Soybean (Glycine max) germination response to Static Magnetic Field treatment

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Abstract

Soybean (*Glycine max* (L.) Merrill) is known as the plant-based protein source for human and animal consumption. Its high protein content emphasizes to meet recent demands to achieve higher yields and more protein production in a organic manner to reduce the usage of chemicals in agriculture. So, the focus of present research is to look over the effect of the static magnetic field (SMF) treatment on soybean seeds, to get a greater number of germinated seeds and improved growth parameters. It is assumed that the application of magnetic field helps to overcome seed dormancy. The parameters examined in this experiment were germination percentage (GP), seedling growth (root and shoot length) and chlorophyll content. Four different soybean cultivars of various earliness (Abelina, Adelfia, Adessa, and Pamela) were tested. The exposure time of seeds to the static magnetic field was 3 and 12 min, whereas the dose of the magnetic induction applied directly to seeds was 250 and 500 mT. The following combinations were tested on seeds: 250 mT + 3 min, 250 mT + 12 min, 500 mT + 3 min, 500 mT + 12 min and control group (seeds not subjected to any treatment). Among the soybean tested varieties, Abelina showed the best results in terms of germination percentage for all tested groups, while Adelfia variety recorded significantly the highest increase in the percentage of germinated seeds – 79% (for the group 500 mT + 3 min) compared to the control group (55%). In the same group (500 mT + 3 min), Adelfia seedling growth parameters and chlorophyll content found positive results in relation to all tested groups and untreated seeds (control). The application of a static magnetic field as a physical treatment to plant seeds is a promising approach for improving emerging parameters such as germination percentage, seedling growth and development, and chlorophyll content.

Introduction

Soybean is one of the legume plants which is highly adaptable, nutritious and crucial in commercial usage[1]. This soybean is native to East Asia and becoming one of the greatly shaped modern agriculture in the world[2]. What is more, it has been an important nutritional part of the diet of many people living in China, Japan, Korea, the Philippines, and Indonesia, among others, through various types of products such as milk, tofu, and cheese. Soybeans provide all nine of the essential amino acids due to its unique kind of plant-based complete protein. Beyond food, soybean also contributing to the worlds edible oil production (25%) and biggest contributor of about two-thirds of protein used in animal feed worldwide[3].

It is worth mentioning that soybean has developed into the fourth most important and fastest growing crop in the world, after rice, wheat, and corn, in terms of global production. According to the estimation of the International Grains Council-IGC 2024, it can be observed that the global soybean cultivation, which reached 357 million tons in the 2021/22 season, has gained 10 million tons in the 2022/23 season, giving a total of 367 million tons[4]. It was speculated that this trend will carry over until the 2023–2024 season, when the production is expected to be superior to current levels[4]. To satisfy the demand for soybean growing in the future, high-quality seeds are needed to achieve maximum germination rates and to continue an increase in plant production. According to Lewandowska et al.[19], soybean cultivation for many farmers is considered as "godsend" for correcting imbalanced crop rotations, which typically consist of cereals, maize, and rapeseed, but also a crop with some fascinating hidden attributes. This plant has another amazing feature that can fix atmospheric nitrogen by symbiotic association with soil bacteria (*Bradyrhizobium japonicum*), reducing the need for nitrogen mineral fertilizers and promoting soil health. In addition, soybean is a nutritious crop and also provides food for humans and feed for farm animals.

Nowadays one of the major challenges in the seed production sector is to eliminate the use of chemicals in agriculture to protect nature but also to get higher yields and better germination percentage. Still one of the major environmental problems that the world is facing at present is the increasing chemicalization of agriculture that through long-term consumption in food may lead to dangerous health problems[5,27]. Such practices not only harm the soil responsible for being incapable of producing nutritious crops, but also contaminate food, gradually poisoning both humans and animals with harmful chemicals. In the 21st century, modern agriculture is facing the challenge of using natural resources wisely in the process of finding safe ways to improve crop quality. One of the key factors to boost crop yields is the preparation of seed material by using safe conditioning methods. This helps to improve plant germination and makes seedlings stronger, more efficient for growing. Nowadays soybean seeds are often treated with insecticides, pesticides, beneficial bacterial to improve nitrogen fixation and protect against pathogens. However, Sartori's[68] recent study, provided that agrochemical seed treatments might disturb the rhizobial survival, nodulation process, and limits consequently plant health and yield[68].

The most important step in establishing healthy seedlings for successful crop production is the process of seed germination[4]. Seed quality plays a significant role in crop growth affected by environmental factors during germination, plant growth, maturation, and storage after harvest. Germination is a complex physiological process that starts when seeds absorb water and ends with the radicle emergence[6]. Increasing the germination rate is at present a challenge for modern farming. As a result, seed companies are constantly looking for new solutions to improve seed germination, vigour, seedling strength, and crop yield. This has led to more studies into different seed improvement methods.

Since soybean is very popular, researchers continue to explore new techniques for promoting and stimulating its growth. One of the ways to enhance the seed production sector involves the use of physical stimulation factors. Physical methods used for improving seed quality include exposure to electromagnetic induction (such as infrared, ionizing, laser, or ultraviolet) or the application of various types of fields including magnetic, electric, or electromagnetic[7].

The main goal of this research is to look for alternative and safe solutions for soybean growth stimulation that will not cause negative effects on nature or significantly reduce them. According to Kataria et al.[8] treating the seeds with a magnetic field before sowing is considered as eco-friendly technology that is healthy for both the environment and plants. Analysing various types of magnetic field, static magnetic field is constant and unchanging in nature. What is more, SMF can stimulate seed germination by affecting only the seeds, hence emergency dynamics are enhanced and protecting seedling growth. The outcomes of such treatments include greater plant vigor, emergence and higher yield[8,9]. Also, in Radhakrishnan's research pointed out the interest of magnetic field (MF) applications particularly in agricultural science, where studies have examined MF's influence on seed germination, biochemical and hormonal changes, plant development, and final crop yield. Although a more research is necessary to clarify the underlying cellular and tissue-level mechanisms of magnetic action[16]. However, examples from many scientists demonstrate the positive impact of static magnetic fields on soybean seeds and other legume species (Table 1).

Table 1
Effect of SMF on different legume plant species.

Magnetic Induction [mT]	**Exposure Time**	**Plant Species**	**Effects on plants**	**Ref.**
200 mT	1 h	soybean (*Glycine max*)	improved growth, carbon and nitrogen fixation in soybean; improvement in seedling growth, development and production of soybean (F) as compared to control	(10)
400 mT + E	3 min	soybean (*Glycine max*)	enhanced germination percentage (86%) as compared to control (83%) (L)	(11)
250 mT	3 min	soybean (*Glycine max*)	increased germination percentage (90%), seedlings length and weight, and pigments content in leaves over control (85%) (L)	(9)
0.1 mT	20 min for the next 5 days	soybean (*Glycine max*)	significant increase in optimum values of germination emergence time, stem growth, chlorophyll content, early flowering time, fresh weight of 10 seeds, and productivity (F) as compared to control	(13)
400 mT + E	12 min	soybean (*Glycine max*)	positive results in terms of mean germination percentage (21%) as compared to control (9%) (L)	(12)
200 mT	60 min	soybean (*Glycine max*)	improvement in rate of photosynthesis (L) as compared to control	(8)
200 mT	60 min	soybean (*Glycine max*)	pre-treatment of seeds with a SMF influenced on seedlings growth and development (root length, plant height, biomass accumulation, rate of photosynthesis) which eventually results in high crop yield (F) as compared to control	(18)
500 mT	3 min	soybean (*Glycine max*)	increased root, epicotyl, hypocotyl, and chlorophyll content (L) as compared to control	(9)
100 mT	2 h	chickpea (*Cicer arietinum*)	better result observed in root and shoot length, dry matter of root and shoot, and seedling vigor were significantly increased (L) as compared to control	(14)
100 mT	1 & 2 h	chickpea (*Cicer arietinum*)	increased all germination-related characteristics such as germination percentage (94%), speed of germination, shoot and root length, seedling dry weight and vigor indices compared to control (85%) (L)	(22)
Where: Control-untreated seeds, L - laboratory experiment, F - field experiment, P - pot experiment, MF - magnetic field, SMF - static magnetic field, E - extract of algae, mT - Millitesla				

Magnetic Induction [mT]	Exposure Time	Plant Species	Effects on plants	Ref.
100 mT	1 h	chickpea (*Cicer arietinum*)	exposure of seeds to MF showed higher germination percentage (95%), seedling root and shoot length and dry weight; enhanced root and shoot growth parameters compared to control (88%) in the greenhouse experiment (L)	(15)
Where: Control-untreated seeds, L - laboratory experiment, F - field experiment, P - pot experiment, MF - magnetic field, SMF - static magnetic field, E - extract of algae, mT - Millitesla				

The aim of this research was to examine the effect of static magnetic field treatment on seed germination, early growth and development of four cultivars of soybean (*Glycine max*) – Adelfia, Adessa, Pamela and Abelina coming from growing season 2023. It was hypothesized that the physical factor, which is SMF would significantly improve soybean germination and early growth parameters under laboratory conditions.

Materials and methods

Soybean seeds

Soybean seeds (*Glycine max*), cv. Adelfia, Adessa, Pamela, and Abelina (not genetically modified) of uniform size were used in the present study. The seeds were obtained in 2023 from SAATBAU Polska plant breeding station located in Poland. They were certified. Different genotypes were chosen of varied maturity groups: Adelfia — according to breeders — is a medium late variety, rich in protein and oil content, with high growth potential in low-yielding plants. Adessa is a very early and early variety. It is distinguished by its high fat and protein content, very high early vigor, tolerance to cold weather and resistance to lodging. It also has very good resistance to pod cracking. Pamela is an early to mid-early cultivar, so it is recommended for cultivation throughout the country - Poland with a guarantee of ripening at the optimum time. It has been confirmed in official and breeding experiments about its high yield potential, high-set of first pod, and excellent health (as per the manufacturer’s information). The last tested variety - Abelina belongs to the group of early varieties and is distinguished by its high yield potential and exceptional percentage over years. It is a purple flowering variety with a dark stigma that reaches very early maturity. Due to its very intensive early vigor, Abelina obtains a medium to high density of plants and is regarded as the best yielding genotype in relation to the length of the vegetation period. In terms of quality, it is a variety with a very high-fat content and a high protein yield.

Exposure of soybean seeds to a static magnetic field

Before stimulation with SMF, soybean seeds were grouped by 100 pcs. Next stimulation with a MF was carried out using SMF with an induction of 250 mT and 500 mT. Permanent NdFeB magnets were used in the experiment. During the stimulation process a special container was used, which allowed to ensure a constant value of the magnetic field vector on the seeds during the magnetization process. Exposure times of 3 and 12 min were used for seed stimulation. Differences in the exposure times result from literature reports and are close to those in which the best positive effects were recorded [55,56,57,59–61]. After stimulations the seeds were delivered to the laboratory for sowing on paper substrate. The experimental groups examined in the present study are listed in Table 2.

Table 2
Tested experimental groups.

Group	Treatments (N = 4)
1.	Soybean seeds-Control (C)
2.	Soybean seeds-SMF 250 mT + 3 min
3.	Soybean seeds-SMF 250 mT + 12 min
4.	Soybean seeds-SMF 500 mT + 3 min
5.	Soybean seeds-SMF 500 mT + 12 min

Preliminary test of soybean seeds

In order to check general germination percentage of raw soybean seeds (without treatment), preliminary tests were conducted before the main experiment. 50 seeds from each soybean variety were sown using two different methods of filter paper substrate – between paper (BP) and pleated paper (PP) to choose the best option. The substrate was soaked in the distillated water. Preliminary test showed the visible germination and seedling growth in pleated paper method over between paper (Fig. 1). Figure 1 presents germination process based on selected variety-Abelina. The same tests were performed for other three varieties and results were the same as for Abelina (PP was a better substrate than BP).

Germination tests

The germination test of soybean seeds was assessed according to the International Seed Testing Association (ISTA) methodology. These tests were performed under laboratory conditions in a growth chamber (FITO, Biogenet, Poland) at a constant temperature of 25°C. A pleated paper substrate was used to conduct the germination experiment, which was carried out in 4 replications for each analysed variety. Each replication contained 100 soybean seeds. According to ISTA, the first counting (energy of seedlings) was done after 5 days and the second one (germination of seedlings) after 8 days. Based on ISTA rules, after 8 days seeds were segregated into normal seedlings and abnormal seedlings (Fig. 2). Seed germination was calculated and expressed in percentage. The minimum germination limit for soybean is 80% (in accordance with ISTA regulation). Soybean germination is considered as epigeal because cotyledons are pulled above the soil. The hypocotyl (part of the stem below the cotyledon) elongates while the length of the epicotyl (part of the stem above the cotyledon) remains the same. The following parameters were analysed in germination tests based on 30 seedlings selected randomly from each repetition: root length, hypocotyl length and chlorophyll content (SPAD).

The soybean seedling is regarded as normal, when the primary root is undamaged or has minor damage in the form of discoloration, cracks, spots or splits. Besides, a seedling can be classified as normal even when the primary root is damaged or missing, but normal secondary roots are developed enough. Tiny defects or undamaged seedlings are accepted like discoloration, spots, splits and surface cracks,. The cotyledons are undamaged or have small defects (according to the current 50% rule, no more than 50% of the total surface might be damaged), there may be even three cotyledons or only one normal cotyledon, provided that it is not damaged and healthy. What is more, the first leaves are undamaged or have small defects (in accordance with the current 50% rule, no more than 50% of the total surface may be damaged), there might be three leaves or only one normal leaf provided that it is not damaged. It is worth adding that the top bud should not be damaged. A seedling is defined as abnormal (with defects) if it is broken, deformed, de-structured, white or yellow, glassy, or rotten as a result of primary infection. Abnormal seedlings are always rejected for biometrical analysis and in natural conditions will never develop in a well-structured plant.

The main purpose of this research is to check whether seeds exposure to a SMF (1) enhances soybean germination and seedling growth compared to untreated seeds, (2) better stimulates the soybean tested parameters (3) and which varieties from tested plant species are showing the best biometric parameters.

Statistical analysis

Statistica version 13.0 (TIBCO Software Inc., Tulsa, Ok, USA) was used to elaborate the obtained results statistically. Basic statistical analysis (mean and standard deviation) of all tested groups was carried out. The Shapiro-Wilk test was used to estimate the normality of the experimental results distribution and the Brown and Forsythe test to estimate the homogeneity of the variances. The one-way analysis of variance (ANOVA) with Tukey multiple comparison test (assuming normal distribution and equal variances homogeneity) was used in determining the differences between groups. In case of normal distribution and homogeneity of variances are not met, Kruskal-Wallis test (non-parametric test) was used. $p < 0.05$ was considered as statistically significant.

Results and Discussion

Present research focused on exposure of soybean seeds to static magnetic fields to increase germination percentage, growth parameters (root and shoot length), and chlorophyll content in leaves.

Figure 3 shows the results of the study on how static magnetic field stimulation influenced soybean seeds in comparison with control. In crop production, seed germination is a crucial phase because most of the time seed faces dormancy that slows germination[53,61,62]. Dormancy may be broken by traditional chemical methods and improve germination, but repeated use harms soil, microorganisms, the environment, and human health[54,63,64,44]. According to Hu et al.[26], Pawelek et al.[27] and Sarraf et al.[28], stated that SMF is one of the physical factors, which gives promising results on plant seedling growth and development[26–28]. Recent years, physical methods like static magnetic fields have been working as a safe, eco-friendly alternatives[40,44]. SMF may impact seed structurally, genetically, and biochemically, depending on parameters like intensity, duration, and plant type[16,40,44]. SMF treatments have been shown to improve germination, seedling growth, and chlorophyll content in many crops such as barley, soybean, cucumber, wheat, and maize[4,6,8,9,38,39].

Effect of SMF on soybean seeds germination percentage

Figure 4 shows the effect of different exposure times (3 and 12 minutes) of soybean seeds to a static magnetic field with different magnetic induction values (250 and 500 mT) on seeds germination percentage.

Generally, in all tested experimental groups (250 mT + 3 min, 250 mT + 12 min, 500 mT + 3 min, 500 mT + 12 min), the percentage of seed germination of all tested soybean varieties was higher than in the control group (except for the Abelina variety in 250 mT + 12 min group). Among the soybean tested varieties, the highest seed germination percentage for all tested groups (with exception of the 250 mT + 12 min group) was achieved for the Abelina variety, followed by Adessa, Pamela, and Adelfia. For almost all experimental groups, the order of seed germination was the same for the different soybean varieties: Abelina, then Adessa, Pamela, and Adelfia. Only in the 250 mT + 12 min group, three soybean varieties – Abelina, Adessa, and Pamela – had similar seed germination percentage and the highest value of germination percentage was obtained for Adessa cultivar. Overall, Adelfia seeds had the lowest germination percentage (55%) in the control group, nonetheless a significant increase in seeds GP for this variety was noted among tested groups, especially with stimulation at 250 mT + 12 minutes (79%).

The effect of exposure time on soybean seed germination for a constant magnetic induction value of 250 mT

When comparing the seed exposure time of 3 and 12 min to the magnetic field (250 mT), the germination percentage of the seeds of the Adelfia, Adessa and Pamela varieties was comparable, and for the Abelina variety a significantly higher GP was obtained for the exposure time of 3 min than for 12 min.

The effect of exposure time on soybean seed germination for a constant magnetic induction value of 500 mT

Differences in the percentage of germinated seeds depending on the exposure time – 3 and 12 minutes for a constant magnetic induction value of 500 mT were more visible than for an induction of 250 mT. Higher GP values were obtained for the 3-minute exposure time compared to the 12-minute time for all tested soybean varieties. Generally, it was observed that a shorter seed stimulation time with a magnetic field of a given induction (250 or 500 mT) determines higher GP values than a longer seed exposure time to this factor.

The effect of the magnetic field induction value on the soybean seed germination for an exposure time of 3 min

With shorter exposure times of seeds to a static magnetic field, the magnetic field induction value does not significantly affect GP. For the Adessa, Pamela, and Abelina varieties, GP results for 3-minute exposure time and inductions of 250 and 500 mT are comparable. Only for the Adelfia variety, higher results were obtained for the 500 mT SMF.

The effect of the magnetic field induction value on the soybean seed germination for an exposure time of 12 min

For a 12-minute exposure time of soybean seeds to a magnetic field, the GP was higher for 250 mT magnetic induction than for 500 mT for three tested varieties, except for Abelina.

Based on the conducted research, the Adelfia variety can be recommended for further research and pre-sowing seed stimulation with a magnetic field with a magnetic induction of 500 mT for 3 minutes.

Similarly, in the work of Dziergowska et al.[9] the influence of SMF (250 mT + 3 min) on the process of soybean seeds germination showed significantly better germination stage (90%) compared to control (85%)[9]. Lewandowska et al.[12] used a 400 mT magnetic field induction and exposure time for 3 min along with macroalgal extract to soybean seeds and showed that GP was increased in comparison with control. Pre-treatment of chickpea seeds with SMF (100 mT for 1 h) significantly enhanced GP and growth parameters (root and shoot length, and vigor indices) under different levels of salinity[51]. Chickpea seeds also showed improvement in germination rate and seedling growth after being treated with SMF with induction of 100 mT for 1 h[15]. Katsenios et al.[25] treated durum wheat seeds with MF (12.5 mT for 45 min), while the author Luo et al.[17] research explained that the brown rice seeds exposed to SMF (10 mT for 60 mins) has increased (81%)[25] of its GP in comparison with control[17]. Few researchers also proved that speed of seeds germination and germination percentage increased by using magnetic field as a seed treatment in crops like barley[66] and wheat[67]. Moreover, high- intensity magnetic field treatment (250 mT for 20 min) on tomato seeds found positive results of germination percentage (95%) than untreated seeds[41], which the authors explained in their research that the reason was an improved absorption of nutrients and then enhanced use of food reserves and more efficient water uptake when the seeds were exposed to high magnetic induction[41].

Effect of SMF on soybean growth parameters: root length (RL), shoot length (SL) and chlorophyll content in leaves

Table 2 presents that the magnetic intensity had a great impact on seedling growth characteristics. Among all the tested groups (250 mT + 3 min, 250 mT + 12 min, 500 mT + 3 min, 500 mT + 12 min), the length of seedling’s root was higher than untreated groups (control) in except for low inductions (250 mT) for Abelina and high inductions (500 mT) for Pamela cultivar. The longer roots were measured in the varieties like Abelina and Pamela under lower exposure time (3 min) than in the control groups of tested varieties. In the case of the shoot length (SL) parameter, significantly higher shoot lengths were observed in the experimental groups compared to the control group, with the exception of the group 250 mT + 12 min of the Abelina variety, which showed shorter lengths than in the control group. The longest SL was found for lower exposure time (3 min) in few cases for Adessa (250 mT + 3 min and 500 mT + 3 min), and Abelina (250 mT + 3 min and 500 mT + 3 min) varieties. Whereas, Adelfia does not show any significant differences between the control and tested groups. In the case of chlorophyll content, the higher chlorophyll content was found almost for all the tested groups than in the control group. But in some cases, lower chlorophyll content was noted especially for lower exposure time (3 min) of Pamela and Adessa seeds with the intensity of 250 and 500 mT. Unfortunately, Abelina variety did not react in any of the tested groups compared to control.

Table 3
Root length (RL), epicotyl length (EL), hypocotyl length (HL), shoot length (SL) and chlorophyll content in leaves of different soybean cultivars grown from seeds treated with SMF - interaction effects.

Interaction effect (Treatments* variety)	**Root length (cm)**	**Hypocotyl length (cm)**	**Epicotyl length (cm)**	**Shoot length (Hypocotyl + Epicotyl) (cm)**	**Chlorophyll content**
	mean ± SD				
Control*Adelfia	9.0 ± 2.8^{f}	5.6 ± 0.9^{gh}	1.0 ± 0.7^{h}	6.6 ± 1.4^{h}	37.19 ± 11.44^{cd}
Control*Adessa	10.7 ± 3.1^{cdef}	5.2 ± 1.3^{h}	2.0 ± 0.9^{efg}	7.1 ± 1.7^{gh}	$30.13 \pm 6.53ef^{g}$
Control*Pamela	12.4 ± 4.2^{abc}	6.1 ± 1.5^{fg}	1.0 ± 0.7^{h}	7.1 ± 2.0^{gh}	$24.82 \pm 7.07f^{gh}$
Control*Abelina	11.6 ± 4.0^{abcd}	7.4 ± 1.5^{d}	2.6 ± 0.7^{cde}	10.0 ± 1.9^{d}	28.67 ± 6.73^{efg}
SMF 250 mT + 3 min*Adelfia	9.2 ± 3.6^{ef}	7.2 ± 1.3^{de}	2.4 ± 1.2^{de}	9.7 ± 2.2^{d}	43.60 ± 11.20^{bc}
SMF 250 mT + 3 min*Adessa	11.0 ± 3.8^{cdef}	8.6 ± 1.5^{c}	4.4 ± 2.0^{b}	13.0 ± 2.9^{b}	32.18 ± 9.39^{de}
SMF 250 mT + 3 min*Pamela	13.4 ± 5.2^{a}	9.4 ± 1.7^{b}	2.2 ± 1.9^{ef}	11.6 ± 2.9^{c}	23.89 ± 6.30^{gh}
SMF 250 mT + 3 min*Abelina	11.4 ± 3.5^{abcd}	11.2 ± 1.4^{a}	2.9 ± 1.1^{cd}	14.1 ± 2.0^{b}	20.92 ± 5.85^{h}
SMF 250 mT + 12 min*Adelfia	10.9 ± 4.5^{cdef}	6.9 ± 1.0^{de}	3.0 ± 1.6^{cd}	9.9 ± 2.3^{d}	41.90 ± 11.62^{c}
SMF 250 mT + 12 min*Adessa	10.9 ± 3.8^{cdef}	5.7 ± 1.0^{gh}	2.4 ± 1.0^{de}	8.1 ± 1.6^{fg}	39.17 ± 6.16^{c}
SMF 250 mT + 12 min*Pamela	13.2 ± 4.8^{ab}	6.7 ± 1.1^{ef}	1.4 ± 1.3^{fgh}	8.2 ± 1.9^{fg}	$31.27 \pm 8.43d^{ef}$
SMF 250 mT + 12 min*Abelina	11.2 ± 4.1^{bcde}	6.6 ± 1.1^{ef}	1.9 ± 0.6^{efg}	8.5 ± 1.4^{ef}	26.62 ± 7.72^{efgh}
SMF 500 mT + 3 min*Adelfia	11.1 ± 4.0^{bcde}	7.3 ± 1.0^{de}	2.5 ± 1.3^{cde}	9.8 ± 1.9^{d}	49.48 ± 11.32^{ab}
SMF 500 mT + 3 min*Adessa	10.7 ± 3.1^{cdef}	9.5 ± 1.3^{b}	6.2 ± 3.0^{a}	15.7 ± 3.4^{a}	24.94 ± 6.31^{fgh}
Where: a, b, c…- differences statistically significant for $p < 0.05$					

Interaction effect (Treatments* variety)	Root length (cm)	Hypocotyl length (cm)	Epicotyl length (cm)	Shoot length (Hypocotyl + Epicotyl) (cm)	Chlorophyll content
	mean ± SD				
SMF 500 mT + 3 min*Pamela	9.9 ± 3.6^{def}	8.2 ± 1.5^{c}	1.4 ± 1.0^{gh}	9.6 ± 2.2^{de}	23.23 ± 9.14^{gh}
SMF 500 mT + 3 min*Abelina	13.4 ± 4.7^{a}	10.9 ± 1.7^{a}	2.5 ± 1.2^{de}	13.3 ± 2.4^{b}	24.78 ± 9.63^{fgh}
SMF 500 mT + 12 min*Adelfia	9.0 ± 3.1^{f}	6.2 ± 1.0^{fg}	1.4 ± 2.4^{gh}	7.6 ± 2.8^{fgh}	53.04 ± 13.15^{a}
SMF 500 mT + 12 min*Adessa	10.0 ± 3.4^{def}	5.3 ± 0.7^{h}	2.5 ± 1.3^{cde}	7.9 ± 1.6^{fg}	40.29 ± 7.60^{c}
SMF 500 mT + 12 min*Pamela	10.4 ± 4.0^{cdef}	7.5 ± 1.7^{d}	2.0 ± 1.2^{efg}	9.5 ± 2.6^{de}	31.54 ± 7.03^{def}
SMF 500 mT + 12 min*Abelina	11.9 ± 4.2^{abcd}	8.2 ± 1.3^{c}	3.3 ± 0.9^{c}	11.5 ± 1.8^{c}	28.09 ± 7.63^{efg}
Where: a, b, c…- differences statistically significant for $p < 0.05$					

The effect of exposure time on soybean root length, shoot length and chlorophyll content for a constant magnetic induction value of 250 mT

Root length (RL) for seedlings of Adessa, Pamela and Abelina varieties of seeds were exposed to 250 mT SMF for 3 and 12 min was similar, but RL for Adelfia cultivar was slightly higher in the group exposed to 12 min of irradiation than to 3 min. In terms of SL, the maximum length of shoot was found in the 3 min exposure time for Adessa, Pamela and Abelina than 12 min. Adelfia variety exhibited almost the same results for both exposure times (3 and 12 min). The chlorophyll content in the leaves of Adessa, Pamela and Abelina was significantly high in the group with a longer exposure time (12 min). Whereas, Adelfia variety has almost equal chlorophyl content in both groups (SMF 250 mT + 3 min and SMF 250 mT + 12 min), but it was higher for 3 min than for 12 min.

The effect of exposure time on soybean root length, shoot length and chlorophyll content for a constant magnetic induction value of 500 mT

For the application of 500 mT SMF, the results were almost the same for both seed exposure times to SMF but were higher for 3 min than for 12 min in Adelfia, Adessa, and Abelina varieties. In the case of Pamela variety, the length of root was higher in the group in which seeds were irradiated for 12 min than for 3 min. Regarding SL, the results were very clear that the dominating exposure time (the highest value of SL) was 3 min over 12 min for all the tested varieties especially in Adessa (significant differences observed). The application of SMF with the induction of 500 mT for 12 min to seeds, increased the chlorophyll content in seedlings in all tested soybean varieties in comparison with the exposure time for 3 min. Longer exposure time (12 min) of seeds to SMF resulted in significantly higher chlorophyll content in seedlings than for shorter time (3 min), due to its potential to trigger the hormonal changes that promote chloroplast development[78], upregulate chlorophyll biosynthesis genes[77], and enhance photosynthetic efficiency[77].

The effect of the magnetic field induction value on the soybean root length, shoot length and chlorophyll content for an exposure time of 3 min

In general, comparing the results of RL of soybean cultivated in the groups treated with 250 and 500 mT SMF for 3 min, were almost parallel to each other in the tested groups. Within the tested varieties, the Adelfia and Abelina variety showed longer roots at high induction (500 mT), whereas Pamela and Adessa variety at 250 mT. For SL, no significant differences were observed between two exposure times but SL of Adelfia and Adessa varieties was higher at 500 mT over 250 mT. For Pamela and Abelina varieties, SL increased in the group treated with SMF at 250 mT in comparison with 500 mT. The dependencies for chlorophyll content were the same as for RL between the tested varieties– For Adelfia and Abelina varieties, higher chlorophyll content was found in the groups treated with higher SMF induction (500 mT), whereas for Pamela and Adessa varieties in the groups with lower induction (250 mT). Notably, statistically significant differences for a given parameter are between two groups (500 mT + 3 min) in Adelfia followed by (250 mT + 3 min) in Adessa.

The effect of the magnetic field induction value on the soybean root length, shoot length and chlorophyll content for an exposure time of 12 min

In the case of longer exposure time of soybean seeds to the magnetic field, the length of roots was higher in the group treated with lower induction (250 mT) than in the case of higher induction of 500 mT for the three tested varieties, except Abelina for which the results were opposite. For SL, Adelfia and Adessa varieties responded well in the groups with 250 mT in comparison with 500 mT but for a Pamela and Abelina, it was opposite. Chlorophyll content in the soybean leaves was higher in the groups treated with SMF with a higher induction (500 mT) than lower (250 mT) for four tested varieties.

In conclusion, based on the conducted experiment, pre-sowing seed stimulation with a magnetic field with a magnetic induction of 500 mT for 3 minutes can be recommended to increase seedling growth and chlorophyll content.

The exact mechanism of growth changes in response to static magnetic fields is not clear, but the production of reactive oxygen species (ROS) and their scavengers might play an important role in plants' responses to magnetic treatment[20,21,17]. ROS contain oxygen and act as a highly reactive molecules. In fact excess ROS accumulation leads to damaging cells and oxidative stress. However, it functions as an essential signaling roles in plant growth and stress responses when it is balanced[20]. Plant seeds could respond differently to SMF, may vary depending on the plant variety and specific conditions, such as the induction and duration of SMF exposure. Generally, many researchers have conducted experiments on magnetic fields and reported that the magnetic seed treatment can explain how electromagnetism affects plants by influencing light, heat, and chemical processes[30,33,34]. Seeds stimulated by electric or magnetic fields can either help or harm their growth. Electric fields cause the movement of water and nutrients in plants, thereby enhancing growth. Similarly, magnetic fields can improve seed sprouting and seedling length by affecting particles (such as ions: Ca^2, K, H, and Cl, as well as electrons and free radicals, which in turn influence metabolism, water movement, and growth processes)[69] in plant cells[44]. But, too much exposure to fields can stress plants and slow their seedling growth as mentioned in the research of Morillo-Coronado[44]. So, according to Morillo-Coronado et al.[44] low magnetic exposure improved seed germination and seedling growth of onion seeds stimulated with magnetic field (21 mT and 10 mT for 1h). Statistically significant differences were observed for examined parameters in all tested groups as compared to control[44].

Having longer roots, especially with many lateral roots, are beneficial for up-taking nutrients which are located in the soil[34]. So far, studies suggest that static magnetic fields significantly improve root length due to its inherent potential making more resistant to environmental stresses. A deep rooting system enables plants to get water, which is quite beneficial in a drought situation[35,36]. Previous studies proved that application of SMF (200 mT for 1 h) on soybean seeds improved the root growth[40]. Likewise, studies on the exposure of magnetic induction on seeds like maize (*Zea mays* L.)[43]and sun flower (*Helianthus annus*)[48] showed that there was a significant improvement in root length compared to untreated seeds (control) under laboratory conditions[43,48]. According to the author[43], root length of maize was increased doubled under pre-sowing exposure of seeds to magnetic fields (200 mT for 1 h) in comparison with the control. Similar results were obtained for maize (*Zea mays* L.) and barley (*Hordeum vulgare* L.), where seed treatment with SMF (200 mT for 1 h) in maize and (125 mT) in barley caused the significant increase in the length of the root system, root diameter and root dry weight[42,47]. The increase in root length in plants grown from seeds treated with SMF is consistent with the results of previous studies, which showed the enhancement of the growth of plant in species such as soybean[56] and lentils[20].

Research results indicate that treating seeds with a magnetic field affects the shoot length. Magnetically stimulated seeds with lower exposure time (3 min) had the better results in terms of shoot length of soybean seedlings compared to control[9]. Corresponding results were observed in a current study that static magnetic fields boost up the shoot growth in soybean seedlings, when seeds were exposed to a shorter time (3 min). Same as in chickpea seeds stimulated with different doses and exposure time of SMF, has significant differences in terms of shoot length interaction with shorter exposure time[22]. According to Maffei[45], high exposure magnetic fields can slow down shoot growth in plants because it disrupts important processes inside plant cells: like cell division and cell elongation[45]. Seeds stimulated by strong MF intensities can cause oxidative stress, which leads to an increase in harmful molecules called reactive oxygen species[20,21]. These molecules act against growth and plant cells. For example, strong magnetic fields find difficulties with the distribution of auxins (the hormones that help plants grow), which leads to stunted shoot development[28]. Moreover, longer duration can interact with the movement of nutrients and water inside the plant, further slowing down growth[28,45,44].

Chlorophyll is necessary in the development of seedlings growth and health. It directly influences the germination percentage to absorb energy from sunlight (photosynthesis process). Moreover, higher chlorophyll content in the leaves nurture better growth and structure of the plant. Chlorophyll content in the leaves after seed treatment with an SMF has been an area of interest in plant physiology, as chlorophyll is vital for photosynthesis and plant growth[46]. Ercan et al.[47] used the magnetic fields of 20, 45, 125, 250 mT, in which 20 mT improved the chlorophyll content of barley (*Hordeum vulgare*) in comparison with untreated seeds. In this case, the highest chlorophyll content was observed in low magnetic induction of 20 mT, whereas the lowest content for 250 mT [47]. However, in few publications and present research observed that chlorophyll content was higher in the leaves of soybean (*Glycine max*)[9,11], maize (*Zea mays*)[48], sunflower (*Helianthus annus*)[48], sugar beet (*Beta vulgaris* L.)[49], lupin (*Lupinus angustifolius*)[50] under higher magnetic inductions based on plant species, size of seed, when compared to control. Because, higher magnetic inductions are responsible for enhancing metabolic activities, then they lead to increase chlorophyll synthesis in the leaves[77,78].

Hence, current experiment presents that the different level of intensities (high and low) clearly show that not every genotype x treatment interaction has a positive effect, sometimes it can be negative. This can possibly indicate an unproductivity of using the magnetic exposure and the too much or inappropriate laboratory conditions leads to suppress the gemination, seedling growth and chlorophyll content in leaves in delicate genotypes[52].

The mechanism of action of the magnetic field on seeds

Exposure of seed to MF can cause biological effects depending on the application. Figure 5 presents that the MF triggers several interrelated processes that ultimately increase germination percentage from the seed.

Magnetic intensities directly penetrate into the plant tissues and influence several cellular structures and processes in plants. Energy needed for seed germination and cellular growth was coming through mitochondrial respiration and ATP production[70]. The cell membrane is also affected, mostly can modify ion transport and membrane permeability, influencing on the important ions such as potassium (K), calcium (Ca^2), and hydrogen (H) by magnetic fields[69,71]. Moreover, MF applied to seeds affects various metabolic reactions, leading to changes in proteins and enzymes[28]. Furthermore, magnetic fields can induce variations in DNA transcription or replication activity[72], which leads to the potentiality of gene expression patterns that result into increased growth and enhanced stress tolerance in plants[72].

Seeds treated with MF lead to significant physiological and biological changes in plants[73]. Enhanced metabolism improves since due to faster enzymatic activity, promotes metabolic pathways, providing energy and materials needed for germination. Magnetic treatment also improves uptake of water through making seeds more hydrophilic, enables absorption during imbibition[73]. Also produces enzymes such as amylase and? it promotes quicker activation of enzymes such as amylase (degrades stored starch into sugars), which is important for seed growth[24]. In addition, hormonal regulation is balanced by auxins and gibberellins to promote cell elongation and division, which supports early development [73,74,75].

As a result of these processes (physiological and biological), the germination percentage of seeds sown in the substrate (e.g., soil) is improved. They then need less time for sprouting and germinate faster, which ensures the successful development of seedlings[74]. Besides, the seedlings developed are more likely to be more vigorously, as they tend to have stronger root and shoot systems, which make them more resilient and productive[76]. Therefore, the effectiveness of MF depends on factors like intensity, exposure time, and field orientation because too weak can be ineffective, while too strong may be stressful.

Conclusion

This study investigated the effects of static magnetic field stimulation on germination percentage, seedling growth, and chlorophyll content in soybean leaves, which is completely regarded as an eco-friendly and non-invasive method to enhance seedling growth and development. The best soybean variety in terms of germination percentage was found to be Abelina (97%) in the group (250 mT + 3 min) in comparison with control (92%), while the variety Adelfia exhibited significant and impressive results in germination and seedling growth compared to the control. The Adelfia cultivar showed a significant increase in germination rate from 55% (control) to 79% following exposure to a 500 mT SMF for 3 minutes. Seedling growth traits also improved under the treatment SMF (500 mT + 3 min), whereas higher chlorophyll content was observed with longer exposure time (12 min). The results from the present experiment suggest that MF treatment is an effective method to break seed dormancy for improving seed performance, and we recommend that magnetic induction should be further assessed on a larger scale farming. Cultivating plants under static magnetic field treatment may serve as a potential approach for crop improvement in future agricultural practices due to its promising nature, which improves seedling growth.

Declarations

Competing interests

The authors declare no competing interests.

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Author Contribution

S.L., conceptualization; S.L., K.N., methodology; S.L., T.S., K.N., investigation; S.L., T.S., visualization; S.L., T.S., K.N., writing—original draft; S.L., T.S., I.M., writing review & editing; K.N., T.S., S.L., statistical analysis; S.L., I.M., supervision. All authors have read and agreed to the published version of the manuscript.

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Data Availability

All relevant data are included in this article.

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Figures

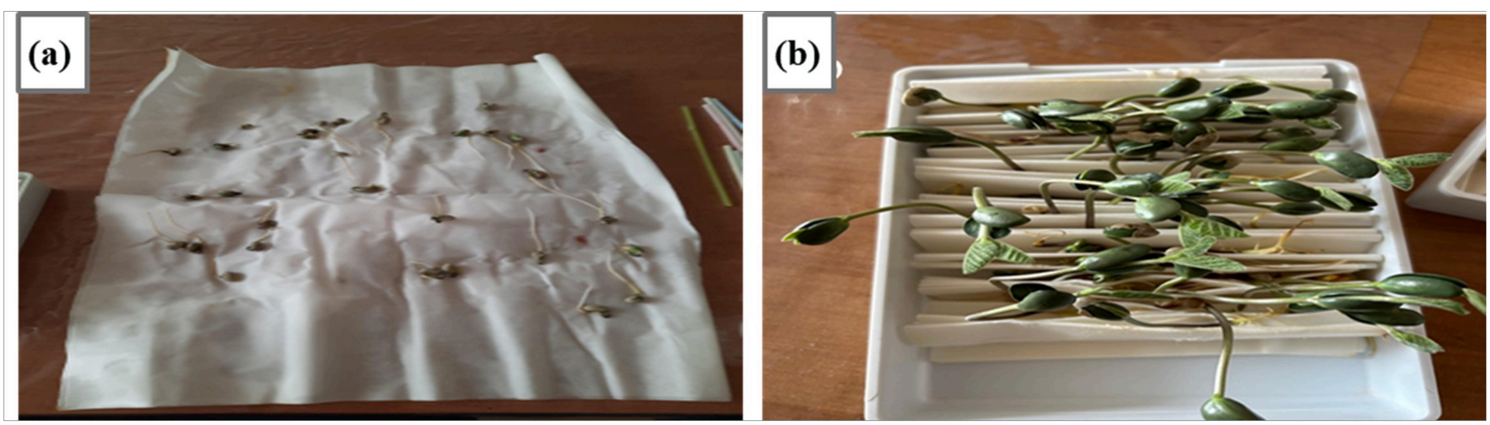

Figure 1

Selection of the best substrate for soybean experiment within (a) between paper method (BP) and (b) pleated paper method (PP) based on preliminary results (Photo: T. Sree).

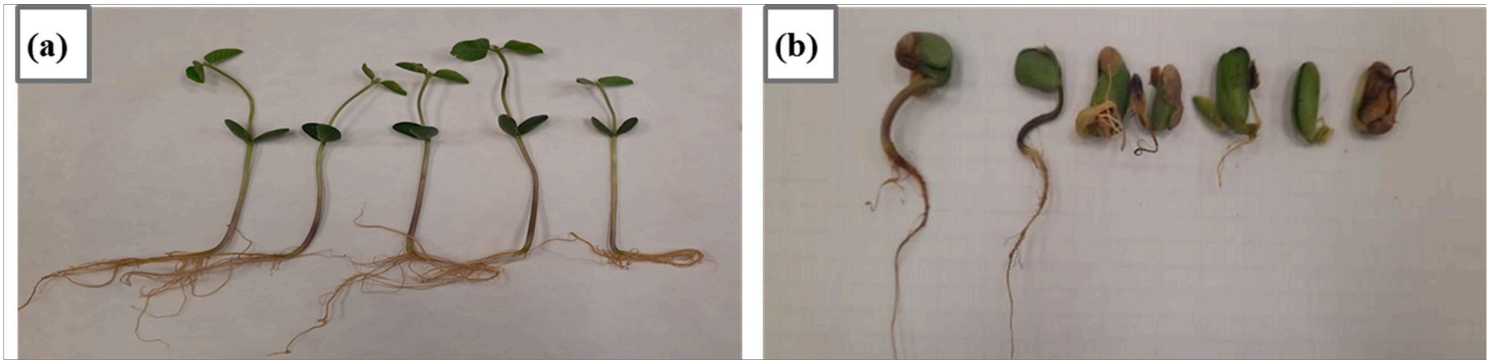

Figure 2

Segregation of soybean into (a) normal seedlings and (b) abnormal seedlings based on the main experiment (Photo: T. Sree).

Figure 3

Impact of SMF on treated seeds from seed to seedling stage compared to control. Visible differences were seen from Adelfia variety between untreated seeds [Control group - 1(a), 2(a), 3(a), 4(a), 5(a)] and treated seeds [SMF 500 mT+3 min - 1(b), 2(b), 3(b), 4(b), 5(b)], the end of germination – 6(a) (Photo: T. Sree).

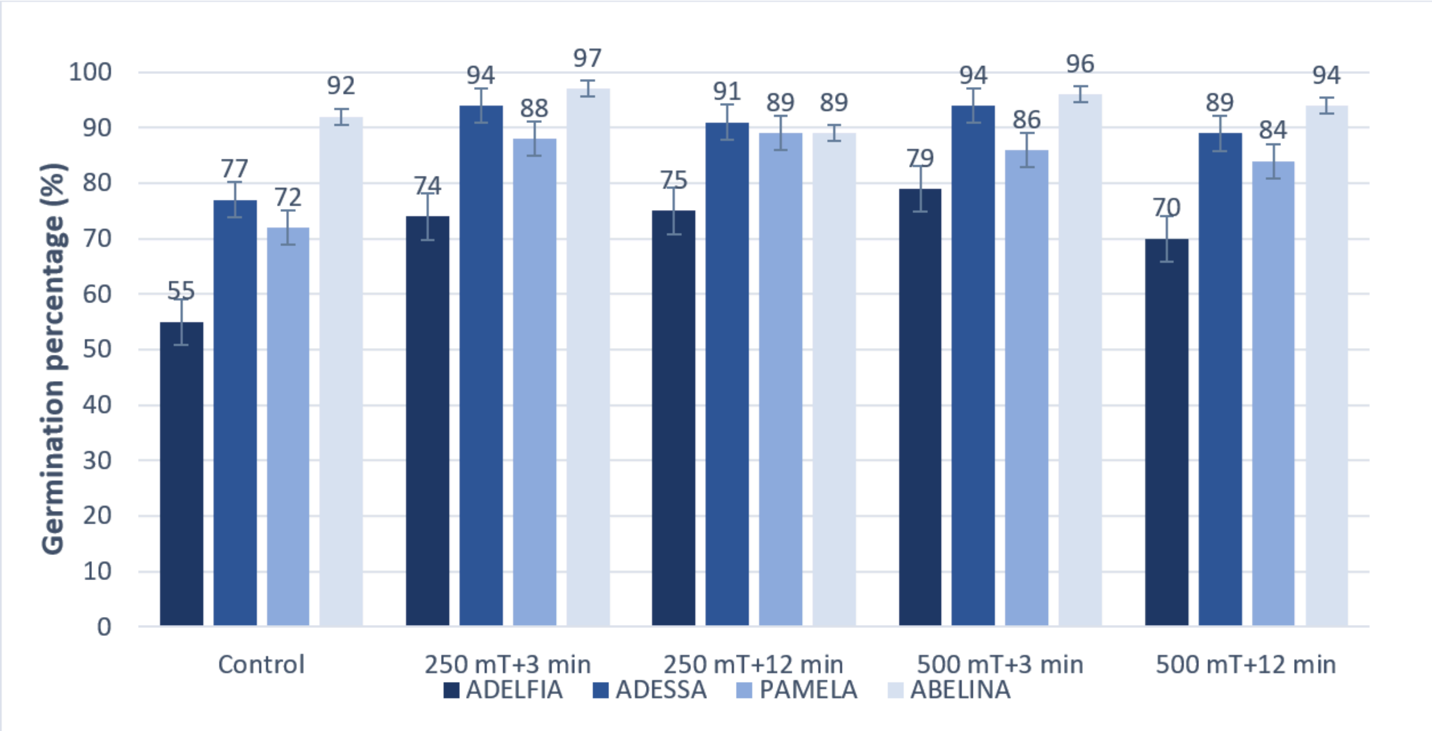

Figure 4

The effect of Static Magnetic Field on soybean seeds germination percentage with 4 varieties (mean±SD).

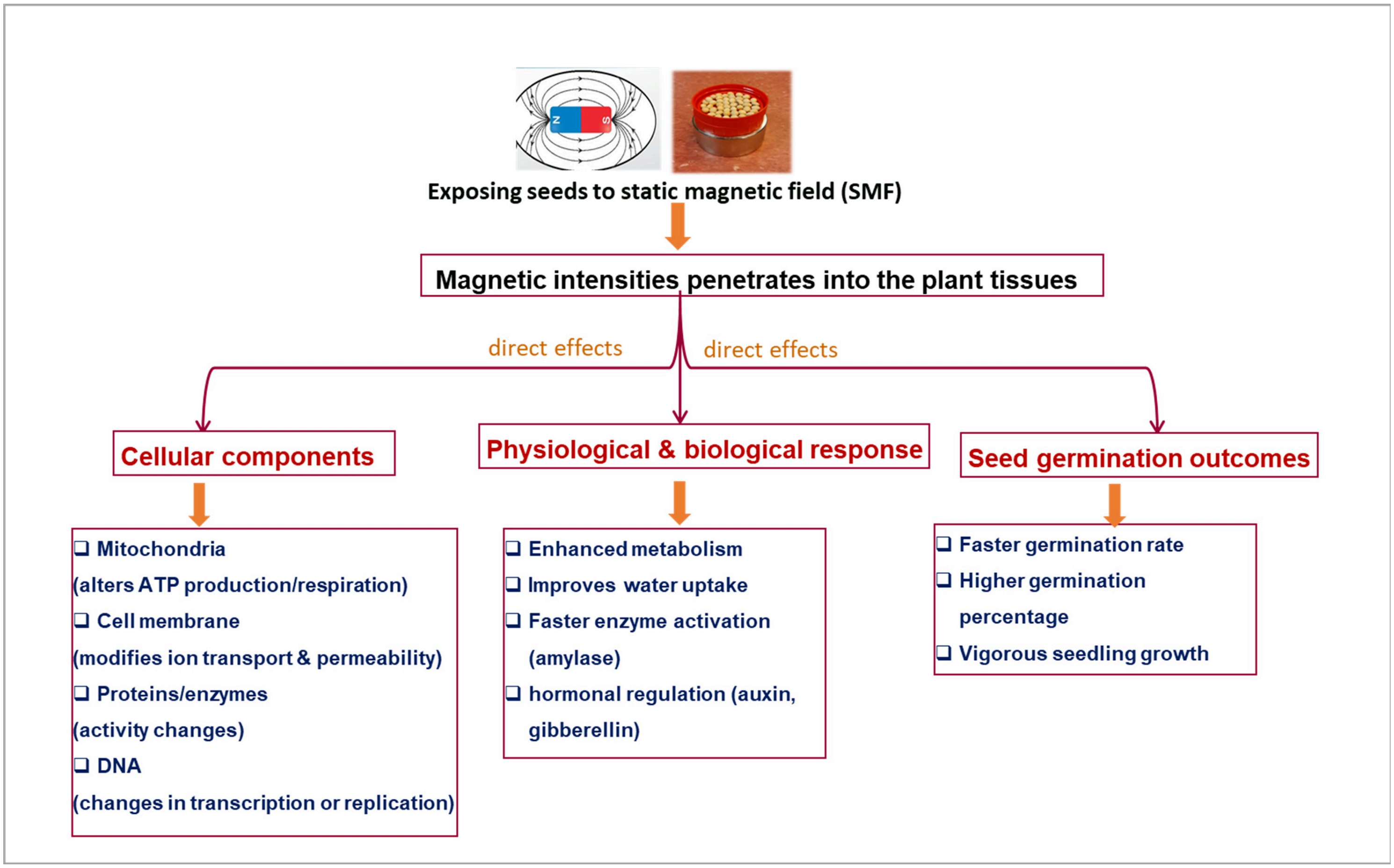

Figure 5

Flow chart of mechanistic pathways linking magnetic field intensity to seed germination.