Design and Evaluation of an Applicator for Magnetopriming Treatments

Gaetano Chirico, Claudio D'Elia, Nicola D'Ambrosio, and Rita Massa

***Abstract*—Seed priming is a physiological seed enhancement method for overcoming poor and erratic seed germination in many crop and flowering plants. Magnetopriming is a pre-sowing seed treatment with magnetic field that appears as a promising method to improve seed performances. This paper presents a cost-efficient design and optimization of an exposure system for magnetopriming treatments. The proposed static magnetic field applicator is modelled and designed with the aid of commercial software. The prototype is realized and tested based on the best set of geometry parameters for optimum performance, in terms of strength and high homogeneity of the magnetic flux density in the Region of Interest. Both analytical and measurement results are found to be in good agreement with the simulated results. The system is low cost, environmentally friendly and easy to operate. It allows seed treatments at different strengths with high homogeneity within the samples. In this way, the treatments can be carried out following good practice requirements strongly recommended for a high quality bioelectromagnetic research to assure reliability and reproducibility of the experiments.**

***Index Terms*—Applicators, design optimization, dosimetry, environmentally friendly manufacturing techniques, magnetic devices.**

I. Introduction

THE world population is expected to increase to over 10 billion by 2100 and this will lead to a growing food demand [1]. Increasing the land surface used for agriculture is not a viable strategy because it is ecologically unsustainable, as this would imply a further increase in deforestation with a consequent loss of biodiversity. In last decades, the Green Revolution has played a central and exclusive role in increasing world agricultural productivity by its proposed approaches as high-yielding varieties, agrochemicals, and intensified farming [2]. On the other hand, intensive agricultural practices have generated a great environmental impact, whose effects are difficult to mitigate. Awareness of the complexity of the interactions between human production activities and the environment requires the urgent development and application of agricultural practices completely based on sustainability.

In the context of a sustainable agriculture, seed quality is an important trait that can improve food crop and contribute to meet the growing food demand [3]. High seed quality means good seed germination, sustaining an efficient growth and high productivity of food crops [4]. Germination is the very critical initial process of the entire seed development program. It is strongly influenced by intrinsic properties of the seed (e.g., genetic characteristics, state of conservation, age of the seed) which can define its quality [5]. Moreover, seed germination is greatly compromised by environmental constrains (abiotic and biotics factors), frequently occurring due to extreme weather events as consequences of the ongoing climate change [6]. Similarly, a slow and not uniform germination makes the development of plants more sensitive to adverse environmental conditions and leads to a not optimal crop production [3].

Pre-sowing treatments to improve seed quality have been known for a long time and are referred to as "seed priming" techniques. Seed priming aims to improve germination efficiency, in terms of speed and uniformity, and makes the seedling development more resistant to environmental stress, with positive effects on crop production [7]. There are numerous seed priming techniques, and their effectiveness depends mainly on the plant species, but also on the variety, morphology, and age of the seeds [8]. The most used seed priming techniques can be classified into chemical, biological and physical treatments. The chemical and biological techniques, although effective, are particularly long, complex, and expensive. They also often require the use of chemical agents which also have an additional cost in terms of environmental impact.

Physical techniques for seed priming have the advantage of being faster in their application, compared to the chemical and biological ones. In recent years, among physical seed priming techniques, magnetopriming had a significant development. There is an increasing number of publications demonstrating that exposure of seeds from different plant species to a magnetic field (MF) before sowing improves germination efficiency, plant development and productivity under both normal and stressed environmental conditions [9], [10], [11], [12], [13]. Despite numerous studies on the effects of MF exposure on seed

Manuscript received 9 November 2022; revised 14 March 2023; accepted 5 April 2023. Date of publication 27 April 2023; date of current version 23 August 2023. This work was supported by Regione Campania in the Framework of PSR 2014-2020, Mis.16.1, CAR.PE.FIME project under Grant CUP B51C1800020007. This paper is an expanded paper from the one presented at the ICEmB 2022, Cagliari (Sardinia), Italy. *(Corresponding author: Rita Massa.)*

Gaetano Chirico is with the Department of Electric and Information Engineering "M. Scarano," University of Cassino and Southern Lazio, 03043 Cassino, Italy (e-mail: gaetano.chirico@unicas.it).

Claudio D'Elia and Rita Massa are with the Department of Physics "Ettore Pancini", University of Naples "Federico II," 80126 Naples, Italy (e-mail: delia.claudio88@gmail.com; massa@unina.it).

Nicola D'Ambrosio is with the Department of Biology, University of Naples "Federico II," 80126 Naples, Italy (e-mail: dambrosi@unina.it).

This article has supplementary downloadable material available at https://doi.org/10.1109/JERM.2023.3267659, provided by the authors.

Digital Object Identifier 10.1109/JERM.2023.3267659

germination, it has been underlined a fragmentation of the results. This is a well-known issue in bioelectromagnetic research, and several authors, actively working in this contest, recommended to apply high methodological quality [14], [15], [16], [17], [18]. Regardless of the applied electromagnetic field frequency, many data reported in the literature are not informative due to inadequate electromagnetic or biological experimental procedures, preventing both the evaluation of the experimental results and the reproduction of the experiments by other laboratories. Accurate dosimetry is one of the mandatory requirements for good laboratory practices. The use of magnetopriming to improve seed quality is very promising, especially due to its low cost of application, ease of use and low environmental impact. However, the large heterogeneity of seeds (morphology and size), endpoints examined and exposure conditions adopted make difficult to summarize and compare the results.

A deep understanding of the interactions between MF and seed responses could revolutionize crop production and increase their resistance to disease and stress conditions, as well as the water and nutrient use efficiency.

Although some hypotheses have been proposed about the mechanisms that explain how this physical event is converted into a cellular response, the exact mechanism is still largely unclear. Magnetopriming induced by static magnetic fields (SMF) is carried out applying MF generated by electromagnets [19], [20], [21], [22] or permanent magnets [11], [23], [24], [25]. The magnetic flux density (B) and the effective dose can vary depending on the species, biological process observed, abiotic/biotic stress conditions, etc. Typically, B is in the range 50 mT - 200 mT while the duration can vary from few minutes up to 24/48 h.

In addition to the MF strength, the uniformity of the field in the Region of Interest (RoI) is an important parameter to be addressed to have reproducible data. However, this information is difficult to obtain in published studies, and when inhomogeneity is reported it can strongly vary from very low values (0.5%–1.5%) typically achieved with electromagnets [19], [26] to relative high values (25%–30%) when permanent magnets are employed [11], [23].

The homogenization of B field conditions is a well-known challenge. For instance, in the Magnetic Resonance (MR) apparatuses, the experimental B field homogenization, called B shimming, is mandatory for reliable investigations. Common concepts and specific solutions for its experimental optimization are summarized in the review [27]. Passive shimming with ferromagnetic substances provides an inexpensive means of efficiently producing very strong and homogeneous magnetic fields. It can be achieved with ferromagnetic substances, opportunely introduced into the scan. However, the creation and adjustment of such passive shim assemblies is cumbersome and not flexible, and its practical shortcomings have prevented it from becoming the common method of choice in MR service best practice.

Inspired by MR apparatuses, in this paper we present an SMF applicator for magnetopriming treatments whose design was driven by the following working hypotheses: possibility to confine the magnetic field lines generated by the magnets, in such a way to maximize the B-field level and uniformity in the sample area; possibility to host samples of different sizes at various B-field strength; device based on permanent magnets, in such a way to avoid confounding factors like heating that could arise in the case of electromagnets or radiofrequency applicators; low cost of realization with low footprint (for use in laboratories/greenhouses); avoiding interference with other electromagnetic field sources (low/high frequencies), as well as guarantee the operators safety.

The applicator was realized and tested. The device works at variable B-strength between 50 mT and 200 mT, i.e., in the range where numerous positive results have been reported in the literature [28], [29], [30]. A high uniformity (about 95%–99%) was achieved in the RoIs by adopting careful design approaches that will be illustrated in the paper. We envision that a reliable, robust, small size applicator easily transported to the application place without requiring specialized installation and power supply, can be extremely advantageous, improving in this way the beneficial effect on the environment of this ecofriendly technique. In our research activity this device will be used either for investigations about the mechanisms promoting this effect or for finding the conditions suitable for potentiate seeds germination of crop plants particularly important in South Italy.

The paper is organized as follows. We present in Section II the numerical approach followed to obtain the B-field distribution in the case of two magnets opportunely located. The good agreement with the results achieved with an analytical approach assured us the accuracy of the method and different scenarios are thus considered to show the improvement attained in the applicator design. We performed a parametric study, allowing the reader to adopt the best scenario depending on the target of the study. The experimental setup for results validation is then described, and in Section III the comparison between analytical, measurement and simulations data are given. Finally, conclusions are drawn in Section IV.

II. Methods

A set of simulations has been performed to achieve the optimal exposure conditions, in terms of maximum B-field and B-field uniformity achieved. Numerical dosimetry was carried out to evaluate B-field distribution in the case of two magnets at distance Δ, and to determine the average, minimum and maximum B value (B_{av}, B_{min}, B_{max}) as well as homogeneity degree in a RoI where the sample is located. To this goal, the magnetostatic solver of CST Studio Suite platform has been employed on a laptop equipped with an AMD RYZEN 9 5900HX, NVIDIA GeForce RTX 3080 and 32GB RAM. The dimensions of the computing grid (hexahedral mesh) in the RoIs were Δx = 1.5 mm, Δy = 2.08 mm, Δz = 1.93 mm. The simulation time varied between few hours up to ten hours depending on the complexity of the scenario. The coefficient of variation (CV), defined as the standard deviation (SD) of B values over the mean B value (B_{av}), was adopted as an indicator of the B nonuniformity degree [31]:

$$CV = \frac{SD}{B_{av}} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{i=N}\left(B_i - B_{av}\right)^2}}{B_{av}} \tag{1}$$

being N the voxel number and B_i the B value calculated in the i-th voxel.

Two permanent cylindrical magnets (radius R = 22.5 mm, height L = 30 mm, remanence magnetic flux density B_r = 1.2905 T) at a distance Δ varying, with 5 mm step, between 60 mm, minimum deviation from routine workflow of biological procedures (e.g., avoiding laborious or poorly reproducible positioning of seed container inside the exposure apparatus), and 120 mm was considered. The isocenter, where the greatest magnetic field homogeneity is expected in its neighborhood, is in (0, 10, 0) coordinates and two different RoIs were evaluated: RoI_{15} (15 mm × 15 mm × 15 mm) and RoI_{30} (30 mm × 30 mm × 30 mm) allowing at least 50/100 seeds contemporary exposed depending on the seed sizes. Results obtained with different configurations are shown in the following, and B-field homogeneity will be reported in terms of CV and B-field value in the isocenter neighbor. The following scenario were compared:

i) B field distribution given by the two magnets at different Δ.
ii) B field distribution given by the two magnets at different Δ when shimming plates with different thickness (1 mm–9 mm, 1 mm step) are located near the magnets.
iii) B field distribution given by the two magnets at different Δ when an iron chamber (409 mm × 328 mm × 218 mm, 10 mm wall's thickness) contain the exposure system.
iv) B field distribution in the case of the two magnets at different Δ when the iron chamber contains both the exposure system and plates with different thickness located near the magnets (Fig. 1(b)).

Case i) is the usual configuration reported in literature. As validation test, the simulation results achieved in this case were compared with that determined by adopting the analytical expression [32] for the magnetic field of a cylinder of finite length. Case iii) describes the previous configuration but with a B field confining structure. Case ii) and iv) represent respectively the shimming procedure applied when only magnets or magnets with shielding are considered.

A device was realized (Fig. 1(a)) and tested. Measurements were carried out at Δ = 70 mm and Δ = 120 mm by mapping the magnetic flux density levels in the area where the sample would lay by means of a Hall gauss-meter (F.W. Bell, model 4048 with T-4048-001 transverse probe, 2% accuracy).

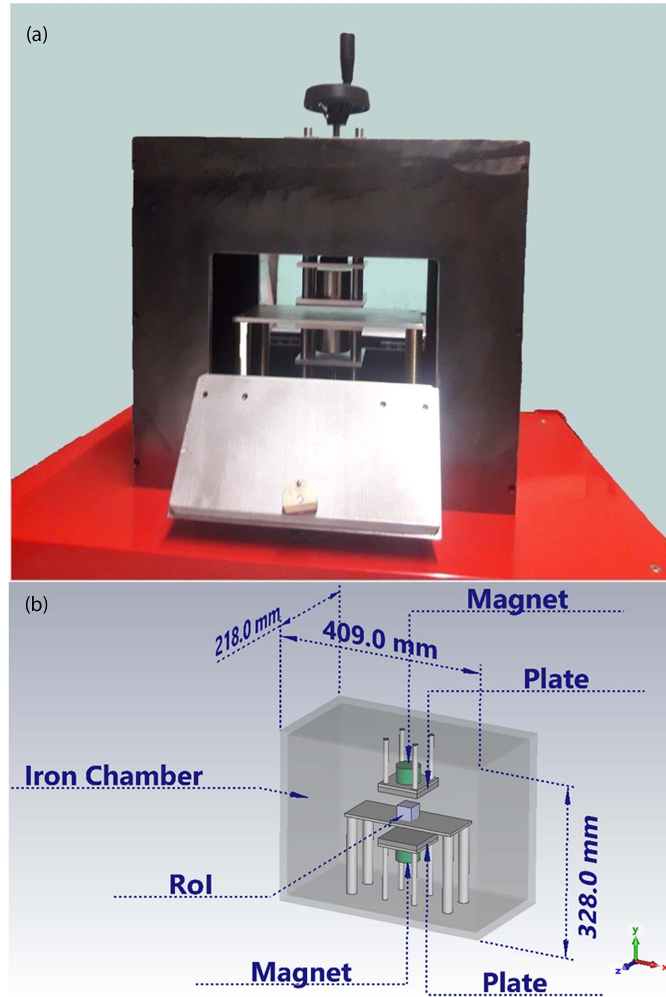

Fig. 1. (a) Device picture: Variable gap magnets and tray to fix seed container are enclosed in an iron chamber; (b) device sketch for numerical simulation.

III. Results

Plots of CV percentage in the different scenarios, depending on either the distance between the two magnets or kind of slab, are reported in Fig. 2 for RoI_{30}. CV values result greater in the RoI_{30}, being the volume wider than that occupied by the RoI_{15}, and an improvement is observed when the system is enclosed in the shielded chamber. In the case i) and ii) a 5 mm slab was necessary to reduce the inhomogeneity of about 60%–80% whatever is the distance Δ (Fig. 2(a)). A similar result is obtained when the iron chamber is added, but a 4 mm slab was sufficient with the advantage of both a higher B strength and a lower SD (scenarios iii) and iv) in Fig. 2(b)). Furthermore, the comparison of the results shown in Fig. 2(a) and (b) highlights that, when the iron chamber is added, an additional CV reduction is achieved with respect to the corresponding scenario without chamber due to a smaller SD. For example, in the case of a 4 mm slab, the insertion of the iron chamber entails a CV percentage decrease of 36% and 15% at Δ = 60 mm and Δ = 120 mm respectively.

The average B-field strengths in the same conditions are shown in Fig. 3 for RoI_{30}. A very similar behavior was observed in RoI_{15}. As expected, B_{av} decreases either with the increase of Δ or, at a fixed Δ, with the increase of the plat thickness. However, at either 4 mm or 5 mm depending on the scenario, B_{av} becomes quite constant when higher thicknesses are adopted (Fig. 3(b) and (d)).

For the sake of clarity, the B-field strength behavior in the isocenter neighbor of RoI_{30} with either a 2 mm or a 4 mm slab is compared to the no plat condition at Δ = 70 mm (Fig. 4(a) and (b)) and Δ = 120 mm (Fig. 5(a) and (b)).

It appears that the different transversal sizes of the chamber do not affect the symmetry along the x-axis and the z-axis (case

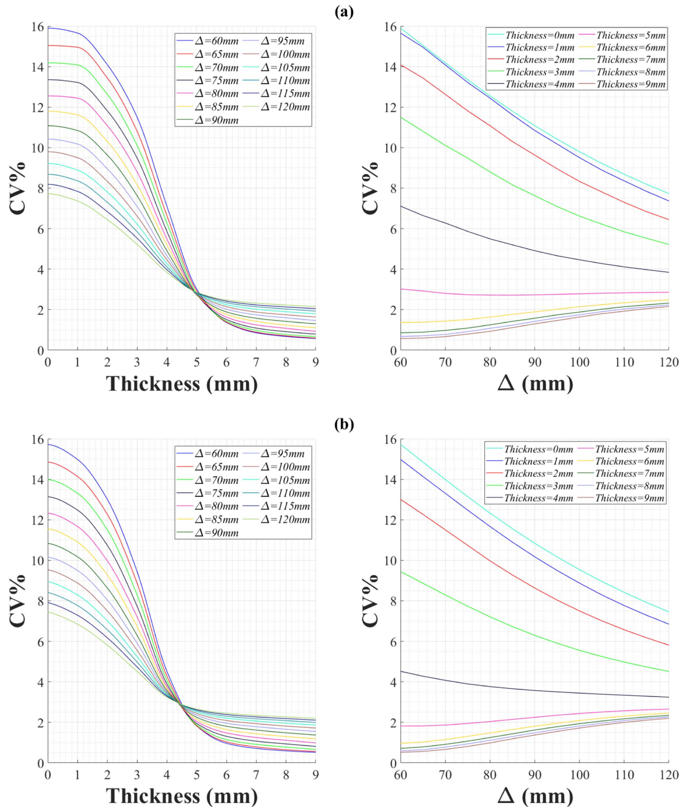

Fig. 2. Coefficient of variation in percentage for the different scenarios in the RoI_{30}: (a) Scenarios (i) and (ii), (b) scenarios (iii) and (iv).

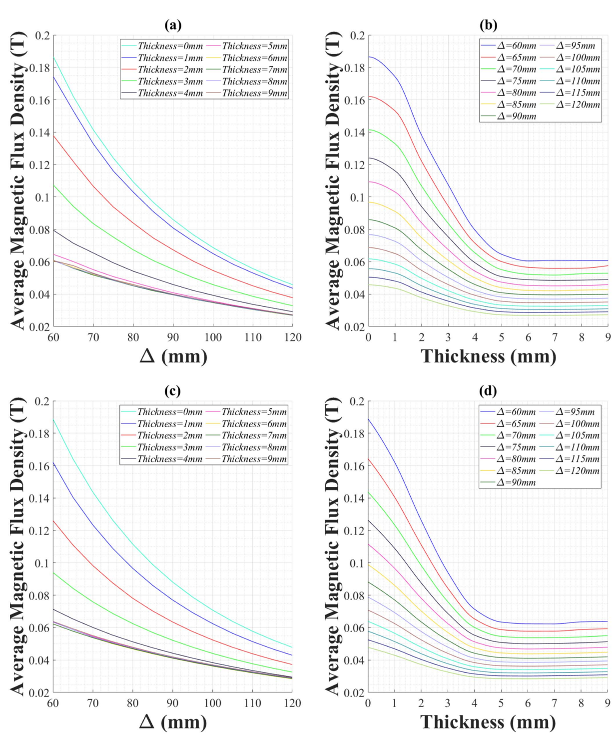

Fig. 3. Average magnetic flux density (B_{av}) behavior respect magnets distance (a, c) and slabs thickness (b, d) in the RoI_{30}. First row: Scenarios (i) and (ii); second row: Scenario (iii) and (iv).

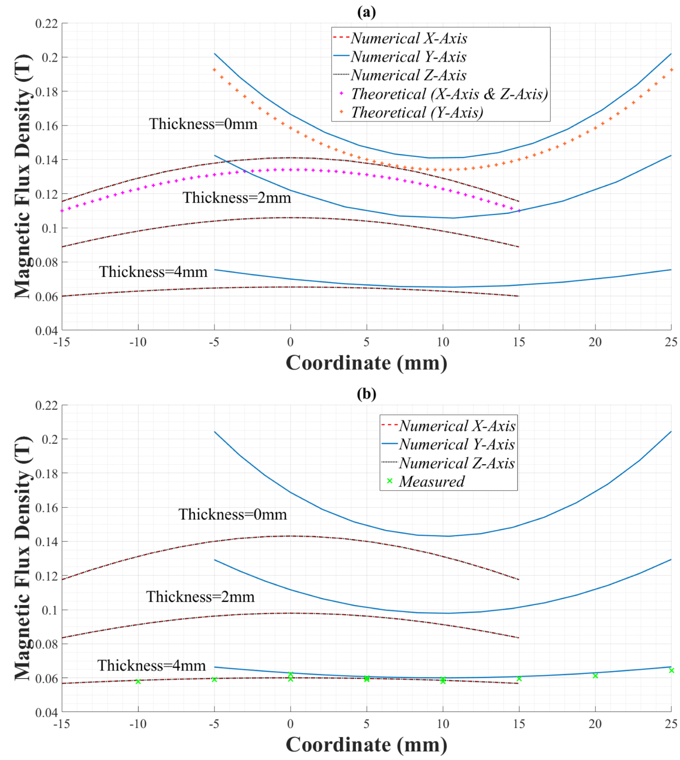

Fig. 4. Magnetic flux density in the isocenter neighbor (RoI_{30}), with and without slabs, when $\Delta = 70$ mm: (a) Scenario (i) and (ii), (b) scenario (iii) and (iv).

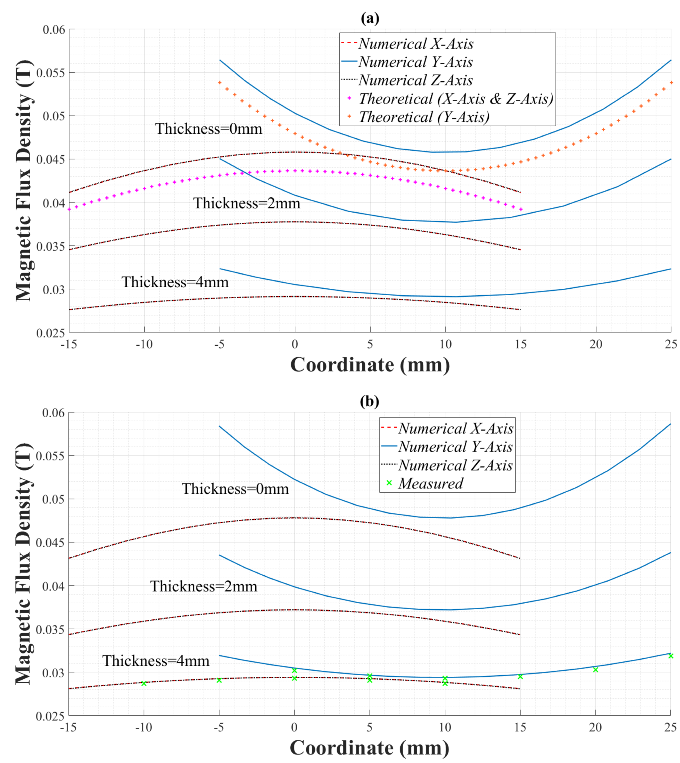

Fig. 5. Magnetic flux density in the isocenter neighbor (RoI_{30}), with and without slabs, when $\Delta = 120$ mm: (a) Scenario (i) and (ii), (b) scenario (iii) and (iv).

iii) and iv)) and a minimum is obtained in the isocenter along the y-axis, increasing the intensity of the field as we get closer to the magnets and bringing about the "bell shaped" curves. The B-field homogeneity improvement thanks to the 4 mm slab is evident, being the curves flattened. In Figs. 4 and 5, the comparison of numerical data with analytical data (case i) and of numerical data with measurements (case iv) are shown for RoI_{30} and cases $\Delta = 70$ mm and $\Delta = 120$ mm. Measurements were carried out around the isocenter (0,10,0) of the prototype with 4 mm slabs inserted. As expected, a high symmetry was found in the transverse plane (*x, z* axes) with the overlap of the curves and similar values along longitudinal *y* axis were achieved. The numerical results closely match the experimental once, with a difference comparable to the accuracy of the instrument. We also found good agreement between numerical and analytical results with a difference of only 5%.

To help the reader interested in realizing one of these configurations, the values of B_{max}, B_{min} and B_{av} numerically calculated in the different scenarios and with different Δ and slab's thickness are reported in Tables I and II in supplementary Appendix. These data allow one to find the best solution for certain values of B-field and show how slabs thicker than 5 mm do not improve the efficiency of the system. It is important to note that a negligeable B-field value is guaranteed outside the shield box. The external B-Field is less than 0.5 mT that is the exposure limit suggested to prevent inadvertent harmful exposure of people or sensible operators (e.g., with implanted electronic medical devices and implants containing ferromagnetic materials), as well as injuries due to flying ferromagnetic objects [33], [34].

IV. Conclusion

The influence of the MF on seeds does not pose any threat to the environment and the increase of the efficiency of physiological processes is particularly interesting. The effect of this action is greater vigor and a higher level of plant yield. The current contradictory and inconsistent outcomes from studies on varying effects of MF on plants could be related to species and/or MF exposure time and intensity. The design, implementation and testing of a portable applicator of magnetic field for magnetopriming treatments were shown.

A very simple configuration has been proposed allowing to easily replicate the applicator towards its ready use in laboratories as well as in greenhouses by unskilled operators, safe for both workers and the public. Other shapes of slabs and solutions will be examined to further improve these encouraging results. Passive shimming is performed with shims of ferromagnetic material in permanent magnet of MR systems with field strengths up to 0.5 T. Such systems often have a Field of View, corresponding with the portion of volume with strong B homogeneity, equivalent to a sphere of 40 cm in diameter or over 30 000 cm^3. Thus, we are particularly confident about the scalability of the method both in terms of B strength and "homogenized" volume.

The prototype was adopted to expose *Capsicum annuum L.* seeds and their germination was compared to that of unexposed seeds considered as a control. Preliminary results indicate that 1 h exposure to 50 mT induced a significant (50%) increase germination *(*$P < 0.05$) in the short observation period (5 days after sowing). More details are reported in [35]. This initial investigation confirms that the magnetopriming treatment is a promising and ecofriendly approach to facilitate seed germination, being able to enhance the speed germination in a plant species characterized by an excellent basic germination capacity (around 98%).

Acknowledgment

The authors would like to thank Dr. M. R. Masullo and Dr. A. Passarelli from the National Institute of Nuclear Physics (Naples - Italy) for their valuable assistance.

This study was carried out within the *Agritech National Research Center* and received funding from the European Union Next-GenerationEU (Piano Nazionale di Ripresa e Resilienza (PNRR) – Missione 4 Componente 2, Investimento 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

References

[1] World Population Prospects 2022, UN, Population Division UN DESA/POP/2022/DC/NO. 9, Sep. 2022. [Online]. Available: https://population.un.org/wpp/Publications/Files/WPP2022_Data_Sources.pdf
[2] K. B. Akhilesh and S. Kavitha, "A study on impact of technology intervention in the field of agriculture in India," in *Smart Technologies: Scope and Application*, K. B. Akhilesh and D. Möller Eds. Berlin, Germany: Springer, 2020, pp. 373–385.
[3] R. M. Osburn and M. N. Schroth, "Effect of osmopriming sugar beet seed on exudation and subsequent damping-off caused by Pythium ultimum," *Phytopathology*, vol. 78, no. 9, pp. 1246–1250, 1989.
[4] F. J. Schwinn, "Seed treatment - a panacea for plant protection?," in *Seed Treatment: Progress and Prospects, Monograph 57*, T. J. Martin Ed. Gottingen, Germany: BCPC Publications, 1994, pp. 3–14.
[5] E. J. Rifna, K. R. Ratish, and R. Mahendran, "Emerging technology applications for improving seed germination," *Trends Food Sci. Technol.*, vol. 86, pp. 95–108, Apr. 2019.
[6] C. Forti et al., "Hydropriming and biopriming improve *Medicago truncatula* seed germination and upregulate DNA repair and antioxidant genes," *Genes*, vol. 11, no. 3, Feb. 2020, Art. no. 242.
[7] S. Paparella et al., "Seed priming: State of the art and new perspectives," *Plant Cell Rep.*, vol. 34, no. 8, pp. 1281–1293, Mar. 2015.
[8] M. Farooq, M. Shahzad, S. M. A. Basra, and M. B. Khan, "Seed priming improves growth of nursery seedlings and yield of transplanted rice," *Arch. Agronomy Soil Sci.*, vol. 53, no. 3, pp. 315–326, May 2007.
[9] D. Panda and S. Mondal, "Seed enhancement for sustainable agriculture: An overview of recent trends," *Plant Arch.*, vol. 20, no. 1, pp. 2320–2332, 2020.
[10] K. Dziergowska et al., "Soybean germination response to algae extract and a static magnetic field treatment," *Appl. Sci.*, vol. 11, no. 18, Sep. 2021, Art. no. 8597.
[11] I. Ercan et al., "Magnetic field effects on the magnetic properties, germination, chlorophyll fluorescence, and nutrient content of barley (*Hordeum vulgare* L)," *Plant Physiol. Biochem.*, vol. 170, pp. 36–48, Jan. 2022.
[12] X. Luo et al., "Effect of static magnetic field treatment on the germination of brown rice: Changes in α-amylase activity and structural and functional properties in starch," *Food Chem.*, vol. 383, Jul. 2022, Art. no. 132392.
[13] V. N. Binhi and A. B. Rubin, "Theoretical concepts in magnetobiology after 40 years of research," *Cells*, vol. 11, no. 2, Jan. 2022, Art. no. 274.
[14] M. O. Mattsson, M. Simkó, and K. R. Foster, "5G new radio requires the best possible risk assessment studies: Perspective and recommended guidelines," *Front. Commun. Netw.*, vol. 2, Sep. 2021, Art. no. 49.

[15] K. Karipidis, R. Mate, D. Urban, R. Tinker, and A. Wood, "5G mobile networks and health-a state-of-the-science review of the research into low-level RF fields above 6 GHz," *J. Exposure Sci. Environ. Epidemiol.*, vol. 31, no. 4, pp. 585–605, Jul. 2021.
[16] *WHO's Agenda for Electromagnetic Fields Research. Health Effects of Static and Time Varying Electric and Magnetic Fields*, World Health Organization, Mar. 1997. [Online]. Available: https://www.who.int/publications/i/item/WHO-EHG-98-13
[17] O. Zeni and M. R. Scarfì, "Experimental requirements for in vitro studies aimed to evaluate the biological effects of radiofrequency radiation," in *Microwave Materials Characterization*, S. Costanzo Ed. London, U.K.: IntechOpen, 2012, pp. 121–138.
[18] M. Simkó, D. Remondini, O. Zeni, and M. R. Scarfi, "Quality matters: Systematic analysis of endpoints related to 'cellular life' in vitro data of radiofrequency electromagnetic field exposure," *Int. J. Environ. Res. Public Health*, vol. 13, no. 7, Jul. 2016, Art. no. 701.
[19] A. Vashisth and D. K. Joshi, "Growth characteristics of maize seeds exposed to magnetic field," *Bioelectromagnetics*, vol. 38, no. 2, pp. 151–157, Nov. 2017.
[20] A. Aladjadjiyan, "Influence of stationary magnetic field on lentil seeds," *Int. Agrophys*, vol. 24, no. 3, pp. 321–324, Apr. 2010.
[21] S. Kataria, L. Baghel, M. Jain, and K. N. Guruprasad, "Magnetopriming regulates antioxidant defense system in soybean against salt stress," *Biocatalysis Agricultural Biotechnol.*, vol. 18, Mar. 2019, Art. no. 101090.
[22] J. Bhardwaj, A. Anand, and S. Nagarajan, "Biochemical and biophysical changes associated with magnetopriming in germinating cucumber seeds," *Plant Physiol. Biochem.*, vol. 57, pp. 67–73, Aug. 2012.
[23] D. Poinapen, D. C. Brown, and G. K. Beeharry, "Seed orientation and magnetic field strength have more influence on tomato seed performance than relative humidity and duration of exposure to non-uniform static magnetic fields," *J. Plant Physiol.*, vol. 170, no. 14, pp. 1251–1258, Sep. 2013.
[24] E. Martinez, M. V. Carbonell, and J. M. Amaya, "A static magnetic field of 125mT stimulates the initial growth stages of barley (*Hordeum vulgare* L.)," *Elect. Magnetobiology*, vol. 19, no. 3, pp. 271–277, Sep. 2000.
[25] A. C. Morillo-Coronado, H. G. Martínez-Anzola, J. D. Velandia-Díaz, and Y. Morillo-Coronado, "Effects of static magnetic fields on onion (Allium cepa L.) seed germination and early seedling growth," *Revista de Ciencias Agrícolas*, vol. 39, no. 1, pp. 30–41, Jun. 2022.
[26] S. Kataria, M. Jain, D. K. Tripathi, and V. P. Singh, "Involvement of nitrate reductase-dependent nitric oxide production in magnetopriming-induced salt tolerance in soybean," *Physiol. Plantarum*, vol. 168, no. 2, pp. 422–436, Feb. 2020.
[27] C. Juchem and R. A. de Graaf, "B_0 magnetic field homogeneity and shimming for in vivo magnetic resonance spectroscopy," *Anal. Biochem.*, vol. 529, pp. 17–29, 2017.
[28] M. Sarraf et al., "Magnetic field (MF) applications in plants: An overview," *Plants (Basel)*, vol. 9, no. 9, Sep. 2020, Art. no. 1139.
[29] M. Sarraf et al., "Effect of magnetopriming on photosynthetic performance of plants," *Int. J. Mol. Sci.*, vol. 22, no. 17, Aug. 2021, Art. no. 9353.
[30] S. S. Araújo et al., "Physical methods for seed invigoration: Advantages and challenges in seed technology," *Front. Plant Sci.*, vol. 7, May 2016, Art. no. 646.
[31] R. R. Sokal and F. J. Rohlf, *Biometry*. San Francisco, CA, USA: Freeman, 1969.
[32] A. Caciagli, R. J. Baars, A. P. Philipse, and B. W. M. Kuipers, "Exact expression for the magnetic field of a finite cylinder with arbitrary uniform magnetization," *J. Magnetism Magn. Mater.*, vol. 456, pp. 423–432, Jun. 2018.
[33] *International Electrotechnical Commission, "Safety of magnetic resonance equipment for medical diagnosis,"* IEC-60601-2-33, IEC, Geneva, Switzerland, 2002.
[34] International Commission on Non-Ionizing Radiation Protection, "Guidelines on limits of exposure to static magnetic fields," *Health Phys.*, vol. 96, no. 4, pp. 504–514, 2009.
[35] N. D'Ambrosio, G. Chirico, C. D'Elia, M. Rapesta, V. Mancuso, and R. Massa, "Magneto-priming improves germination in *capsicum annuum L.*," in *Proc. VI Int. Conf. Essential Mol. Biol. Nat. Congr. Proc.*, 2022.

Gaetano Chirico received the biomedical engineering degree (*summa cum laude*) from the University of Naples "Federico II," Naples, Italy, in 2021. He is currently working toward the Ph.D. degree in methods, models, and technologies for engineering with the Univeristy of Cassino and Southern Lazio, Cassino, Italy. After the graduation degree, he started a collaboration with the Department of Physics "Ettore Pancini" of the University of Naples "Federico II" and with the Department of Electrical and Information Engineering (DIEI) "Maurizio Scarano" of the Univeristy of Cassino and Southern Lazio.

Claudio D'Elia received the graduation degree in physics from the Alma Mater Studiorum University of Bologna, Bologna, Italy, in 2014. In 2019, he was the Holder of the research grant entitled Applications of innovative technologies with very low environmental impact in the agri-food sector as part of the CARPE-FIME project (PSR Campania 2014–2020) with the University of Naples "Federico II." His research focuses on MRI hardware.

Nicola D'Ambrosio received the graduation degree in biological sciences from the University of Naples Federico II, Naples, Italy, in 1985 with full marks cum laude discussing an experimental thesis in Ecology. Since March 1991, he has been a Researcher of plant ecology with the Department of Plant Biology, University of Naples Federico II. In November 2002, he was appointed as an Associate Professor of environmental and applied botany with the Department of Biology, University of Naples Federico II. His study and research interests include study of the ecophysiology of photosynthesis and limitations of the photosynthetic process in response to the main environmental factors. His main research includes: definition of stomatal and non-stomatal limitations of photosynthesis in response to water stress; study of the photoprotective mechanisms of the photosynthetic apparatus in conditions of excessive light absorption; effects of exposure of seeds and plants to ionizing radiation for the use of plants in bio-regenerative systems to support life in space; seed invigoration techniques by exposure to SMF; effects of exposure to MF and EMF on germination, plant development and photosynthetic activity.

Rita Massa received the bachelor's degree in physics and the Ph.D. degree in electronic and computer science from the University of Naples "Federico II," Naples, Italy, in 1983 and 1987, respectively. In 2001, she became a Professor of electromagnetic fields with the University of Naples "Federico II." She is currently with the Department of Physics, and the Chief of Non-Ionizing Radiation Laboratory. Since 2017, she has been the Director of the Interuniversity Center for the Study of Interactions between Electromagnetic Fields and Biosystems (ICEmB), University of Genoa, Genoa, Italy. She has coauthored more than 200 papers published in peer-reviewed journals, proceedings, and conference papers. Her research interests include the interactions of electromagnetic fields and materials, dealing with the biological effects, electromagnetic dosimetry/exposure assessment, therapeutic and industrial applications of electromagnetic fields, and nondestructive testing of materials. She has been involved in research projects (some in cooperation with small, medium, and/or great enterprises) for which she played and is currently playing the role of scientific coordinator/WP Leader.

Open Access funding provided by 'Universitá degli Studi di Napoli 'Federico II'' within the CRUI CARE Agreement