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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

Magnetopriming enhanced seed germination in six vegetable species: tomato, pepper, onion, cauliflower, cabbage and carrot

Domates, biber, soğan, karnabahar, lahana ve havuç türlerinde magnetopriming ile tohum çimlenmesinin iyileştirilmesi

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ABSTRACT

This study was conducted to assess the impact of magnetopriming on seed germination, root and shoot length in six vegetable species: tomatoes, peppers, onions, cauliflowers, cabbages, and carrots. The seeds of the first three species were exposed to magnetopriming for approximately 5 minutes at 15-17 mT, while the remaining species underwent a 15-minute room temperature treatment. Magnetopriming was found to be more effective in enhancing regular germination across all species. Although the improvements observed in tomatoes, cabbages, and carrots were not statistically significant ($p<0.05$), it increased regular germination percentages by 8-14% in all species. The most significant benefit from the treatment was observed in onions, with a 14% increase, while the lowest enhancement was recorded in cabbages and tomatoes as 8%. While the mean germination time increased significantly for onions, it remained unchanged for the other species. Additionally, magnetopriming significantly ($p<0.05$) influenced the shoot and root lengths of seedlings in all species. The most substantial improvement in shoot length was observed in tomatoes and onions, with an increase of 1.4-1.3 cm, while the maximum enhancement in root length was found in cabbages and tomatoes, increasing by 3.5-2 cm, respectively. The results indicate that magnetopriming not only improves germination but also significantly enhances the potential for root and shoot growth in these vegetable species.

ÖZET

Bu çalışma, magnetopriming'in altı sebze türünde (domates, biber, soğan, karnabahar, lahana ve havuç) tohum çimlenmesi, kök ve sürgün uzunluğu üzerindeki etkisini test etmek amacıyla yapılmıştır. Tohumlar 15-17 mT ile türlerin ilk üçünde yaklaşık 5 dakika ve geri kalan türlerde 15 dakika oda sıcaklığında işleme tabi tutulmuştur. Magnetopriming normal çimlenme üzerinde daha etkili bulunmuştur. Domates, lahana ve havuçta önemli olmasa da ($p<0.05$), tüm türlerde normal çimlenme yüzdelerini %8-14 arasında artırmıştır. Uygulamadan en büyük fayda %14 ile soğanda, en düşük ise %8 ile lahana ve domateste elde edilmiştir. Ortalama çimlenme süresi soğanda önemli ölçüde artarken diğerlerinde artmamıştır. Magnetopriming tüm türlerde fidelerin sürgün ve kök uzunluklarını önemli ölçüde ($p<0.05$) etkilemiştir. Sürgün uzunluğunda en büyük avantaj 1,4-1,3 cm olarak domates ve soğanda görülmüştür. Kök uzunluğunda avantaj en fazla lahana ve domateste 3,5-2 cm olarak etki etmiştir. Sonuçlar, magnetopriming'in bu sebze türlerinde sadece çimlenmeyi değil aynı zamanda fide kök ve sürgün büyüme potansiyelini de geliştirdiğini göstermiştir.

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INTRODUCTION

Seed germination is a critical stage of plant production. Slow and inconsistent germination resulted in non-uniform and smaller plants. Deterioration reduces seed vitality and causes its loss. Various physiological seed primings and enhancement treatments, such as osmopriming, hydropriming, halopriming, and solid matrix priming, are used to improve germination performance by hydrating the seeds (Kataria et al., 2019; Waqas et al., 2019). However, primed seeds reach high moisture contents during treatment and needed to be dried for safe storage of seed moisture contents (i.e. 7-8%) and have to be sown soon after the treatment. In many cases, primed seeds do not survive long in storage they may deteriorate faster than untreated batches when storage conditions are adverse (Argerich et al., 1989; Fabrissin et al., 2021). There are several physical seed-enhancing treatments, such as magnetopriming, UV treatments, and chlorophyll fluorescence, in which seeds are not imbibed and treated in a dry state. Therefore, seeds do not need to get dry or be stored. The agricultural industry has embraced the use of magnetic field treatment for seeds. Magnetopriming, a pre-sowing seed treatment involving a non-destructive and dry seed priming process, has been found to boost the germination rate and seedling vigour of multiple crops, according to several studies (Shine et al., 2011; Bhardwaj et al., 2012; Kataria et al., 2015; Xia et al., 2020; Sari et al., 2023). Kataria et al. (2019) reported that priming of the seed with a magnetic field (MF) may give an alternative method for improving seed germination and vigour. It was reported that MF-treated seeds/plants beyond the germination rates have high cell proliferation capacity, increased photosynthetic pigments, and performance of the photosystem and mitigating the adverse effects of salt, water, and UV-B stress (Dhawi et al., 2014; Baghel et al., 2016). However, getting maximum efficiency from MF depends on various factors, such as exposure period, species, cultivar, age, ploidy, and complexity of the target organ or tissue (De Micco et al., 2014). The disadvantage of the method is the need to precisely adjust the exact treatment conditions for seeds of each species, cultivar, or even seed lot (Holubowicz, 2014).

Fast germination in vegetables is necessary not only for successful stand establishment in the field (Ozden et al., 2021) but also in modules for transplant production (Demir et al., 2008). Some reports faster-germinating seed lots produce well-developed seedlings (Ermis et al., 2016). One of the primary goals of seed treatments is to improve germination, seedling development, and uniformity (Thakur et al., 2022). Researchers have previously hypothesized that magnetopriming is promising as it stands out as an efficient, clean, and affordable technique that promotes both plant resistance and high productivity. The study's main objectives were to confirm the earlier data about the positive effect and to find out if MF could improve both seeds germination rate shoot and root length in seeds of tomato, pepper, onion, cauliflower, cabbage, and carrot.

MATERIALS and METHODS

Sample collection and preparation

The seeds of tomato (*Solanum lycopersicum* cv. SC-2121), pepper (*Capsicum annuum* L. Cv. Sera Demre), onion (*Allium cepa* cv. Karbeyazı), cauliflower (*Brassica oleracea* var. Botrytis. Cv. İgloo), cabbage (*Brassica oleracea* var *capitata* cv. Yalova 1) and carrot (*Daucus carota* L. Cv. Nantes Scarlet) were obtained from commercial seed companies.

Magnetopriming treatment

Magnetopriming was performed by using the electromagnetic tool as shown in Figure 1. Magnetic treatment at a strength of 15-17 mT was applied to the seeds for 5 minutes for tomato, pepper, and onion seeds and 15 minutes for cauliflower, cabbage, and carrot seeds. The optimum duration of the treatment was determined by the preliminary work that had been conducted earlier. Untreated seeds were considered a control.

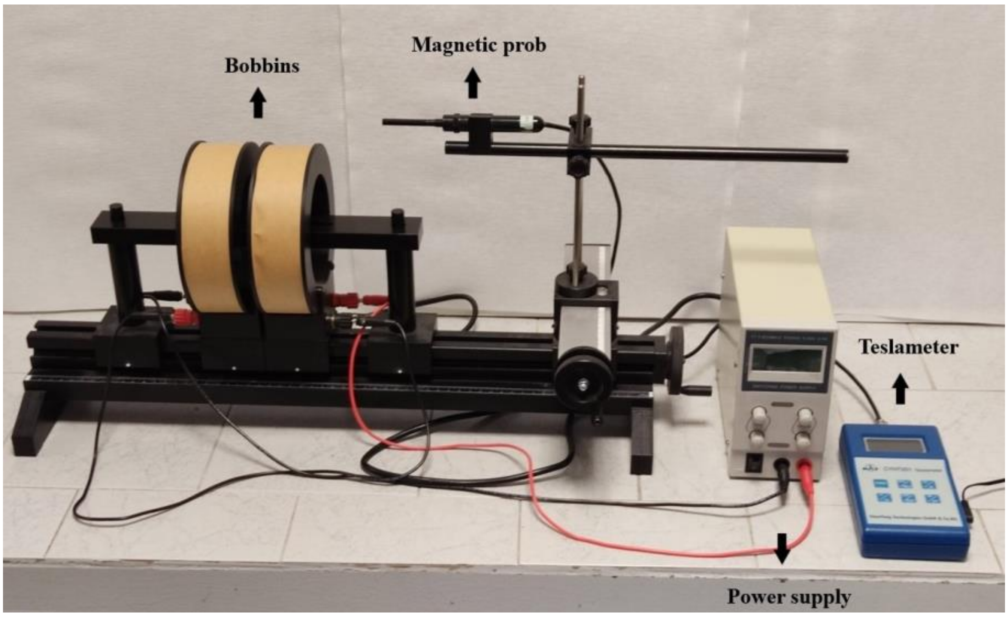

Figure 1. Magnetopriming was performed by using the electromagnetic tool. For magnetopriming the seeds (tomato, pepper, onion about 5 minutes and cauliflower, cabbage and carrot about 15 minutes) are kept in the pole gap of the magnet at 15-17 mT intensity

Şekil 1. Tohumlarda magnetopriming işlemi, elektromıknatıs kullanılarak gerçekleştirilmiştir. Magnetopriming uygulaması için tohumlar (domates, biber, soğan için yaklaşık 5 dakika; karnabahar, lahana ve havuç için yaklaşık 15 dakika) manyetik alanın şiddeti 15-17 mT olan manyetik kutuplar arasında tutulmuştur

Germination tests

This study was conducted in 2022 at the Seed Science and Technology Laboratory, located within the Department of Horticulture at the Faculty of Agriculture, Ankara University. Standard laboratory germination tests of treated and control seeds were conducted immediately after the treatment on three replicates of 50 seeds. Seeds were placed between wet filter paper (10 ml distilled water, 20x20 cm, Filtrak, Germany). Papers were then placed in plastic bags. Germination tests were carried out at 20°C for onion, cauliflower, cabbage, and carrot and at 25°C for tomato and pepper in the dark. Standard germination was evaluated after 14 days for tomato, pepper, carrot, cauliflower, and cabbage after 12 days for onions. Seeds producing a 2 mm radicle were counted every day at the same time as having germinated and considered total germination (TG). At the final count, normal seedling percentages (NG, well-developed seedlings) were determined. At the end of the germination test, each species' root and shoot lengths of 40 seedlings (10 seedlings x 4 replicates) were measured as cm/plant in the treated and control seed batches.

Using the daily radicle emergence counts, the mean germination (MGT) was calculated for each treated and control lot in each species using the formula cited by Ellis and Roberts (1980):

$$MGT = \frac{\sum n.t}{\sum n}$$

where n=number of seeds newly germinated at time t; t=days from sowing, and Σn = final emergence.

Statistical analysis

Means of total and normal germination percentages, mean germination time, shoot and root length in treated and control seeds in each species were compared by Duncan’s multiple range tests by using the SPSS package program at the significance 5% level. Before the analyses, the percentages were angular transformed.

RESULTS AND DISCUSSIONS

Pre-treatment range total germination was between 77 and 100% and normal germination was between 62 and 87 % among the species being the highest in onion and the lowest in pepper and tomato (Table 1).

Table 1. Changes in total (TG, %), normal germination (NG, %) and seed moisture content of vegetable species that were used in the study

Çizelge 1. Çalışmada kullanılan sebze türlerinin toplam (TG, %), normal çimlenme (NG, %) ve tohum nem içeriğindeki değişiklikler

Species	TG (%)	NG (%)	Seed m.c. (%)
Tomato	79[d]	62[d]	8.1
Pepper	77[d]	62[d]	7.6
Onion	100[a]	87[a]	8.8
Cauliflower	86[c]	64[cd]	5.5
Cabbage	93[b]	78[b]	6.5
Carrot	79[d]	71[bc]	8.7

Magnetopriming increased total germination percentages compared to those of control in all species of seeds except pepper, which varied between 6 % in onion and cabbage and 11 % in carrot (Figure 2). While the differences were greater in normal germination percentages even though statistically not significant in all species. The greatest and most significant differences were observed in pepper and cauliflower seeds as %10 and onion as %14 seeds (Figure 3). The mean germination time was shorter in treated seeds, but the difference was only significant ($p<0.05$) in onions but not in the others (Table 2).

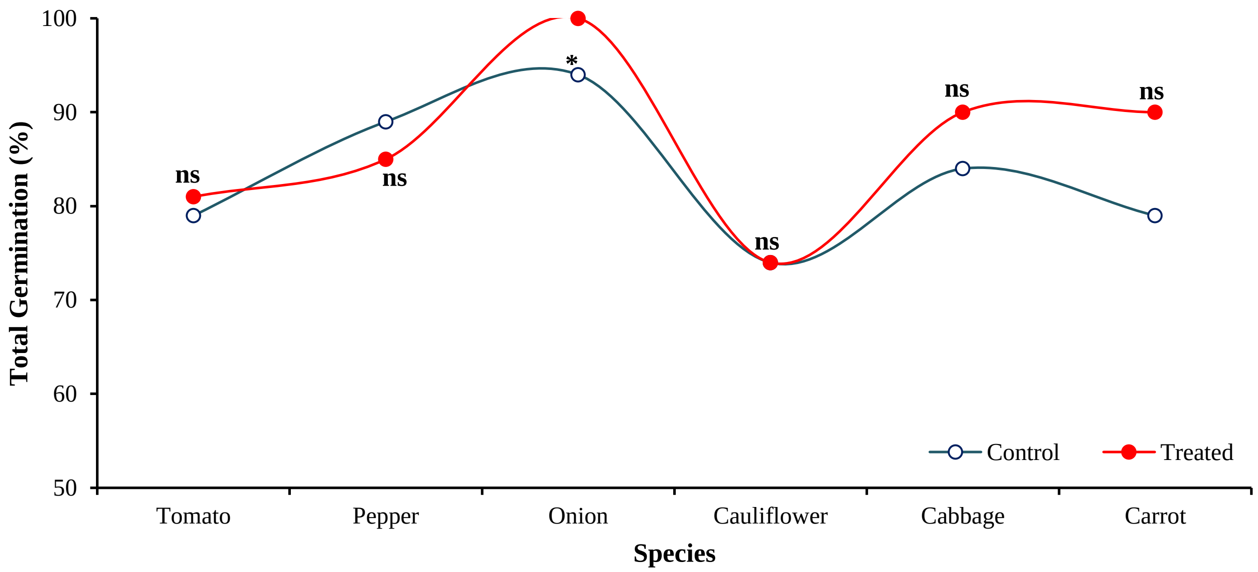

Figure 2. The effect of magnetopriming on the total germination of tomato, pepper, onion, cauliflower, cabbage and carrot species. (*: p<0.05, ns: not significant)

Şekil 2. Magnetopriming uygulamasının domates, biber, soğan, karnabahar, lahana ve havuç türlerinin toplam çimlenmesi üzerindeki etkisi. (: p<0.05, ns: önemli değil)*

Table 2. Changes in mean germination time (day) in control and treated seeds

Çizelge 2. Kontrol ve uygulama yapılan tohumlardaki ortalama çimlenme zamanındaki değişiklikler (gün)

Species	Control	Treated
Tomato	4.0±0.5	3.9±0.8 ^{ns}
Pepper	5.2±0.5	5.0±0.5 ^{ns}
Onion	3.5±0.1	3.3±0.1*
Cauliflower	2.9±0.5	2.5±0.6 ^{ns}
Cabbage	2.3±0.5	2.2±0.6 ^{ns}
Carrot	4.8±0.4	4.5±0.6 ^{ns}

Several studies (Martinez et al., 2000; Houbowicz et al., 2014; Xia et al., 2020) have shown that magnetic stimulation has a beneficial effect on the ability of seeds from various plant species to germinate. Yet the results show that the influence of the magnetic field depends not only on the magnetic induction levels used but also on the kinds of seeds (plants) that are stimulated (Sarraf et al., 2020). Our results agreed with this assumption that some species respond more than others. Treated onion seeds had higher normal seedling percentages (14%) than tomatoes and cabbages (8%) compared to control seeds (Figure 3).

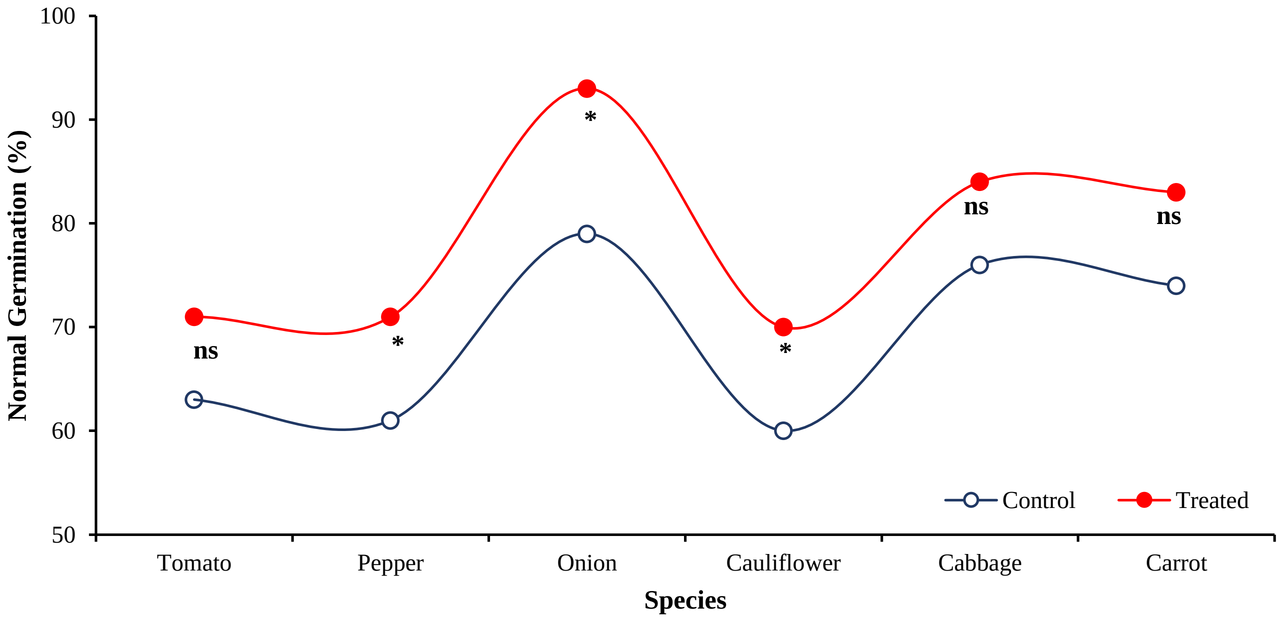

Figure 3. The effect of magnetopriming on the normal germination of tomato, pepper, onion, cauliflower, cabbage and carrot species. (*: p<0.05, ns: not significant)

Şekil 3. Magnetopriming uygulamasının domates, biber, soğan, karnabahar, lahana ve havuç türlerinin normal çimlenmesi üzerindeki etkisi. (: p<0.05, ns: anlamlı değil)*

This obviously shows that plant species respond differently to magnetopriming treatments. The necessity for precise adjustment of treatment conditions for seeds of each species or even a cultivar was reported as one of the main disadvantages of magnetopriming (Xia et al., 2020). Some of the reports indicated that the influence of magnetic field treatments depends on the exposition time of samples and the pre-history of the samples (Aladjadjiyan, 2007). Paramagnetic properties of the tissues so their absorption level of the magnetic field can vary among the species due to metabolically active tissues of the plant cells such as free radicals. Free radicals play an important role in electron transfer and in the kinetics of the chemical reactions which may be changed relatively from seed to seed in the same seed batch. As a result of the interaction between the external magnetic field of unpaired electrons, the energy was absorbed (Shine and Guruprasad, 2012). Then it was transformed into chemical energy and induced the vital processes in seeds. The mechanism of energy absorption by molecules can be influenced not only by the strong and the weak magnetic fields but also can be variable due to the chemical composition of the seeds (Galland and Pazur, 2005). Our results indicated that the magnetopriming effect on normal seedling emergence (i.e. well-developed root and shoot-structured seedlings) was more prominent than total germination (i.e. 2 mm radicle emergence) (Figure 3). Total germination percentages are based on radicle protrusion, but not all radicle protruded seeds may form normally developed seedlings. Standard laboratory germination tests were based on normally developed seedling percentages in seed testing laboratories (ISTA, 2021). Because normal seedlings were described as complete and have a higher potential to produce healthy and strong seedlings in sowing conditions. The mechanism by which plants perceive magnetopriming and regulate the signal transduction pathway is not fully understood. While it has been proposed that MF perception/signaling in plants is mediated by the blue light photoreceptors, along with reactive oxygen species (ROS) and nitric oxide (NO) are the signaling molecules for magnetopriming induced seed germination (Sarraf et al., 2020).

As a result of the interaction between MF and ionic current in the membrane of the embryo cell, changes in ionic concentrations and osmotic pressure occur on both sides of the membrane (Yaycili and Alikamanoglu, 2005). These effects are related to other physiological impacts. The reason why magnetoprimed seeds germinate more quickly than unexposed seeds is that magnetotreated seeds showed faster hydration of macromolecules and membranes, as well as higher activity of enzymes like -amylase and nitrate reductase during seed germination (Moon and Chung, 2000; De Souza et al., 2014).

Magnetopriming increased seedling shoot length significantly ($p<0.05$) in all species without exception. The greatest difference between treated and control seedlings was observed in tomato and onion as 1.4-1.3 cm respectively. While the difference was the smallest in pepper seedlings at 0.2 cm (Figure 4, Figure 6). Pepper shoot lengths were the shortest seedlings of all species. Similarly, root length was affected by the treatment significantly ($p<0.05$) in all species (Figure 5). The greatest differences were observed in cabbage seedlings at 3.5 cm followed by tomato seedlings at 2 cm. The difference in onion was the smallest at 0.5 cm. Onion root lengths were the shortest among all the species. The early appearaence of the radicles and longer root and shoot systems in the seedlings of these vegetable species may help with stand establishment in the field or transplant production in the greenhouse (Demir et al., 2020). Stronger root and shoot systems can contribute to greater adaptation and resistant response to abiotic and biotic stress conditions. We have not tested the seedling growth of MF seeds under the field in this work, but results in lettuce, tomato, and onion seeds showed that MF-treated seeds had higher emergence and stronger seedlings (De Souza et al., 2008; 2010; 2014; Sari et al., 2023). Increased seedling height in response to MF may also be implicated in the production of better-sized transplant production which is used in these vegetable crops (Thakur et al., 2022) in the Horticulture industry. On that matter, we should mention that MF treatments have also proved beneficial to impact tolerance to plants from abiotic stresses that seeds may encounter during germination (Mridha et al., 2016; Baghel et al., 2016) which may be helpful to produce better transplants under stressful environments. Despite numerous research papers on the positive effect of magnetopriming, questions about its effect on seeds were unanswered. How plants regulate their physiological processes in response to magnetopriming will need to be addressed in future studies.

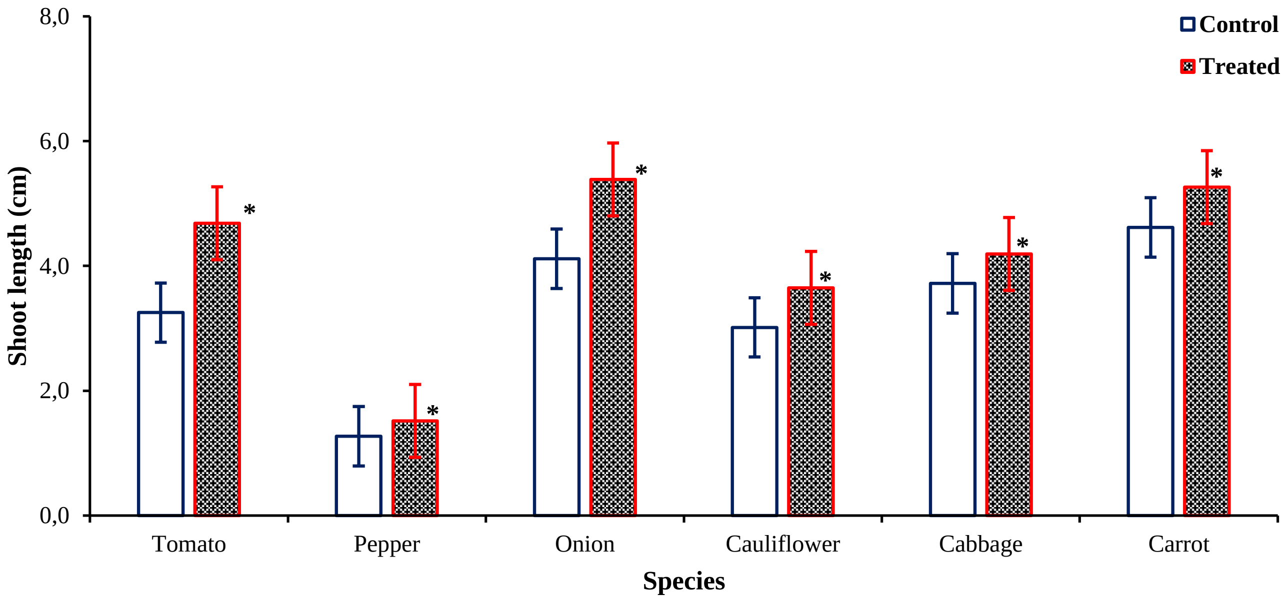

Figure 4. The effect of MT on tomato, pepper, onion, cauliflower, cabbage and carrot species' shoot length (cm)
Şekil 4. Magnetopriming uygulamasının domates, biber, soğan, karnabahar, lahana ve havuç türlerinin sürgün uzunluğu (cm) üzerindeki etkisi

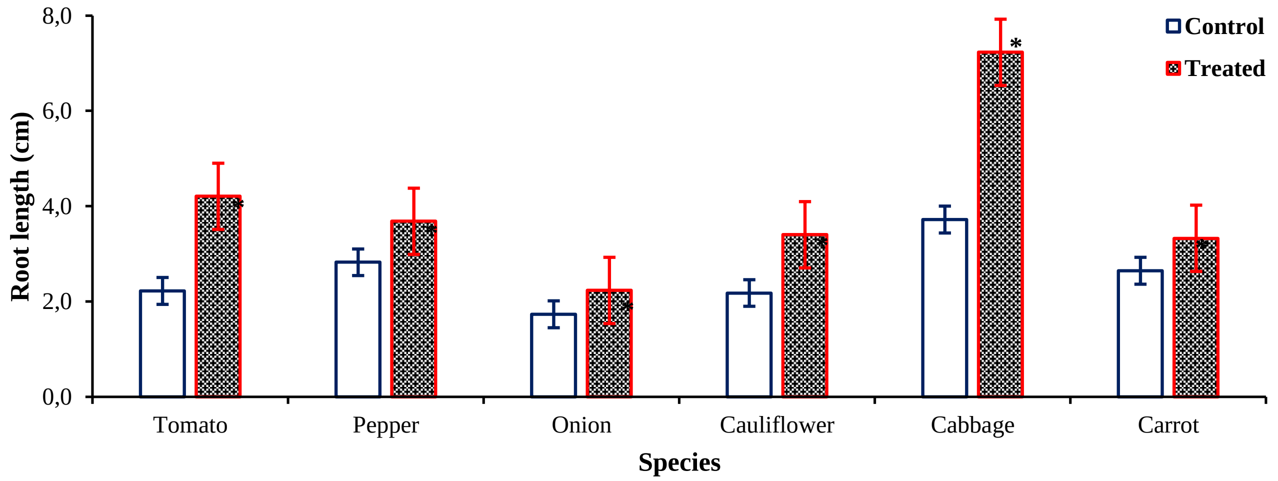

Figure 5. The effect of MT on tomato, pepper, onion, cauliflower, cabbage and carrot species' root length (cm)
Şekil 5. Magnetopriming uygulamasının domates, biber, soğan, karnabahar, lahana ve havuç türlerinin kökçük uzunluğu (cm) üzerindeki etkisi

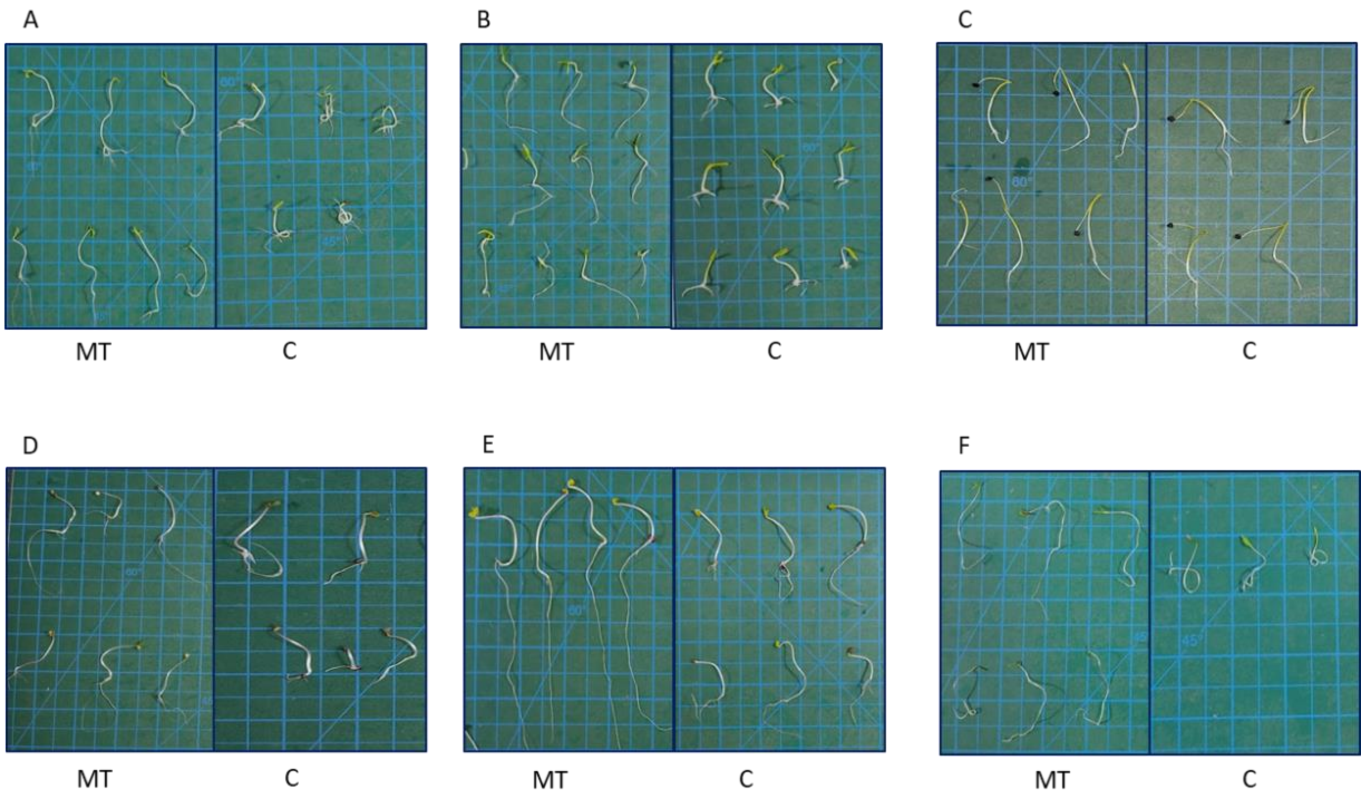

Figure 6. Tomato (A), pepper (B), onion (C), cauliflower (D), cabbage (E) and carrot (F) of magnetoprimed (MT) and control (C) seedlings

Şekil 6. Domates (A), biber (B), soğan (C), karnabahar (D), lahana (E) ve havuç (F) tohumlarına manyetik alan uygulanmış(MT) ve kontrol (C) fideleri

As a result, suitable ratio of MF intensity to exposure time is necessary to improve seed germination, crop productivity, and development. Many studies have demonstrated that its beneficial effects can increase root and shoot length and seed germination. One of the simplest, most effective, non-invasive ways to increase seed vigour is the magnetopriming of seeds. Under both normal and stressful circumstances, magnetoprimed seeds germinate more quickly and perform well. Magnetopriming was found as more effective on normal germination. Exposure of pepper, onion and cauliflower seeds to magnetic fields 15-17 mT about 5 and 15 minutes significantly increased normal germination compared to unexposed controls under controlled conditions. The shoot and root length of seedlings were significantly ($p<0.05$) impacted by magnetopriming. All of these studies have emphasized the need for additional research to increase our understanding of the seed varieties responsible for accelerating seed germination, increasing seedling vigour, and increasing the photosynthetic ability of magnetoprimed seeds. Therefore, it is necessary to work with magnetopriming, especially in seeds of different species.

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STATEMENT OF CONFLICT OF INTEREST

The authors declare no conflict of interest for this study.

AUTHOR'S CONTRIBUTIONS

All authors contributed to the study's conception and design. Neslihan KADIOGLU; performed the research and analyses. Ibrahim DEMIR, Sıtkı ERMIS and Güleda OKTEM produced the figures supervised the research structured the paper and edited the manuscript. All authors read and approved the final version of the manuscript.

COMPLIANCE WITH ETHICAL STANDARDS

This article does not contain any studies with human participants performed by any of the authors. This study is a part of the first author's master's thesis.

REFERENCES

Aladjadjiyan, A. (2007). The use of physical methods for plant growing stimulation in Bulgaria. *Journal of Central European Agriculture, 8* (3), 369-380.

Argerich, C.A., Bradford, K.J., & Tarquıs, A.M. (1989). The effects of priming and ageing on resistance to deterioration of tomato seeds. *Journal of Experimental Botany, 40* (5), 593-598. https://doi.org/10.1093/jxb/40.5.593

Baghel, L., Kataria, S., & Guruprasad, K.N. (2016). Static magnetic field treatment of seeds improves carbon and nitrogen metabolism under salinity stress in soybean. *Bioelectromagnetics, 37* (7), 455-470. https://doi.org/10.1002/bem.21988

Bhardwaj, J., Anand, A., & Nagarajan, S. (2012). Biochemical and biophysical changes associated with magnetopriming in germinating cucumber seeds. *Plant Physiology and Biochemistry, 57,* 67-73. https://doi.org/10.1016/j.plaphy.2012.05.008

De Micco, V., Paradiso, R., Aronne, G., De Pascale, S., Quarto, M., & Arena, C. (2014). Leaf anatomy and photochemical behaviour of *Solanum lycopersicum* L. plants from seeds irradiated with low-LET ionising radiation. *The Scientific World Journal*, 1-13. https://doi.org/10.1155/2014/428141

De Souza, A., Sueiro, L., Gonzalez, L.M., Licea, L., Porras, E.P., & Gilart, F. (2008). Improvement of the growth and yield of lettuce plants by non-uniform magnetic fields. *Electromagnetic Biology and Medicine, 27* (2), 173-184. https://doi.org/10.1080/15368370802118605

De Souza, A., Sueiro, L., García, D., & Porras, E. (2010). Extremely low frequency non-uniform magnetic fields improve tomato seed germination and early seedling growth. *Seed Science and Technology, 38* (1), 61-72., https://doi.org/10.15258/sst.2010.38.1.06

De Souza, A., García, D., Sueiro, L., & Gilart, F. (2014). Improvement of the seed germination, growth and yield of onion plants by extremely low frequency non-uniform magnetic fields. *Scientia Horticulturae, 176,* 63-69. https://doi.org/10.1016/j.scienta.2014.06.034

Demir, I., Ermis, S., Mavi, K., & Matthews, S. (2008). Mean germination time of pepper seed lots (*Capsicum annuum* L.) predicts size and uniformity of seedlings in germination tests and transplant modules. *Seed Science and Technology, 36* (1), 21-30. https://doi.org/10.15258/sst.2008.36.1.02

Demir, I., Ozden, E., Gökdas, Z., Njie, S.E., & Aydın, M. (2020). Radicle emergence test predicts normal germination percentages of onion seed lots with different cultivars and genotypes. *Mustafa Kemal Üniversitesi Tarım Bilimleri Dergisi, 25* (3), 434-442. https://doi.org/10.37908/mkutbd.697450

Dhawi, F. (2014). Why magnetic fields are used to enhance a plant's growth and productivity?. *Annual Research & Review in Biology*, 886-896. https://doi.org/10.9734/ARRB/2014/5983

Ellis, R.H., & Roberts, E.H. (1980). Improved equations for the prediction of seed longevity. *Annals of Botany, 45* (1), 13-30. https://doi.org/10.1093/oxfordjournals.aob.a085797

Ermis, S., Kara, F., Ozden, E., & Demir, I. (2016).Solid matrix priming of cabbage seed lots: repair of ageing and increasing seed quality. *Journal of Agricultural Sciences, 22* (4), 588-595. https://doi.org/10.1501/Tarimbil_0000001417

Fabrissin, I., Sano, N., Seo, M., & North, H.M. (2021). Ageing beautifully: can the benefits of seed priming be separated from a reduced lifespan trade-off?. *Journal of Experimental Botany, 72* (7), 2312-2333. https://doi.org/10.1093/jxb/erab004

Galland, P., & Pazur, A. (2005). Magnetoreception in plants. *Journal of Plant Research, 118,* 371-389.

Hołubowicz, R., Kubisz, L., Gauza, M., Yilin, T., & Hojan-Jezierska, D. (2014). Effect of low frequency magnetic field (LFMF) on the germination of seeds and selected useful characters of onion (*Allium cepa* L.). *Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 42* (1), 168-172. https://doi.org/10.15835/nbha4219131

ISTA (International Seed Testing Association) (2021). *International rules for seed testing.* Switzerland, p. 298.

Kataria, S., Lokesh, B., & Guruprasad, K.N. (2015). Acceleration of germination and early growth characteristics of soybean and maize after pre-treatment of seeds with static magnetic field. *International Journal of Tropical Agriculture, 33* (2 (Part II)), 985-992.

Kataria, S., & Jain, M. (2019). Magnetopriming alleviates adverse effects of abiotic stresses in plants. *In Plant Tolerance to Environmental Stress.* CRC Press, pp. 427-442.

Martinez, E., Carbonell, M.V., & Amaya, J.M. (2000). A static magnetic field of 125 mT stimulates the initial growth stages of barley (*Hordeum vulgare* L.). *Electro-and Magnetobiology, 19* (3), 271-277. https://doi.org/10.1081/JBC-100102118

Moon, J.D., & Chung, H.S. (2000). Acceleration of germination of tomato seed by applying AC electric and magnetic fields. *Journal of Electrostatics, 48* (2), 103-114. https://doi.org/10.1016/S0304-3886(99)00054-6

Mridha, N., Chattaraj, S., Chakraborty, D., Anand, A., Aggarwal, P., & Nagarajan, S. (2016). Pre-sowing static magnetic field treatment for improving water and radiation use efficiency in chickpea (*Cicer arietinum* L.) under soil moisture stress. *Bioelectromagnetics, 37* (6), 400-408. https://doi.org/10.1002/bem.21994

Özden, E., Memis, N., Kenanoglu, B.B., & Demir, İ. (2021). Vigour assessment of dill (*Anethum graveolens* L.) seed lots in relation to predicting seedling emergence potential. *Journal of Agricultural Sciences, 27* (1), 50-55. https://doi.org/10.15832/ankutbd.577254

Sari, M.E., Demir, I., Yildirim, K.C., & Memis, N. (2023). Magnetopriming enhance germination and seedling growth parameters of onion and lettuce seeds. *International Journal of Agriculture, Environment and Food Sciences, 7* (3), 468-475. https://doi.org/10.31015/jaefs.2023.3.1

Sarraf, M., Kataria, S., Taimourya, H., Santos, L.O., Menegatti, R.D., Jain, M., Ihtisham, M., & Liu, S. (2020). Magnetic field (MF) applications in plants: An overview. *Plants, 9* (9), 1139. https://doi.org/10.3390/plants9091139

Shine, M.B., Guruprasad, K.N., & Anand, A. (2011). Enhancement of germination, growth, and photosynthesis in soybean by pre-treatment of seeds with magnetic field. *Bioelectromagnetics, 32* (6), 474-484. https://doi.org/10.1002/bem.20656

Shine, M.B., & Guruprasad, K.N. (2012). Impact of pre-sowing magnetic field exposure of seeds to stationary magnetic field on growth, reactive oxygen species and photosynthesis of maize under field conditions. *Acta Physiologiae Plantarum, 34,* 255-265. https://doi.org/10.1007/s11738-011-0824-7

Thakur, M., Tiwari, S., Kataria, S., & Anand, A. (2022). Recent advances in seed priming strategies for enhancing planting value of vegetable seeds. *Scientia Horticulturae, 305,* 111355. https://doi.org/10.1016/j.scienta.2022.111355

Waqas, M., Korres, N.E., Khan, M.D., Nizami, A.S., Deeba, F., Ali, I., & Hussain, H. (2019). Advances in the concept and methods of seed priming. *Priming and pretreatment of seeds and seedlings: Implication in plant stress tolerance and enhancing productivity in crop plants*, 11-41. https://doi.org/10.1007/978-981-13-8625-1_2

Xia, X., Padula, G., Kubisz, L., & Hołubowicz, R. (2020). Effect of low frequency magnetic field (LFMF) on seed quality of radish (*Raphanus sativus* L.) seeds. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 48* (3), 1458-1464. https://doi.org/10.15835/nbha48311918

Yaycili, O., & Alikamanoglu, S. (2005). The effect of magnetic field on Paulownia tissue cultures. *Plant Cell, Tissue and Organ Culture, 83,* 109-114. https://doi.org/10.1007/s11240-005-4852-0