^{cd}	23.01	165.30	42.96	−18.57^{abc}	24.14	160.36
H-10	43.42^{a}	−19.36 ^{d}	23.36	171.60	44.23	−17.39^{a}	23.06	154.64
H-20	42.97^{a}	−18.88 ^{abc}	22.71	146.90	43.32	−17.94^{abc}	24.66	167.80
H-30	40.84^{b}	−18.48 ^{a}	22.80	151.90	44.42	−19.03^{bc}	24.83	165.50
F_{treat}	2.980 *	4.137 **	0.859 ^{ns}	1.619 ^{ns}	0.630 ^{ns}	0.041 *	0.459 ^{ns}	0.743 ^{ns}
Spinach								
Control	41.59	−17.51	23.59 ^{a}	43.64	41.75	−17.73 ^{b}	23.20	49.02
S-15	42.67	−17.60	23.07 ^{ab}	50.64	41.99	−17.57 ^{b}	22.74	47.94
S-30	41.27	−16.94	21.69 ^{cd}	44.83	40.04	−17.80 ^{b}	23.30	49.63
S-45	41.92	−17.35	22.49 ^{abc}	49.53	40.85	−16.75 ^{ab}	21.55	53.89
P-5	42.76	−17.61	22.98 ^{abc}	50.64	39.96	−16.52 ^{ab}	21.79	58.09
P-10	42.60	−16.97	21.67 ^{cd}	44.83	40.28	−16.94 ^{ab}	23.13	54.34
P-15	42.75	−17.66	23.10 ^{ab}	45.89	39.41	−16.68 ^{ab}	22.65	49.73
H-10	41.50	−17.21	22.26 ^{abc}	46.99	41.95	−17.57 ^{b}	22.92	50.88
H-20	42.03	−17.17	22.00 ^{bc}	48.54	40.44	−16.64 ^{ab}	22.56	53.10
H-30	41.46	−16.57	20.56 ^{d}	48.07	39.59	−15.95 ^{a}	21.72	57.06
F_{treat}	1.729 ^{ns}	2.176 ^{ns}	4.674 **	1.317 ^{ns}	1.142 ^{ns}	2.416 *	0.983 ^{ns}	0.461 ^{ns}

S: treatment with PEMF on seeds for 15, 30, and 45 min. P: treatment with PEMF on newly developed plants for 5, 10, and 15 min. H: treatment with PEMF on microgreens before harvest. DAH: days after harvest. Means followed by the same letter for treatments are not significantly different according to Duncan's test ($p < 0.05$). Values presented are mean values of three replicates. Significance levels: * $p < 0.05$; ** $p < 0.01$; ns = not significant.

Table 3. Influence of pulsed electromagnetic field treatments, at three different growth stages and three different times of exposure at each stage, on respiration as O_2 and CO_2 consumption of kale (*Brassica oleracea*), wheat (*Triticum durum*), and spinach (*Spinacia oleracea*) microgreens.

	At Harvest		Postharvest (8 DAH)		Weight Loss (%)
	Respiration as O_2 Consumption (mL/kg/h)	Respiration as CO_2 Production (mL/kg/h)	Respiration as O_2 Consumption (mL/kg/h)	Respiration as CO_2 Production (mL/kg/h)	
Kale					
Control	132.38	88.25	70.06	86.86	1.923
S-15	84.02	98.37	76.48	84.23	2.090
S-30	122.84	122.84	72.95	104.36	2.148
S-45	141.27	141.27	98.67	110.01	2.076
P-5	103.53	103.53	66.77	103.30	2.208
P-10	110.56	122.06	71.70	96.89	2.136
P-15	96.74	96.74	75.59	92.08	2.103
H-10	93.72	121.66	80.44	80.44	2.251
H-20	110.22	101.47	75.94	83.22	1.923
H-30	144.91	144.91	86.08	104.95	2.666
F_{treat}	2.082^{ns}	2.074 ^{ns}	0.599 ^{ns}	0.821 ^{ns}	0.247 ^{ns}
Wheat					
Control	65.53 ^{b}	78.89 ^{cd}	89.10	65.97 ^{bc}	1.229
S-15	64.29 ^{b}	75.82 ^{cd}	85.76	37.18 ^{c}	1.447
S-30	62.65 ^{b}	78.54 ^{cd}	73.48	36.41 ^{c}	1.485
S-45	61.02 ^{b}	67.99 ^{d}	101.15	75.81 ^{abc}	1.608
P-5	75.85 ^{ab}	89.90 ^{bcd}	100.77	88.45 ^{ab}	1.599
P-10	87.25 ^{ab}	99.43 ^{abc}	101.94	91.17 ^{ab}	2.034
P-15	82.93 ^{ab}	97.76 ^{abc}	108.73	94.17 ^{ab}	1.999
H-10	80.47 ^{ab}	104.65 ^{ab}	74.38	76.40 ^{abc}	1.927
H-20	87.05 ^{ab}	104.33 ^{ab}	142.93	119.40 ^{a}	2.194
H-30	98.14 ^{a}	121.26 ^{a}	113.86	107.08 ^{ab}	2.688
F_{treat}	2.563 *	5.195 **	1.237 ^{ns}	3.894 *	1.982 ^{ns}
Spinach					
Control	60.42	60.42 ^{e}	34.66 ^{b}	10.93 ^{d}	2.272
S-15	57.66	63.35 ^{e}	47.43 ^{b}	20.64 ^{d}	2.397
S-30	61.69	80.32 ^{cde}	37.82 ^{b}	24.95 ^{cd}	2.588
S-45	71.44	77.17 ^{de}	39.72 ^{b}	39.72 ^{bc}	2.069
P-5	62.84	80.70 ^{cde}	52.89 ^{b}	41.26 ^{bc}	2.037
P-10	63.48	103.78 ^{abc}	45.33 ^{b}	45.33 ^{b}	1.660
P-15	72.75	78.49 ^{cde}	43.65 ^{b}	50.23 ^{b}	1.374
H-10	70.26	92.33 ^{bcd}	51.72 ^{b}	45.33 ^{b}	2.202
H-20	96.57	119.57 ^{a}	50.76 ^{b}	56.97 ^{b}	1.704
H-30	75.84	108.70 ^{ab}	91.47 ^{a}	91.47 ^{a}	2.224
F_{treat}	1.379 ^{ns}	5.763 **	5.116 **	13.541 ***	1.121 ^{ns}

S: treatment with PEMF on seeds for 15, 30, and 45 min. P: treatment with PEMF on newly developed plants for 5, 10, and 15 min. H: treatment with PEMF on microgreens before harvest. DAH: days after harvest. Means followed by the same letter for treatments are not significantly different according to Duncan test's ($p < 0.05$). Values presented are mean values of three replicates. Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns = not significant.

3.2. Fresh and Dry Weight Production

For the measurement of fresh weight of kale microgreens (Figure 1), the treatments P-15 (5.92), S-30 (5.67), S-15 (5.66), and P-10 (5.64) gave the highest values with statistically significant differences compared to control (4.88). Considering the measurement of dry weight, all treatments of pulsed electromagnetic field gave values higher than control; however, the differences were not statistically significant.

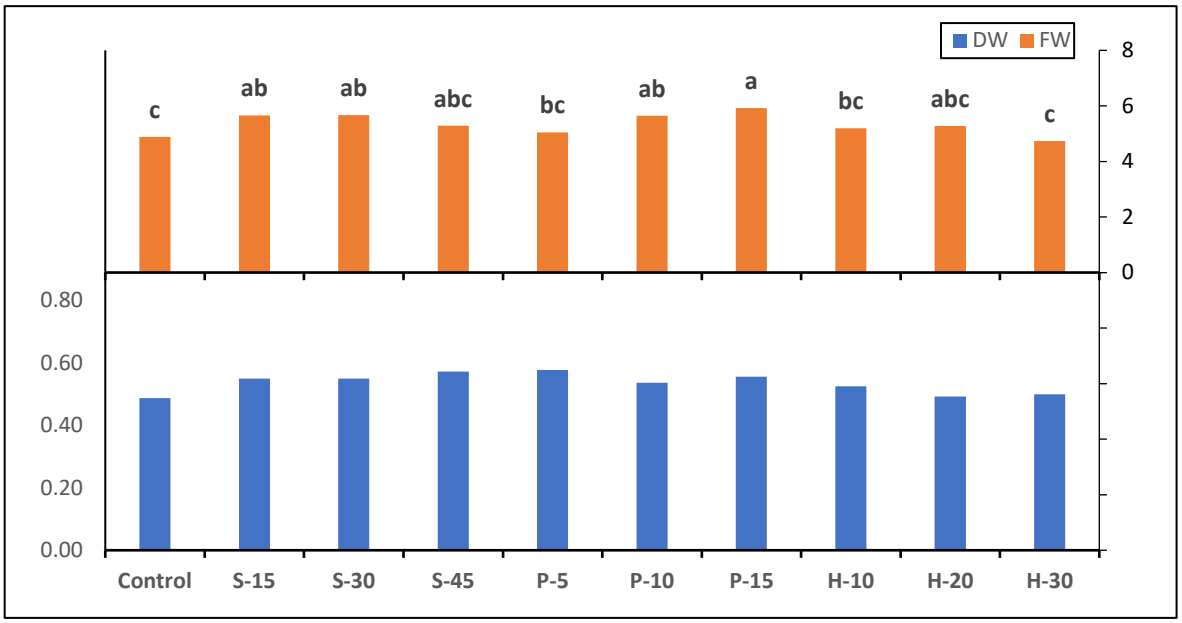

Figure 1. Influence of pulsed electromagnetic field treatments, at three different growth stages and three different times of exposure, on fresh and dry weight (g tray^{-1}) of kale (*Brassica oleracea*). F values of ANOVA: FW: 3.361 ***; DW: 1.488 ^{ns}. Significance level: ***: $p < 0.001$; ^{ns}: not significant. S: treatment with PEMF on seeds for 15, 30, and 45 min. P: treatment with PEMF on newly developed plants for 5, 10, and 15 min. H: treatment with PEMF on microgreens before harvest. Means followed by the same letter for treatments are not significantly different according to Duncan's test ($p < 0.05$). Values presented are mean values of three replicates.

Regarding wheat microgreens, the treatment S-30 (7.60) gave the highest fresh weight with statistically significant differences compared to all other treatments (Figure 2). The treatments S-15, S-45, P-5, and P-10 followed, with statistically significant differences compared to control. As for the dry weight, S-30 (0.745) and S-15 (0.728) gave the highest values with statistically significant differences compared to control (0.601).

Concerning spinach microgreens (Figure 3), the three treatments of S (S-15, S-30, and S-45) where PEMF was applied on seeds as a pre-sowing treatment had the higher fresh weight (6.99, 6.90, and 6.95, respectively) with statistically significant differences compared to control (5.86). For the measurement of dry weight, the treatments S-15 (0.439), P-15 (0.433), S-30 (0.429), and P-10 (0.418) gave the highest values with statistically significant differences compared to control (0.355).

Priming techniques have been used to improve the early growth of microgreens. A germination treatment of 2 and 3 days for table beet and chard, respectively, increased shoot fresh weight up to 2.79 times [7]. The use of cold plasma as a pre-sowing treatment of mustard seeds gave the highest germination (88.66%) and dry weight per microgreen (7.30 mg) compared to the plants derived from untreated seeds [8]. Specifically, the use of magnetic field in wheat was found to increase plant weight by 17.6% to 29.9%, depending on the intensity [23]. Increased fresh and dry weight has also been reported in corn [15], young sunflower, and wheat seedlings [24]. Different types of magnetic field at different times of exposure have been found to increase plant growth and yield in different plant species. However, in the case of microgreens, yield is considered the fresh weight of young plants approximately 25–30 days old. Nevertheless, even at this early stage, the application of magnetic field on seeds or seedlings seems to have an important effect on their growth. Due to the early stage of plant development, microgreens dry weight is less than 10% of their fresh weight. This result is in accordance with similar studies. For example, in a recent study, lettuce dry weight was approximately 5.2–5.5% of fresh weight [2].

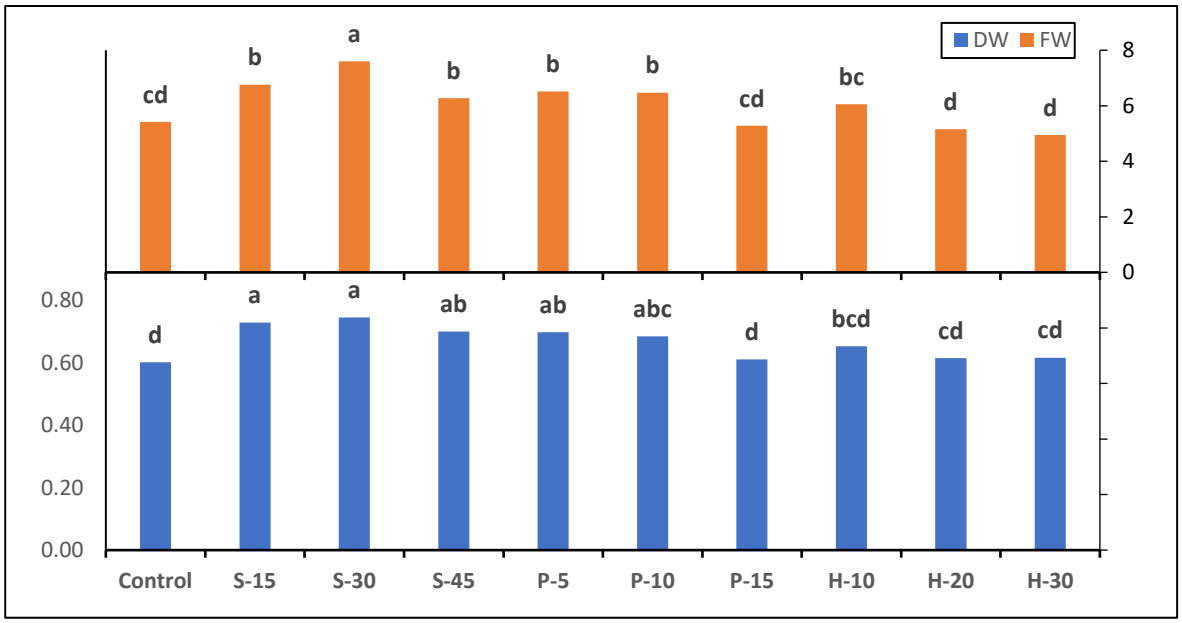

Figure 2. Influence of pulsed electromagnetic field treatments, at three different growth stages and three different times of exposure, on fresh and dry weight (g tray^{-1}) of wheat (*Triticum durum*). F values of ANOVA: FW: 10.771 ***; DW: 5.853 ***. Significance level: ***: $p < 0.001$. S: treatment with PEMF on seeds for 15, 30, and 45 min. P: treatment with PEMF on newly developed plants for 5, 10, and 15 min. H: treatment with PEMF on microgreens before harvest. Means followed by the same letter for treatments are not significantly different according to Duncan's test ($p < 0.05$). Values presented are mean values of three replicates.

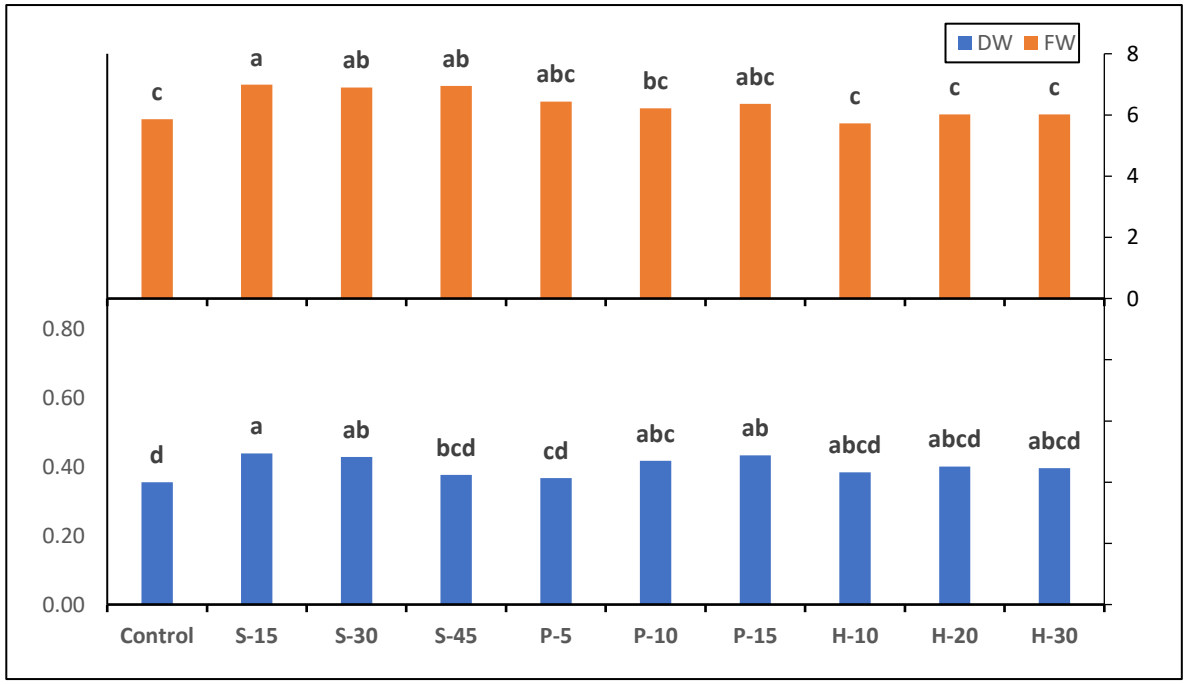

Figure 3. Influence of pulsed electromagnetic field treatments, at three different growth stages and three different times of exposure, on fresh and dry weight (g tray^{-1}) of spinach (*Spinacia oleracea*). F values of ANOVA: FW: 4.220 **; DW: 2.706 *. Significance level: **: $p < 0.01$; *: $p < 0.05$. S: treatment with PEMF on seeds for 15, 30, and 45 min. P: treatment with PEMF on newly developed plants for 5, 10, and 15 min. H: treatment with PEMF on microgreens before harvest. Means followed by the same letter for treatments are not significantly different according to Duncan's test ($p < 0.05$). Values presented are mean values of three replicates.

3.3. Color Parameters and Texture at Harvest and Postharvest

Regarding the color parameters L*, a*, and b*, at the harvest and postharvest, the treatment with pulsed electromagnetic field had no statistically significant differences for kale microgreens (Table 2). In contrast, the use of pulsed electromagnetic on wheat microgreens affected L* and a* parameters at harvest and the a* parameter at postharvest, with statistically significant differences. More specifically, H-30 treatment had the lowest L* value (40.84) with statistically significant differences compared to all other treatments, except P-10, which means that PEMF, when applied to wheat microgreens before harvest for 30 min, reduced the lightness of the leaves. Regarding the a* parameter of wheat microgreens at harvest, the treatments of H-30 (−18.48), control (−18.78), H-20 (−18.88), and P-5 (−18.90) were found to have the highest values, which means less green color compared to the other treatments. Similarly, at the measurement that was conducted after 7 d in storage, the lowest values, which represent more green color, were found in the treatments of S-45 (19.49) and P-5 (19.46) with statistically significant differences compared to control (17.66). Concerning spinach, the use of pulsed electromagnetic affected the b* parameter at harvest and the a* parameter only after storage with statistically significant differences. More specifically, H-30 treatment (20.56) gave the lowest value, with statistically significant differences compared to control (23.59), which was represented by less yellow color of the leaves. At the measurement of a* after storage, H-30 treatment (−15.95) gave the highest value, with statistically significant differences compared to control (−17.73).

A bright green color corresponds to high quality index for microgreens of green vegetable species, and yellowing suggests quality deterioration of the product. The presented results show that PEMF treatments had no negative effects on color of the studied microgreen species, either at harvest or at green color retention, during storage. PEMF treatments improved green color in wheat (S-45, P-15, H-10) and restricted yellow color in spinach (S-30, P-10, H-20, H-30). These positive effects of PEMF treatments on the color were probably related to regulation of chlorophyll metabolism. A magnetic field of 5 mT increased chlorophyll metabolism in *Beta vulgaris* seedlings [25], but the effect of magnetic field on chlorophylls is probably plant species-dependent, as is implied by the present data. Indeed, chlorophyll concentrations decreased in maize plants, but increased in sunflower under a static magnetic field [26].

3.4. Respiration Rates as O_2 Consumption and CO_2 Production at Harvest and During Storage

At harvest, the respiration rates assessed as O_2 consumption were 84–144, 61–98, and 58–97 mL/kg/h for kale, wheat, and spinach microgreens, respectively (Table 3). The respective rates assessed as CO_2 production were 88–123, 68–121, and 60–120 mL/kg/h for kale, wheat, and spinach microgreens, respectively (Table 3). PEMF treatments showed significant effects on respiration only for wheat (both O_2 consumption and CO_2 production) and for spinach (CO_2 production). In wheat, the PEMF treatments at harvest caused a significant increase in O_2 consumption rates by 1.5-fold (H-30), and an increase in CO_2 production rates by 1.3-fold (H-10 and H-20) and 1.5-fold (H-30) in comparison with control. Wheat microgreens treated with PEMF on seed or seedling stage had statistically similar respiration rates with control. In spinach, the PEMF treatment applied at harvest increased the CO_2 production rates by 1.5-fold (H-10), 2-fold (H-20), and 1.8-fold (H-30) in comparison with controls, whereas PEMF treatments on seed and seedlings stages showed statistically similar results with control.

After 7 d of microgreen cold storage, the PEMF treatments had no effect on respiration rates of kale but affected the CO_2 production in wheat and both O_2 consumption and CO_2 production in spinach (Table 3). In wheat, PEMF treatment applied at harvest showed as 1.8-fold (H-20) and 1.6-fold (H-30) higher O_2 consumption in comparison with control. In spinach, the O_2 consumption was increased only by H-30, but CO_2 production was increased by all PEMF treatments except for S-15 and S-30. The weight loss during storage

was about 1.5–2.5% (*w*/*w*) for all microgreen species without any significant effect of PEMF treatments (Table 3).

The data about PEMF or magnetic field effect on respiration rates of plant tissues are very limited. A trend for increased respiration rate shortly after PEMF treatment was observed in strawberry fruits treated with PEMF for 15 min [27], and this is in agreement with the present study where increased respiration rates were observed only in wheat and spinach microgreen species with the PEMF treatment applied just before harvest. The increased respiration rates could be attributed to an enhancement of various metabolic processes by PEMF, as implied by the increased growth rate of microgreens in the present study. The shelf life of microgreens and their postharvest quality has been the subject of several studies using modified atmosphere packaging [10].

4. Conclusions

Microgreens are a novel type of plant cultivation with a short duration of production. Innovative techniques, such as pulsed electromagnetic field that could increase plant production, without affecting the quality or shelf-life of the production, could contribute to the expansion of this type of cultivation. In the case of microgreen cultivation, these techniques could also be applied during the early stages of plant growth, unlike crops that are cultivated in large areas, such as field crops.

The application of pulsed electromagnetic field affected the physiology of kale, wheat, and spinach microgreens. Photosynthetic rate of kale microgreens was increased in the treatments of S and H by 16.88–27.06% compared to control, while in wheat microgreens, all electromagnetic field treatments gave higher values by 22.61–31.06% compared to control, whereas in spinach microgreens, the H treatments gave higher values by 26.02–31.06% compared to control. Regarding plant growth, PEMF treatments were found to increase fresh weight in all three plant species, while dry weight was higher in the treated plants for wheat and spinach. Specifically, the highest value of fresh weight in kale was found for the P-15 treatment, while all other treatments had also increased values compared to control, except H-30. For wheat, the highest values of fresh weight were found in the S treatments, while H treatments gave values close to control in both fresh and dry weight. As for the spinach, S treatments gave the highest values of fresh weight of microgreens.

As for the color parameters L*, a*, and b*, at the harvest and postharvest, PEMF treatments had no negative effects on the studied microgreen species, either at harvest or in green color retention during storage. Moreover, PEMF treatments improved green color in wheat, and restricted yellow color in spinach. Another important finding was that PEMF treatments showed significant effects on respiration for wheat (both O_2 consumption and CO_2 production) and for spinach (CO_2 production).

The results of this study suggest that pulsed electromagnetic field could be used to increase the fresh production of kale, wheat, and spinach microgreens with no negative effects to their color at harvest and during storage. Concerning the growth stage of application and the duration of exposure, our results indicate that the choice of the more suitable combination is plant species-dependent. Moreover, further studies should be conducted to investigate the mechanisms of action of pulsed electromagnetic fields on microgreens.

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