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Development and evaluation of an electromagnetic device to improve the physiological properties of some crop seeds

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Abstract: This research aims to develop an eco-friendly technique for treating seeds before sowing and improving their physiological features. The developed technique depends on utilizing synchronized electro-magnetization and microwave radiation. An electromagnetic device was evaluated to provide multiple treatment ranges. The treatments are regulated electronically according to the seeds' physiological properties and storage duration. The device was designed to accommodate small and medium seeds for a variety of strategic crops, including wheat, barley, etc. Three different treated wheat varieties were tested and compared to the control. Also, eight different levels of synchronized electro-magnetization and microwave radiation were tested. The treated wheat seeds' vegetative properties, such as germination percentage, germination rate index, germination speed coefficient, and vigour indexes, were highly significant compared to the control. The treated wheat seeds' physiological properties were highly significant. The device productivity ranged from 0.023 to 0.059 Mg·h^{-1} with minimum energy consumption rates of 0.396 to 0.018 kWh·Mg^{-1}, while the operating costs decreased to 11.53–44.13 USD·Mg^{-1}.

Keywords: chlorophyll; frequency; radiation; sowing; vigour; wheat

The abundance of food presents significant issues for the global agricultural industry (Reisch et al. 2016). It has become crucial to treat seeds before sowing using clean procedures, such as magnetization and microwave radiation (Bera et al. 2021). In contrast to hazardous chemical seed stimulation treatments, using physical methods improves crop quality and yield. Physical techniques such as the use of microwaves and electro-magnetization are safe, cost-effective, and environmentally friendly (Rudnyk and Yaruta 2016; Rhaman et al. 2020). The amount of polluting residue on land and in water increases due to dangerous chemical seed germination stimulants (Vashisth and Joshi 2017). Nevertheless, seed magnetization treatments significantly improve crop productivity by increasing germination percentage (Dastgeer et al. 2019). Crop seeds exposed to a strong magnetic field treatment revealed a significant increase in photosynthesis and enzymatic chemical reactions, accelerating plant growth (Wang et al. 2018). Due to the higher enzymatic activity of magnetically treated seeds, there were significant biochemical changes in the plant's cells. The seed magnetic treatments increase the speed of calcium ion flow (Ca^{+2}) through plant cell membranes, significantly improving photosynthesis (Isaac et al. 2011; Vashisth and Joshi 2017). The seed vigour and the seedling growth are increased using magnetization due to a significant increase in nutrient absorption and photosynthesis (Marcos Filho 2015). The seed magnetization process enhanced the rate of plant respiration, ion concentra-

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tion, and root development (Ijaz et al. 2015). Nevertheless, using magnetic treatments increased the energy compounds generated and thus increased the germination rates (Haq et al. 2012). Microwaves are non-ionizing radio frequencies that act by absorbing energy at the cellular level and manifesting it as thermal or vibrational energy (Ragha 2011). The enzymes catalase and peroxidase in treated seeds are significantly impacted by microwave radiation, which activates plant growth (Abu-Elsaoud 2015). Microwave radiation is only exposed for 40 s to protect seed embryos from heat damage (Oprica 2008). Microwave radiation dosages of 1 cm wavelength were applied to wheat, oats, and barley seeds, which displayed significantly greater germination rates (Aladjadjiyan 2007). Plant height and relative weight increased when exposed to microwaves during laboratory plant development tests compared to the control (Soran et al. 2014). By maintaining a safe distance from the microwave source and employing a shield, the harmful microwave radiation emitted can be prevented (Monteiro et al. 2008). The problem is that storing agricultural seeds for a long period decreases the seeds' vitality and vigour (Saeed et al. 2020; Baskin and Baskin 2020). Carrying out thinning and grafting operations for absent plants requires labor and is therefore, not economically viable (Kumar and Kalita 2017). To stimulate seeds, chemical stimulators such as humic acid and folic acid must be used with caution (Ebrahimi and Miri 2016). Natural methods such as soaking or hot water can also be used to stimulate the seeds' germination. The use of hot water leads to atrophy in embryos and reduces their vitality (Amusa 2011). Mechanical seed stimulation methods such as scratching destroy and damage a large portion of the seeds (Dobrin et al. 2015). There is a dearth of production devices to magnetize the seeds, except for using some small, non-productive magnetic cones (Ijaz et al. 2015). Electromagnetic technology is one of the most recent technologies that solve the problem of low seed germination due to poor storage conditions (Sarraf et al. 2020). Microwave radiation for seeds increases germination rates, which increases crop yield and reduces production costs (Wang et al. 2019). In the crucial stage of a plant's initial life, the enhancement of treated seeds' vegetative growth using stimulating procedures rapidly grows plants over weeds (Singh et al. 2015). The study aimed to improve the physiological properties of seeds before sowing by using electro-magnetization and microwave radiation for some strategic crops, such as wheat. Also, this work aimed to evaluate an innovative electromagnetic device instead of using harmful chemical stimulants for seeds.

MATERIAL AND METHODS

Experimental procedure. The experiments were carried out at the El-Serw agricultural research station, Damietta, Egypt (31°24'38"N, and 31°79'92"E) on wheat (*Triticum astivium L.*) in 2021–2022. The experiments were conducted to test the new electromagnetic seed stimulation device. The laboratory experiments were conducted in a split-plot randomized complete block design (RCBD, SPSS version 2020) with five replicates. Every replicate has 10 seeds in a sterilized Petri glass dish (Gomez and Gomez, 1984). Three laboratory experiments were carried out to test the studied variable's effect on the main plot factor of three different varieties of wheat (*Giza 168, Gemmiz 9,* and *Sakha 95*) as listed in Table 1. The tested wheat varieties, *Giza 168* and *Sakha 95*, are suited for the conditions of most Egyptian soils, while *Gemmiz 9* is cultivated in high-salinity soil. The standard moisture content of the wheat seeds used in the experiments was 12.5%. The first laboratory experiment was conducted to test eight electro-magnetization treatments (*MG*) as follows: four ratios between the electromagnetic field strengths of the electromagnet (1.7, 2.8, 6.8, and 13.6 mT) at two-time levels of 300 and 600 seconds. The second laboratory experiment tested eight treatments of the microwave radiation ratios, (*MR*) of four frequencies (2 455, 2 460, 2 465, and 2 470 MHz) at two exposure times (15 and 30 s). Third, a laboratory experiment is conducted to test the combined effects of electro-magnetization and microwave (*MGR*: *MG* + *MR*) using the ratios ($MG_{5–8}$) and ($MR_{1\ min}$ and $MR_{8\ max}$), as listed in Table 1.

$Var._1$: *Giza 168*; $Var._2$: *Gemmiz 9*; $Var._3$: *Sakha 95*; $T_{1–8}$: treatments levels; *MG*: electro-magnetization treatments; *MR*: microwave radiation treatments; *MGR*: electro-magnetization and microwave radiation treatments; *Con.*: control.

General description. The proposed device is powered by a 220-volt alternating current power source. The device is provided with four wheels for easy portability. The device is electrically insulated through grounding and the use of polyethylene insulators (Figure 1; No. 14). The device has a top cover that shields it from microwave radiation during seed

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Table 1. The experimental "split plot" design for the tested electromagnetic seed device factors

Experimental design: split-plot design	Main-plots			Sub-plots (replications: 5)							
	Var_1	Var_2	Var_3	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
MG				MG_1 1.7 mT/300 s	MG_2 1.7 mT/600 s	MG_3 2.8 mT/300 s	MG_4 2.8 mT / 600s	MG_5 6.8 mT/300 s	MG_6 6.8 mT/600 s	MG_7 13.6 mT/300 s	MG_8 13.6 mT/600 s
MR	Giza 168	Gemmiz 9	Sakha 95	MR_{1Min} 2 455 MHz/15 s	MR_2 2 455 MHz/30 s	MR_3 2 460 MHz/15s	MR_4 2 460 MHz/30 s	MR_5 2 465 MHz/15 s	MR_6 2 465 MHz/30 s	MR_7 2 470 MHz/15 s	$MR_{8Max'}$ 2 470 MHz/30 s
MGR (MG + MR)				MGR_1 MG_5/MR_1	MGR_2 MG_5/MR_8	MGR_3 MG_6/MR_1	MGR_4 MG_6/MR_8	MGR_5 MG_7/MR_1	MGR_6 MG_7/MR_8	MGR_7 MG_8/MR_1	MGR_8 MG_8/MR_8
Control				$Con._1$	$Con._2$	$Con._3$	$Con._4$	$Con._5$	$Con._6$	$Con._7$	$Con._8$

MG – electro-magnetization; *MR* – microwave radiation treatments; *MGR* – electro-magnetization and microwave radiation treatments; $T_{1–8}$ – treatments levels; var_1 – *Giza 168*; var_2 – *Gemmiz 9*; var_3 – *Sakha 95*

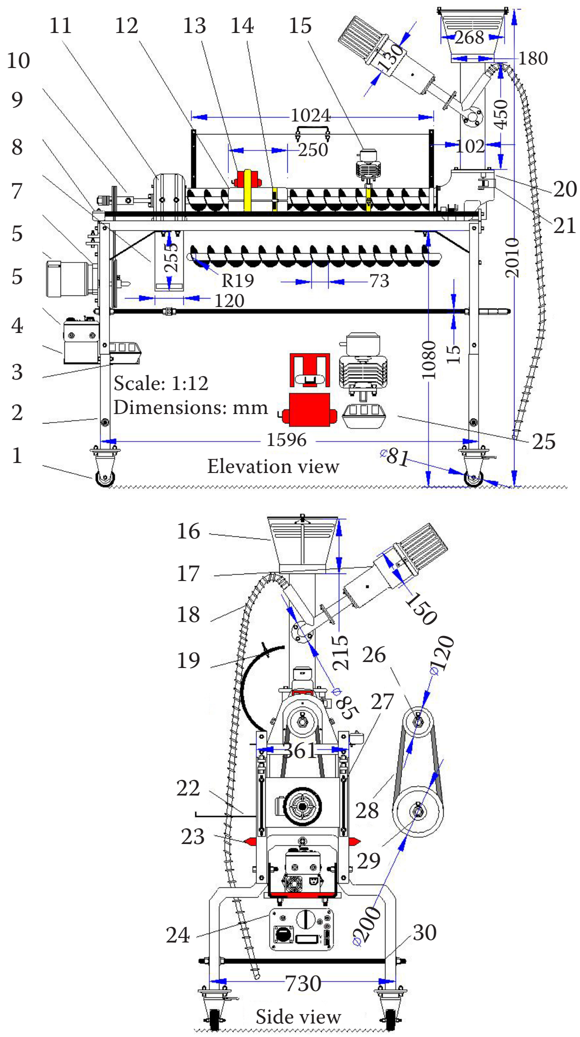

Figure 1. The geometric drawing views of the electromagnetic pre-sowing seed stimulation device

1 – solid wheels; 2 – frame; 3 – microwave circuit; 4 – supply; 5 – electro-magnet control; 6 – auger AC motor; 7 – motor tensioner; 8 – seed exit part; 9 – seed motor switch; 10 – connecting auger shaft; 11 – seeds bat collector; 12 – seeds tube; 13 – electro-magnet; 14 – polyethylene insulator; 15 – magnetron; 16 – seed hopper, 17 – seed suction vacuum; 18 – seeds hose; 19 – protector metal cover; 20 – seeds differential; 21 – cleaning door; 22 – seeds zipper door; 23 – sacks holder; 24 – electronic control; 25 – microwave magnetron; 26 – auger pulley; 27 – motor tensioner stream; 28 – belt; 29 – motor pulley; 30 – accidental tensioner

treatment (Figure 1; No. 19). The geometric dimensions and specifications of the electromagnetic seed device are shown in Figures 1 and 2 and Supplementary Table S1 (Table S1).

An auger conveying system was used for the treated seed, as shown in Figure 2B; No. 4. The seed auger's geometry is visualized in Figure 1. The auger was

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driven by a differential device attached to a 101.6 mm diameter steel pipe with an external shaft connected to the auger shaft (Figure 1; No. 12 and 20). The auger differential housing has a pair of perpendicular cleaning doors to make maintenance and lubrication easier (Figure 2B; No. 7). An upper seed feeding hopper is connected to the auger differential housing by a 101.6 mm-diameter pipe, as shown in Figure 2A; No. 10. A seed suction motor is attached to a device that is connected to the seed feed pipe (Figure 2A; No. 11). Rubber interior valves were employed to keep the seeds from being withdrawn. To make feeding the device easier, the seed extractor motor is attached to a hose with a 38.1 mm diameter and a 2 000 mm length (Figure 2A; No. 12). The seed auger's end is attached to a box with a sliding door (Figure 2A; No. 13). The sliding door allows the treated seeds to be packed directly into the hanging sacks using a metal holder, as illustrated in Figure 2A; No. 14. A pair of bats is attached to the auger's end to direct the seed into the collecting case (Figure 2B; No. 3). The motor is a 220 V alternating current bipolar electric motor with a reducer-type gear (Figure 2A; No. 4). A reduction ratio of 1 : 100 reduces the rotational speed transmitted from the alternating current driving motor to the seed auger. The device's frame is designed to resist various loads during operation while maintaining a high safety factor. The device's height and width have been optimized for usage within seed silos (Figure 1; No. 2). The rotating sections were shielded by barriers, as shown in Figure 2A. An electromagnet with a high flux density is used to magnetically treat the seeds (Figure 2A; No. 7). An electromagnetic transformer converted to operate on direct current generates the electromagnetic field. Using opposite pairs of 5 mm-thick plastic insulators, the electro-magnetizer was secured to the top of the seed conveyor (Figure 2B; No. 14). The plastic insulator was only employed to magnetize the cores, preventing magnetization of the device's metal components.

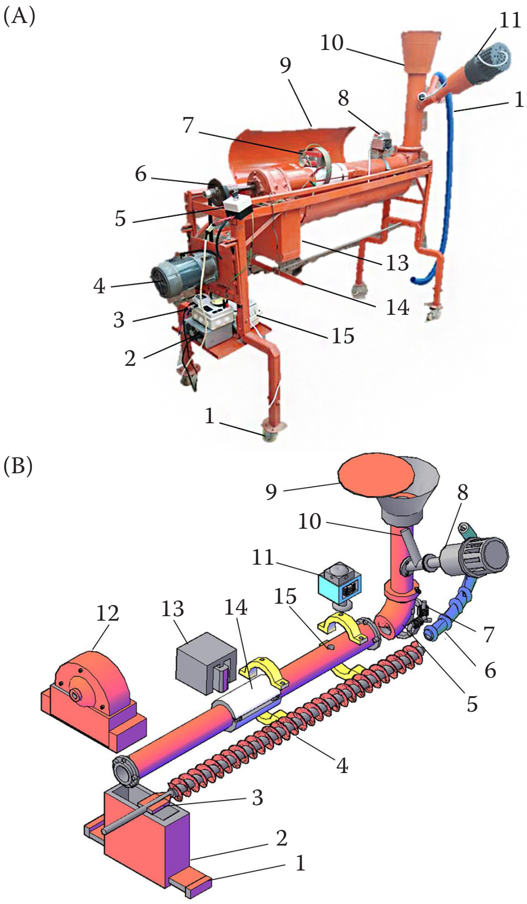

Figure 2. (A) The elevation view of the electromagnetic seed device and (B), the isometric view of the inlet components of the electromagnetic pre-sowing seed device

(A) 1 – solid wheels; 2 – power supply; 3 – electro-magnet control; 4 – auger motor; 5 – motor switch; 6 – auger pulley; 7 – electro-magnet; 8 – magnetron; 9 – protector metal cover; 10 – seed hopper; 11 – seed suction vacuum; 12 – seeds hose; 13 – outlet seeds part; 14 – sacks holder; 15 – microwave circuit; (B) 1 – seeds zipper door; 2 – seeds can; 3 – seeds bat; 4 – auger; 5 – seeds differential; 6 – seeds hose; 7 – seeds cleaning doors; 8 – seeds suction vacuum; 9 – hopper; 10 – seeds suction tube; 11 – microwave magnetron; 12 – seeds bat collector; 13 – electro-magnet; 14 – polyethylene insulator; 15 – emission microwave path

As illustrated in (Figure 3C), there is an electronic circuit to feed the electro-magnetizer with direct current, utilizing a 1600-watt power supply that converts alternating current to direct current (Figure 2A; No. 2). A variable level switch incorporated in the control box is used to connect the direct current, which is easily disputed, as shown in Figure 3A; No. 5. For simplicity of use, the controller has a volt and ampere indication (Figure 3A; No. 1). For easy connecting of the cables to the electro-magnetizer, color-coded plugs in black and red were employed (Figure 3A; No. 3). The microwave unit, as well as the electro-magnetizer, motor, and seed suction vacuum, are controlled by an electronic timer with 16 programs in the control box (Figure 3A; No. 7). To generate microwave radiation, a magnetron (Figure 2A; No. 8) was utilized, which was connected to a high-voltage circuit that included a huge transformer, a capacitor, a diode, and a safety fuse (Figure 3B; No. 1 and 2). The frame was supported

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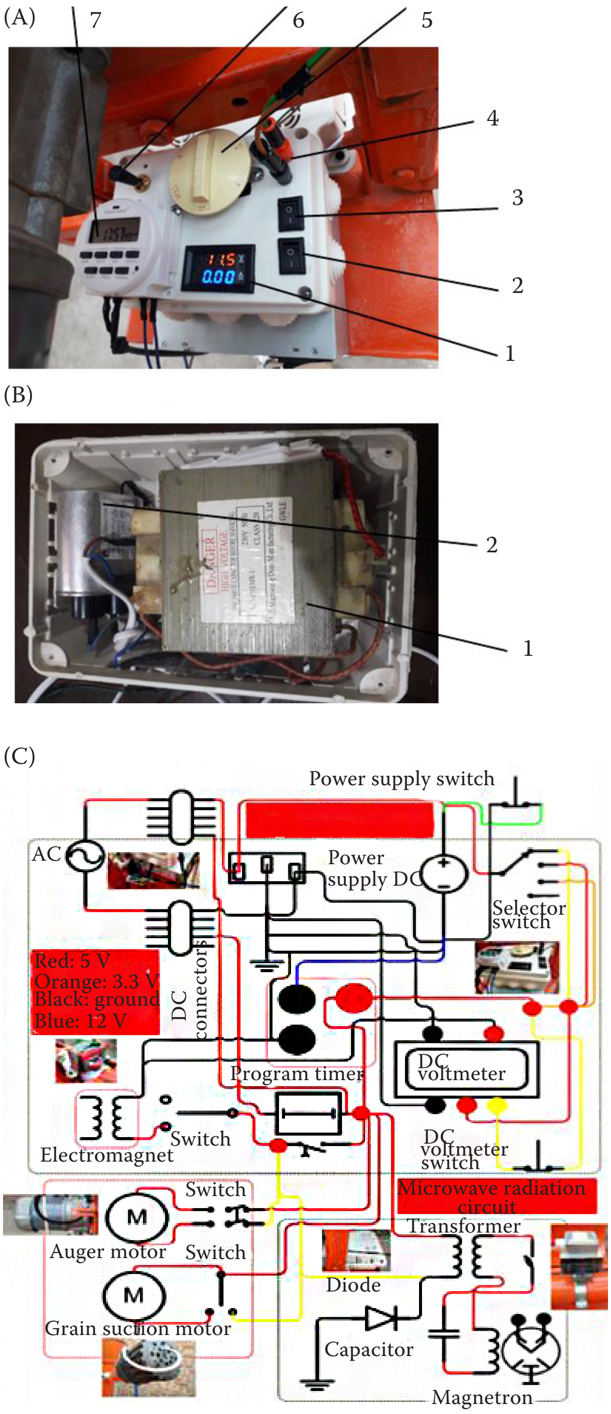

Figure 3. The electrical circuit of the electromagnetic pre-sowing seed device: (A) the electro-magnet control, (B) microwave circuit for the electromagnetic device and (C) the electrical and electronic circuit wiring diagram for the electromagnetic seed stimulation device

(A) 1 – DC direct current volt-ampere indicator; 2 – power supply switch; 3 – DC direct current indicator switch; 4 – ground connector wire; 5 – volt selector switch; 6 – electro-magnet switch; 7 – digital programmed timer; (B) 1 – micro-wave high voltage transformer; 2 – microwave capacitor

by a pair of top and bottom semi-cylinder bulkheads to defend against microwave rays during operation, as illustrated in Figure 2A; No. 9. To feed the seeds, the seed suction motor is first started. The treatments of *MG* and *MR*, or *MGR*, begin using the digital timer once the seeds have entered the auger at the appropriate alternating rotation to prevent seed friction (Figure 3A; No. 7). The magnetron emits radio waves directly through a tube that is fitted internally through a perforated shaft connected to a hole in the seed auger tube's outer surface (Figure 2B; No. 15). To set the right frequency, a changeable alternative current of 110–220 V was connected to the transformer (Figure 3B; No. 1). At the end, the seeds are moved from the seed exit tray to the sacks, as shown in Figure 2A; No. 14.

Statistical analysis. The data were statistically analyzed using the software applications SPSS (version 2020) and Minitab (version 19.1.1). The ANOVA tests were used to determine the significance of the investigated parameters. Also, regression analysis was carried out. The vegetative growth tests using various treatments of *MG*, *MR*, and *MGR* and the interaction between them were conducted with a probability of ($P < 0.01$) compared to the control. Also, the mechanical and economic performance of the developed electromagnetic seed device was evaluated with a probability of ($P < 0.05$).

Prototype evaluation performance. The vegetative growth properties of the tested wheat seed varieties were evaluated by measuring the growth rate under the effects of *MG*, *MR*, *MGR*. Plants were randomly uprooted from each treatment at each growth stage for 10 days. Samples were weighted separately, packed in paper bags, and oven-dried for 72 h at 70 °C. Also, the germination rate (*G*) was estimated by counting the germinated seeds once every 3 days, starting from the first germination. The germination rate was calculated as presented in Equation (1) (AOSA 1983).

$$G = \frac{\sum ni}{N} \times 100 \qquad (1)$$

where: G – germination rate (%); ni – number of germinated seeds on the 1st day; N – total seed number.

The germination index (*GI*), which was used to observe both the germination percentage and the velocity of germination, was evaluated as shown in Equation (2) (AOSA 1983). Besides, the germination rate index (*GRI*), which represents the percent of the daily germination percentages as presented

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in Equation (3), was conducted (Orchard 1977). The mean germination time (*MGT*) showed how fast the seed emerged in the population and was calculated, as shown in Equation (4) (Bakhshandeh et al. 2017). Also, the germination velocity coefficient (*GVC*), which represents the daily germination rate, was recorded to determine the seed germination response. Equation (5) was used to calculate the germination velocity coefficient (Scott et al. 1984).

$$GI = (10 \times n_1) + (9 \times n_2) + \cdots + (1 \times n_{10}) \tag{2}$$

where: *GI* – germination index; n_{1-10} – the number of germinated seeds from the first day until the tenth day.

$$GRI = \frac{G1}{1} + \frac{G2}{2} + \frac{G3}{3} + \frac{Gx}{x} \tag{3}$$

where: *GRI* – germination rate index; *G*1–*G*3 – the germination percentage for the first, second, and third day; *Gx* – the germination percentage on day *x*.

$$MGT = \frac{\sum fx}{f} \tag{4}$$

where: *MGT* – mean germination time (day); *f* – the number of germinated seeds on day x.

$$GVC = \left[\frac{N1 + N2 + N3 + \cdots + Nx}{100}\right] \times \left[N1T1 + N2T2 + \cdots + NxTx\right] \tag{5}$$

where: *GVC* – germination velocity coefficient; N_i – the number of germinated seeds on a day I; T_i – the number of days from seeding corresponding to *N*.

The vigour indexes, V_i *(I and II)*, were calculated by measuring the root and shoot lengths (cm) of five randomly selected treatment samples, as indicated in Equations (6 and 7). To determine V_i *II*, the treated growing plants were also weighed separately by fresh weight (g) and their dry weight following the use of an oven at 70 °C for 72 hours (Vashisth and Joshi 2017). The photosynthetic pigments (chlorophyll content, *Chl a, b,* and *t*) were estimated by extracting chlorophyll in test tubes of 0.09 g of fresh weight of healthy leaves in 10 mL of 80% aqueous ethanol and heating them in a water bath at 70 °C for 15 minutes. Afterward, the samples were inserted directly into the ice, and the volume was adjusted to 10 mL. A spectrophotometer (Spectro 22 LaboMed, Inc., U.S.A.) was used. The optical density of the extract was measured at two wavelengths, 645 and 663 nm, which is the maximum absorption of chlorophyll a, b, and total (Welfare et al. 1996). The optical pigments were expressed in mg g^{-1} fresh weight according to Equations (8–10).

$$V_i I = \text{Ger.}(\%) \times \text{seedling lenght (root+shoot) (fw)} \tag{6}$$

$$V_i \Pi = \text{Ger.}(\%) \times \text{seedling lenght (root+shoot) (dw)} \tag{7}$$

$$Chl\,a = (12.7\,OD663 - 269\,OD645) \times \frac{V}{1000} \times W \tag{8}$$

$$Chl\,b = (22.9\,OD645 - 4.68\,OD663) \times \frac{V}{1000} \times W \tag{9}$$

$$Chl\,t = (20.2\,OD645 + 8.02\,OD663) \times \frac{V}{1000} \times W \tag{10}$$

where: *V* – liquid sample volume (mm); *OD* – optical density of a spectrophotometer (mg·mm^{-3}); *W* – leaves samples fresh weight (mg); Ger – germination; fw – fresh weight, dw – dry weight.

In addition, wheat seed physiological features and the chemical analysis of plants in the treated and control treatments were estimated (Sadasivam and Manikam 1992). The biochemical parameters for the treated seeds are determined by extracting the enzymes. Wheat seeds of 1 g were disintegrated in a mortar with a pestle using liquid nitrogen. The sample was suspended in 5 mL of buffer pH 7.2 and extracted for 1 h at 4 °C with vortexing for 30 s every 10 minutes. Afterward, extracts were centrifuged (15 000 g, 20 min at 4 °C) (Strelec et al. 2007). The mechanical and economic performances of the prototype were evaluated. The prototype productivity (*P*) was calculated using Equation (11). The specific energy consumption for the electromagnetic device was calculated using Equation (12) (Culpin 1986). The device's operating cost (*C*), USD·Mg^{-1} was determined according to the methodology of Hunt (1983).

$$P = \frac{Mw}{t} \tag{11}$$

where: *P* – device productivity (Mg·h^{-1}); *Mw* – treated seed weight (Mg); *t* – consumed operation time (h).

$$SE = \frac{\text{consumed power (kWh)}}{\text{productivity (Mg·h}^{-1}\text{)}} \tag{12}$$

where: *SE* – the specific energy consumption (kWh·Mg^{-1}).

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RESULTS AND DISCUSSION

Vegetative growth parameters. The effect of *MG*, *MR*, and *MGR* on vegetative measurements is shown in Figure 4. There are direct proportional relationships between *G*, *GI*, *GRI* and the treatments. The higher the value of the various (*MG*), (*MR*), and ($MGR_{1–8}$) treatments, the higher the *G*, *GI*, and *GRI* values, and *vice versa*. There is a highly significant increase in *G*, *GI*, and *GRI* values due to treatments over the control, with a probability of ($P < 0.01$). Figure 4 shows that using *MGR* was superior to using *MG* and *MR* separately on the treated seeds. As shown in Figure 4A, the quality of the effect of the treatments on the seeds is arranged in ascending order for *G*. The ascending effect of the $MR_{1–8}$ comes first, followed by the $MG_{1–8}$, and finally the $MGR_{1–8}$. Furthermore, Figure 4A shows that the *G* values increased from 73.44 to 96.05% at treatments MR_1 and MR_8 for the wheat varieties *Gemmiz 9* and *Giza 168*, respectively. The lowest values of *G* for the control were recorded under the influence of *MR* treatments in the order of the variants $var_{2,\,3,}$ and var_1, which were as follows: 70, 75, and 80%, respectively. The *G* values were increased from 84.49 to 98.05, 75.44 to 89.53, and 80.65 to 97.02%, respectively, at the $MG_{1–8}$ treatments for the tested wheat varieties $var_{1–3}$, as shown in Figure 4A. The increment ratios for the effect of the highest value of *G* at $var_{1–3}$ for *MG* treatments over the control were 13.05, 14.53, and 17.02 %, respectively. The treatment (*MGR*) outperformed both *MG* and *MR*, while *G* values at Var_1 ranged from 86.49 to 99.65% at MGR_1 to MGR_8, respectively. The *G* values at $MGR_{1–8}$ for var_2 and var_3 were increased from 77.44 to 91.53% and from 82.65 to 99.02%, respectively. The increment ratios for the highest *G* values for *MGR* treatments at $var_{1–3}$ were increased by 14.65, 16.53, and 19.02%, respectively, over the control.

The effect of seed treatments on the *GI* is shown in Figure 4B. There is a direct relationship between *GI* and treatments. The germination rate increased as the *GI* value increased. Under the impact of *MG*, *MR*, and *MGR*, the *GI* increased significantly compared to the control treatments. The highest *GI* values were 75.79, 70.92, and 75.41 for $MGR_{1–8}$ treatments. Subsequently, the *GI* values were decreased to 74.83, 69.72, and 74.21 for $MG_{1–8}$ treatments at $var_{1–3}$. The effect of *MR* treatment on *GI* had the lowest values of 73.63, 68.52, and 73.01 for the three treated wheat varieties, respectively. For $MGR_{1–8}$, $MR_{1–8}$, and $MG_{1–8}$, the lowest *GI* values were (61.90, 56.46, and 59.95); (60.70, 55.26, and 58.39); and (59.50, 53.06, and 57.19) for $var_{1–3}$, respectively. The *MGR* treatment had the highest values, followed by the *MG* and *MR* treatments. The increment ratios of GI values were 13.79, 13.83, and 12.43% for MGR_1 and *Giza168*, respectively, over the control. In addition, the increment ratios for MG_2 at *Gemmiz 9* over

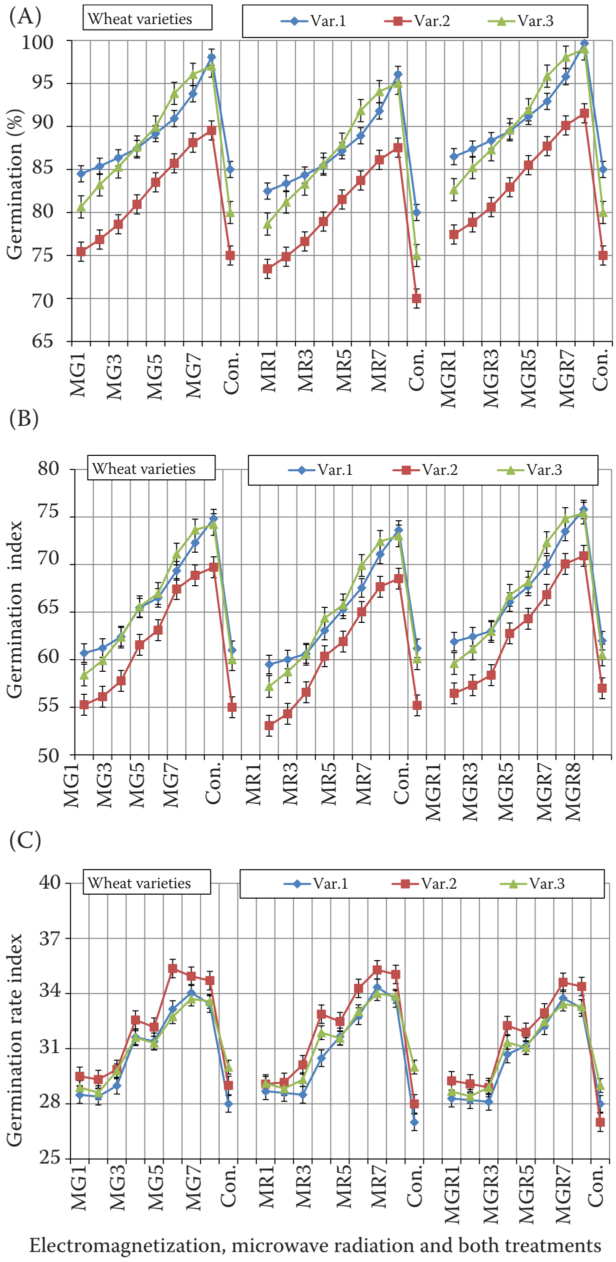

Figure 4. The effect of electro-magnetization, microwave radiation, and both treatments on (A) germination percentage, (B) germination index, and (C) germination rate index of three wheat varieties: *Giza 168*, *Gemmiz 9*, and *Sakha 95*

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control were 13.92, 14.72, and 13.32%, respectively. Furthermore, the increment ratios for *GI* values at wheat varieties *Sakha 95* and MR_3 over the control were 14.91, 14.21, and 12.91%, respectively. The influence of seed treatment procedures on the germination rate index *GRI* and the daily germination rate is shown in Figure 4C. The lowest *GRI* values for *MG, MR*, and $MGR_{1–8}$ were (28.48, 29.50, and 28.89), (28.69, 29.08, and 29.11), and (28.29, 29.25, and 28.67), respectively, for the treated varieties $var_{1–3}$. The increment ratios for *GRI* over the control for *Giza 168*, *Gemmiz 9*, and *Sakha 95*, were (14.80, 15.01, and 14.01%); (14.89, 17.01, and 14.01%); and (14.83, 14.92, and 13.89%), respectively. The *GRI* increment ratios over the control at $var_{1–3}$ for *MG, MR*, and $MGR_{1–8}$ were (16.24, 16.44, and 10.63%); (19.90, 20.09, and 11.39%); and (15.70, 21.48, and 12.90%), respectively. The germination rate of the treated wheat seeds using *MGR* treatments was nearly 100%. The highest treatment of MGR_8 allows treated seeds to absorb more energy. The electro-magnetic treatment boosts enzymatic and chemical processes. Also, the rate of energy compound transmission in plant cells (ATP – Adenosine tri-phosphate) and metabolic rates were significantly increased due to treatments, in agreement with Zhang et al. (2017). The treated wheat plants have significantly longer stems and roots, according to Dastgeer et al. (2019). According to Das (2020), lignin and cellulose synthesis during vegetative propagation increases plant strength and resistance to slumber in wheat. In agreement with Wang et al. (2018), the magnetic flux significantly affects the germination speed. The *MG* and *MR* treatments increase the rate of nutrient and water absorption compared to the control, with the agreement of Isaac et al. (2011). According to Abu-Elsaoud (2015), microwave treatment only had a significant effect on some wheat varieties. Also, microwaves enhance the acceleration of plant cell divisions by reducing the thickness of their membranes and thus increasing their reproduction, according to Monteiro et al. (2008). According to Oprica (2008), microwave radiation increases the potential energy for seed and bio-system activities. Additionally, microwaves increase water movement in plant cells. The water movement opens cellular water channels within the plant cell membranes and lowers the plant's water stress, as demonstrated by Razi and Muneer (2021). According to Kader (2005), the higher the *GI* value the higher the germination percentage and speed, and *vice versa*. The use of *MGR* treatment increases the germination index gradually. This is because combining the two treatments (*MG* and *MR*) results in the seeds retaining a lot of energy, which stimulates all the biochemical processes, according to Aladjadjiyan (2007). The higher the *GRI* values, the higher the percentage of germination, which is inversely proportional to the germination period. According to Kader (2005), the shorter the germination period, the higher the GRI values.

Average germination rate and germination speed coefficient. The average germination rate *MGT* and germination speed coefficient *CVG* are shown in Figures 5A and B. There is an inverse relationship between *MGT* and the treatments. As illustrated in Figure 5A the MG_8 treatment of *Gemmiz 9* had the lowest *MGT* value of 3.21 days. The MG_1 treatment at *Giza 168* had the highest *MGT* value of 3.83 days. The wheat varieties var_2 and var_1 had the lowest and highest *MGT* values of 3.41 and 3.81, respectively, at MR_7 and MR_3. The minimum and maximum *MGT* values were 3.22 and 3.87 days, re-

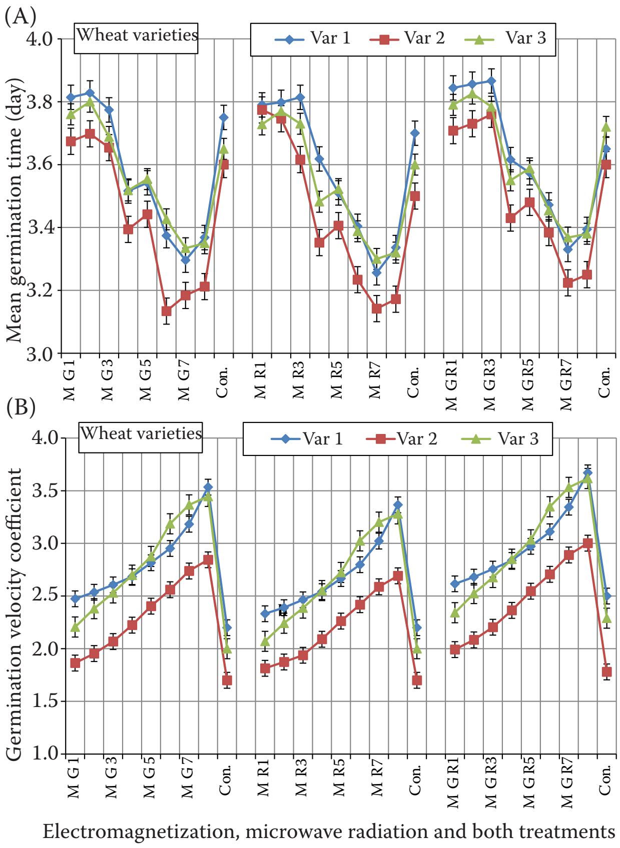

Figure 5. The effect of electro-magnetization, microwave radiation, and both treatments on (A) mean germination time and (B) germination velocity coefficient of three wheat varieties: *Giza 168*, *Gemmiz 9*, and *Sakha 95*

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spectively, for MGR_7 and $_3$ and var_2 and var_1. The *MG* treatment had the lowest *MGT* value or the minimum number of days required for germination. Figure 5B demonstrates a positive, direct relationship between the treatments and *CVG*. The wheat variety *Giza 168* had the highest coefficient of germination speed, which was 3.37 with the treatment MGR_8. The lowest *CVG* value was recorded at MR_1 for *Gemmiz 9*, and it was 2.04.

There is a highly significant difference for the *MGT* and *CVG* values over the control, with a probability of ($P < 0.01$), as demonstrated in Figures 5A and B. The high-energy seeds germinate rapidly; even inert seeds are activated; however, their germination may be delayed, according to Haq et al. (2012); Parmoon et al. (2018). The *MGT* indicates the determination of the highest daily percentage of germination. The degree of intensity of treatments and the time spent exposing wheat seeds accelerate seedling growth and emergence. The *CVG* indicates the speed required to reach the final percentage of germination without considering the number of germination days, with the agreement of Kader (2005). The *MGR* treatment shortens the seed germination period compared to the *MG* and *MR* treatments.

Germination vigour indexes. The germination vigour indexes *Vi* I and II were determined using the vegetative measurements on the treated seeds' stem and root lengths, as shown in Figures 6A and B. Figure 6 shows a directly proportional increase in the effect of $MGR_{1–8}$, $MG_{1–8}$, and $MR_{1–8}$ treatments in descending order for *Vi, I*, and *II* values. The highest *Vi I* values were 3 345.01, 3 094.33, and 2 675.0, respectively, at MGR_8, MG_8, and MR_8 for wheat variety $var._1$. The minimum *Vi I* values for MGR_1, MG_1, and MR_1 at $var._2$ were 1 653.61, 1 459.27, and 1 287.72, respectively. The difference between the used treatments and the control is significant. The control of the untreated seeds for the *Gemmiz 9* variety had the lowest *Vi I* values of 1 600, 1 400, and 1 200, respectively. Figure 6B shows a significant direct proportional relationship between the treatments and *Vi II* values. The wheat variety *Giza 168* had the maximum *Vi II* value of 66.90 at MGR_8. The wheat variety *Giza 168* had a minimum value of 36.28 at MR_1. The wheat variety *Gemmiz 9* had the highest *Vi II* value of 53.12 using MGR_8. The *Vi II* had a minimum value of 25.76 using MR_1 treatment. The maximum *Vi II* value was 61.43 for the variety *Sakha 95* at MGR_8. The lowest value of *Vi II* was 33.26 for the wheat variety *Sakha 95* at MR_1.

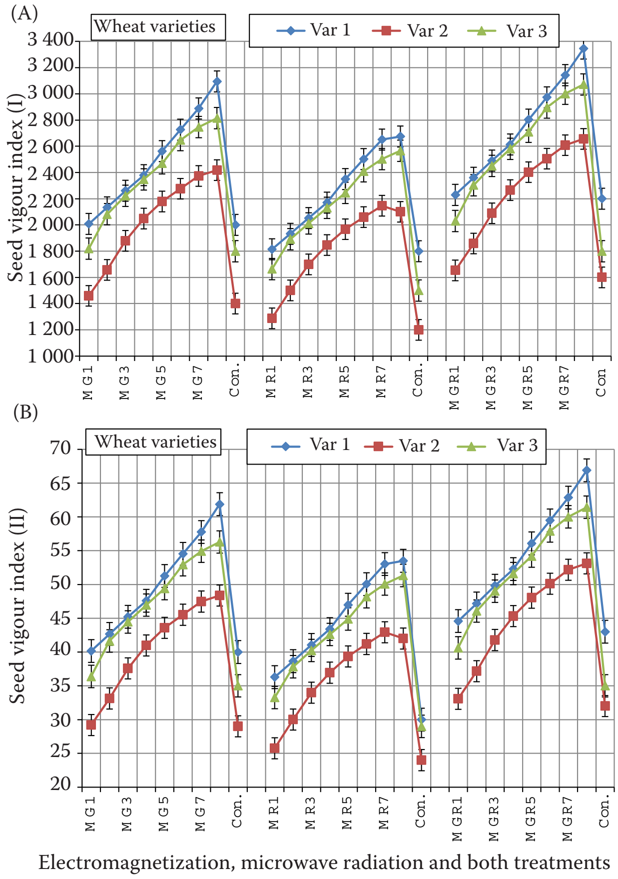

Figure 6. The effect of electro-magnetization, microwave radiation, and both treatments on (A) seed vigour index, (*Vi I*) and (B) seed vigour index (*Vi II*) of three wheat varieties: *Giza 168, Gemmiz 9*, and *Sakha 95*

The reduction ratios for *Vi II* values over the control for *MG* treatments were 35.37, 40.04, and 37.82% for $var_{1–3}$, respectively. The reduction ratios for the *Vi II* values over the control treatments were 43.93, 42.86, and 43.49% and 35.73, 39.76, and 43.03%, respectively, for the *MR* and *MGR* treatments. The maximum *MR* level for 30 s significantly increased the values of the vigour indexes over the control. The germination vigour indexes are used to model the natural stresses during growth, such as soil salinity and other environmental conditions. According to Ghaderi et al. (2010), the used treatments significantly improved the physiological properties of treated wheat seeds over the controls. The metabolic and photosynthesis processes have a significant impact on the dry matter formed in treated plants. The results obtained for the seed vigour indexes are consistent with the reported results of Ijaz et al. (2015). Figure S1 show the effects of *MG*, *MR*, and *MGR* on chlorophyll pigments in treated wheat

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varieties and the control. The highest value of *Chl t* at the treatment MGR_8 was 8.49 mg g^{-1}, which was 29.26% higher than the control for the wheat variety var_3 (Figure S1A). The wheat variety *Gemmiz 9* had the highest value of 7.53 mg g^{-1} of total chlorophyll pigments at MR_8, which was higher than the control by 40.27% (Figure S1B). The total chlorophyll pigments value for the treatment MGR_8 at wheat variety *Sakha 95* was 9.49 mg g^{-1}, which was 34.70% higher than the control (Figure S1C). The *MGR* treatment has a significantly higher photosynthetic efficiency rate than the *MG* or *MR* treatments. The treated seeds had significantly higher levels of chlorophyll pigment than the controls. The chlorophyll pigment increment results were due to an increase in the metabolism of auxin, cytosine, and gibberellin, in line with the results of Isaac et al. (2011). The metabolism acceleration resulted in maximizing the growth of treated seed roots, in agreement with the results from Poghosyan and Mukhaelyan (2018). According to Aladjadjiyan (2007), electro-magnetization improves plants' absorption of micro- and macro-minerals from the soil. The statistical analysis demonstrates a significant probability of interaction between the levels of the tested wheat varieties and each of the treatments (*MG, MR*, and *MGR*) at $P < 0.01$, as shown in Table S2. The levels of the tested variables *MG, MR*, and *MGR* were highly significant for all the measurements. Table S3 shows the linear regression formulas for the interaction between the tested factors.

Prototype performance evaluation. The highest productivity of the electromagnetic device was 0.059 Mg·h^{-1}, while the lowest productivity was 0.023 Mg·h^{-1} (Figure S2A). The maximum energy consumption was 0.396 kWh·Mg^{-1}, while the minimum value was 0.018 kWh·Mg^{-1} (Figure S1B. The hourly operating cost for the proposed device is 10 USD·h^{-1}. The lowest operating cost was 11.53 USD·Mg^{-1}, while the highest operational cost was 44.13 USD·Mg^{-1}. The technique used is considered cheap and inexpensive when compared to chemical stimulation, with the agreement of Ijaz et al. (2015).

CONCLUSION

The use of the combined electro-magnetization and microwave treatments increased the germination rate significantly for the tested wheat seeds, up to 99.65%. The application of microwave and electro-magnetization separately achieved lower germination rates of 96.05 and 98.05%, respectively. Combining both treatments resulted in the highest significant increases in the germination speed coefficient of 3.81 and 8.17%, respectively, over the electromagnetic and microwave treatments separately of the wheat variety *Giza 168*. There is an ascending increment due to the use of microwaves and electromagnetization, and then their combined effects, respectively, on the first type of vigour index over the control treatments for the wheat variety *Giza 168* by 32.73, 35.37, and 34.23%, respectively. The device's energy consumption was 0.396 kWh·Mg^{-1}, while the operating costs decreased to 44.13 USD·Mg^{-1}. The new electromagnetic seed stimulation device could be recommended for use in seed stations and silos.

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