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Evaluation and feasibility of innovative weed control strategies: Harnessing magnetic fields in field and laboratory settings

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Abstract: Background: Weed management continues to be a significant challenge in agriculture due to extreme use of chemicals which have adverse effects on environment and human health. **Objective:** This study investigates the potential of magnetic fields as an innovative and effective technique for weed control, aiming to determine their efficacy in modulating weed germination characteristics. **Methods:** It was evaluated the impact of a static electromagnetic field on the germination behavior of two weed species—*Chenopodium album* and *Echinochloa crus-galli*—under both laboratory and field conditions. Key parameters measured included germination percentage, germination rate, and average germination time, with variations in magnetic field intensity and exposure duration systematically assessed. Additionally, regression analysis was conducted, yielding mathematical models with coefficients of determination between 0.86 and 0.98, and a multi-objective genetic algorithm was employed to optimize the treatment parameters. **Results:** Optimal magnetic treatment conditions were identified as 10 minutes at 25 mT for *Chenopodium album* and 7.22 minutes at 22.46 mT for *Echinochloa crus-galli*. The results showed that magnetic treatment increased the germination percentage by up to 14% in *Echinochloa crus-galli* and 21% in *Chenopodium album*, respectively. Although the laboratory experiments yielded robust predictive models, the outcomes observed under field conditions did not fully replicate the laboratory results, indicating a potential divergence in treatment efficacy between controlled and real-world environments. **Conclusions:** The findings underscore the need for species-specific and tailored magnetic treatment parameters in weed management. The promising laboratory results coupled with the partial validation in field conditions provide a foundation for further research into sustainable alternatives to conventional herbicides.

Keywords: Weed management; Seed germination; Electromagnetic field; Mathematical modeling; Non-chemical weed control

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1. Introduction

Weeds are among the primary constraints to global agricultural productivity, making effective weed management essential for sustainable crop production. Several approaches have been developed for weed control, including mechanical, physical, biological, and cultural methods. These include tillage, hand weeding, crop rotation, and the use of cover crops. However, chemical herbicides remain the most widely used method due to their efficiency and ease of application. Both pre-emergence and post-emergence herbicides are commonly applied in modern farming systems, and new active ingredients such as QYC101 continue to be developed to enhance control and combat herbicide resistance (Wang et al., 2019). Despite their widespread use, chemical herbicides raise significant concerns due to their potential environmental and health impacts. In addition, conventional tillage practices may contribute to greenhouse gas emissions and accelerate climate change. These challenges have led to growing interest in alternative, non-chemical weed management strategies. Such approaches include thermal techniques like flaming, hot water, and foam application, as well as smart hoeing machines, mechanical tools, and the use of electrical and magnetic energies for targeted weed control (Sahin, Yalınkılıc, 2017). Nevertheless, in many developing countries as well as developed world, the reliance on herbicides continues to grow, largely driven by labor shortages and the increased cost of manual weed control. This growing dependence has led to a range of concerns, particularly the adverse effects on human health and environmental safety, as well as the alarming rise in herbicide-resistant weed populations (Hossain, 2015). Data from 1964 to 2012 indicate that global herbicide consumption increased more than eightfold during this period. Notably, only about 36% of herbicide usage occurs in developed nations, meaning that populations in developing regions are more likely to experience higher exposure levels and associated risks (Hossain, 2015). Despite the proven efficacy of herbicides in suppressing weed growth, their widespread and often indiscriminate use underscores the urgent need for integrated weed management (IWM) approaches that balance effectiveness with sustainability and environmental stewardship (Wu et al., 2020). Moreover, the evaluation of herbicide performance is inherently complex, influenced by a multitude of factors such as weed species, environmental conditions, and application techniques (Kniss, 2017). The toxicological impact of herbicides is closely linked to both dosage and duration of exposure, with residual chemicals frequently contaminating air, water, and soil ecosystems. These challenges highlight the necessity for a holistic and science-based approach to weed control, where the benefits of herbicide use are carefully weighed against their long-term ecological and health consequences.

In recent years, exposure to magnetic fields (MFs) has been increasingly recognized as an environmentally friendly and non-chemical strategy for influencing seed germination behavior and regulating weed seed banks. As a sustainable alternative, MFs are being investigated as part of IWM approaches. While a considerable number of studies have focused on agricultural and forestry crops, investigations into the effects of MFs on weed species remain limited. A growing body of evidence, however, supports the stimulatory role of magnetic fields on seed germination under varying environmental conditions. A systematic review and meta-analysis conducted by Ureta-Leones et al. (2021) confirmed that low-intensity static magnetic fields – SMF (1–50 mT) can consistently enhance germination in a broad range of plant species, although the magnitude of this effect is strongly influenced by MF intensity, exposure duration, and species-specific sensitivity (Ureta-Leones et al., 2021). In contrast, fields with intensities ranging from 51 to 300 mT produced variable outcomes, highlighting the dose- and species-dependent nature of the response. One of the early studies in this area was conducted by Flórez et al. (2007), who demonstrated that SMF of 125 and 250 mT significantly increased germination rates and seedling biomass in maize under controlled conditions (Flórez et al., 2007). Similarly, Vashisth and Nagarajan (2010) reported improved germination, seedling elongation, and enzymatic activity in sunflower seeds exposed to magnetic fields of 50–250 mT for 2 hours, with the best results observed at 50 and 200 mT (Vashisth, Nagarajan, 2010). Subsequent studies have reinforced these findings. For example, Afzal et al. (2021) found that a 100 mT field applied for 10 minutes enhanced emergence, seedling vigor, and overall crop performance in sunflower (Afzal et al., 2021). Moreover, when combined with moringa leaf extract priming in magnetized water, the treatment led to notable improvements in biochemical traits and field yield. In addition to direct magnetic exposure, research on the use of magnetized water has revealed similar benefits. A study on wheat and barley showed that exposure to a 0.15 T static MF altered physicochemical properties of water—including pH, electrical conductivity, and total dissolved solids—resulting in enhanced germination and seedling biomass, particularly in wheat (Al-Akhras et al., 2024). In quinoa, magnetic pretreatment has also been shown to influence biochemical activity. Wang et al. (2024) reported that a 10 mT field applied for 10 minutes not only improved germination in the Sanjiang-1 variety but also increased total phenolic content and antioxidant enzyme activity, effects attributed to stimulation of the phenylpropanoid biosynthetic pathway (Wang et al., 2024). Further physiological changes were observed in wheat (Triticum turgidum L.) following exposure to 12.5 and 25 mT MFs for 15–30 minutes across six consecutive days. Erez and Özbek (2023) found that such treatments enhanced chlorophyll and carotenoid content, water retention, and gene expression related to photosynthesis and growth, with the most significant transcriptional activation occurring at 25 mT for 30 minutes (Erez, Özbek, 2023). In brown rice, Luo et al. (2022) demonstrated that a 10 mT field applied for 60 minutes significantly boosted α-amylase activity, starch hydrolysis, and germination—by as much as 158.8%—alongside improved shoot and root growth and modified starch structure (Luo et al., 2022). Evidence of similar physiological enhancements has also been reported in sunflower. Bukhari et al. (2021) found that a 50 mT magnetic field applied for 45 minutes increased total biomass, shoot and root length, and tocopherol (vitamin E) content, with the FH620 variety showing the greatest response (Bukhari et al., 2021). In soybean, Dziergowska et al. (2021) observed that the combination of a 250 mT field with a 20% aqueous extract of *Cladophora glomerata* for 3 minutes significantly enhanced germination, seedling vigor, and pigment content, suggesting a synergistic interaction between magnetic stimulation and bioactive compounds (Dziergowska et al., 2021). In barley, Ercan et al. (2022) reported that low-to-moderate intensities of MFs (≤125 mT) improved photosynthetic efficiency, whereas 250 mT exposures altered root magnetic properties and membrane integrity, influencing nutrient uptake patterns. Notably, this treatment reduced macroelement levels while increasing microelements such as iron, boron, copper, and zinc (Ercan et al., 2022). In parallel, Cecchetti et al. (2021) demonstrated that electromagnetic field (EMF) exposure (50 Hz, 7 mT) modulated phytohormone concentrations—particularly by reducing IAA and ABA levels—in winter wheat. These hormonal changes accelerated germination and early seedling growth, especially in larger seeds and under dark conditions (Cecchetti et al., 2022). Lastly, research on deeply dormant seeds such as those of *Tilia miqueliana* has demonstrated that integrating MF treatment (150 mT for 85 minutes), gibberellic acid (GA_3) soaking at 1443 $\mu mol \cdot L^{-1}$, and 75-day cold stratification can significantly enhance germination (up to 89%). This effect was associated with mobilization of starch and lipid reserves, and increased levels of soluble sugars and proteins, indicating that metabolic reactivation played a central role in dormancy release (Shi et al., 2024).

Among the various strategies proposed for sustainable weed management, the targeted manipulation of seed dormancy and germination has received increasing attention as a promising approach. Weed seedbanks, which serve as long-term reservoirs of viable seeds in agricultural soils, remain a major challenge to effective and durable weed control. Inducing premature germination of dormant weed seeds under unfavorable or non-competitive conditions can accelerate seedbank depletion and reduce weed emergence in subsequent growing seasons. Several physical and biochemical methods have been investigated to promote seed germination, with magnetic field treatment emerging as a particularly promising non-chemical alternative (Table 1). Research has demonstrated that exposure to SMF can stimulate seed metabolic activity, enhance germination rates, and shorten germination time across a range of plant species. For instance, treatment with a 25 mT magnetic field for 10 minutes has been shown to significantly improve germination performance in problematic weed species such as *Chenopodium album* and *Echinochloa crus-galli* (Ureta-Leones et al., 2021). These effects are likely mediated through increased water uptake, enhanced enzymatic activity, and the regulation of hormonal pathways involved in dormancy release. Due to its environmentally friendly nature and potential for field-level application, magnetic field treatment holds considerable promise as a novel tool for breaking seed dormancy in weed species and controlling soil seedbanks in agricultural systems. Nevertheless, despite encouraging preliminary findings, the physiological and molecular mechanisms underlying these responses remain insufficiently understood—particularly in weed species with complex or conditional dormancy traits. Therefore, further research is essential to clarify these mechanisms and to develop robust, standardized protocols for the practical application of magnetic field treatments in weed management.

Weed species such as *Chenopodium album* and *Echinochloa crus-galli* are among the most persistent and damaging in agricultural systems, primarily due to their strong ecological adaptability, high seed production, and aggressive competition for water and nutrients. *C. album* can germinate early under low-temperature conditions, establishing rapidly and outcompeting many crop species (Schuster et al., 2007). Likewise, *E. crus-galli* thrives under a wide range of temperature and humidity conditions and is a particularly problematic weed in rice cultivation (Bajwa et al., 2015). Traditional weed control strategies, especially those relying on chemical herbicides, face growing limitations due to environmental concerns, increasing costs, and the evolution of herbicide-resistant biotypes. Although physical methods such as magnetic field exposure have shown promise in enhancing seed germination in various crops, their targeted use to suppress or regulate the germination of weed seeds remains underexplored. In particular, the application of SMFs as a tool for disrupting weed seed dormancy and reducing the viability of the soil seed bank offers a potentially sustainable and non-chemical approach to IWM. However, little is known about how SMFs influence dormancy-breaking mechanisms in dominant weed species under controlled conditions. To address this gap, the present study investigates the effects of SMF treatment on the germination behavior of *C. album* and *E. crus-galli*. The objective is to evaluate whether controlled magnetic exposure can reduce dormancy and synchronize germination, thereby facilitating more effective post-emergence control through light mechanical operations such as chisel cultivation. Laboratory-based germination experiments were conducted, and the results were analyzed using regression models optimized by genetic algorithms to improve prediction accuracy and interpretation. This research contributes to the development of environmentally sustainable weed management strategies by offering new insights into the potential of SMFs as a pre-sowing

Table 1 - Comparative analysis of seed germination control methods: A review of contemporary strategies

Method	Purpose	Result	Ref.
Maternal environment	Assess the effects of soil moisture content and shading of maternal plants on seed germination, and evaluate the response to gibberellin.	Freshly collected mature seeds exhibited a germination percentage of 0.89% for the high-altitude population (HAP) compared to 7.33% for the low-altitude population (LAP).	Chen et al. (2022)
Juniper essential oils	Investigate the allelopathic effects of essential oils from two juniper species on weed seed germination.	The application of juniper essential oils enhanced the germination energy of Mentha officinalis seeds.	Semerdjieva et al. (2022)
Hydrolase genes	Evaluate gene expression and quantify metabolites and hormones during seed germination.	Over one thousand genes were differentially co-expressed across five distinct germination stages.	Cao et al. (2021)
Pre-sowing enrichment	Determine the impact of nutrient enrichment on the germination indices of Echinacea angustifolia, a valuable medicinal plant.	Nutrient-enriched seeds showed improved final germination percentage and higher germination rate indices.	Sagvand et al. (2022)
Synthetic seeds	Enhance the germination efficiency of synthetic seeds using a filter paper (M-bridge) soaked in ½ Murashige and Skoog liquid medium.	Synthetic seeds inoculated on ½ MS liquid medium, SW, or ½ MSS media exhibited slower germination and reduced performance compared to control conditions.	Gantait et al. (2022)
Magnetic field (10, 20, and 25 mT)	Explore the potential of a static electromagnetic field to enhance the germination parameters of *Chenopodium album* and *Echinochloa crus-galli* seeds.	A magnetic field intensity of 25 mT applied for 10 minutes increased both the germination speed (GS) and average germination time (AGT) of the tested weed species.	*This work*

treatment. The findings are expected to support future efforts in reducing herbicide reliance and enhancing the ecological compatibility of integrated weed control practices.

2. Material and methods

2.1 Design and development of a magnetic field generator for weed seed germination

To generate a uniform magnetic field for the experiments, a pair of Helmholtz coils was employed. Helmholtz coils consist of two identical circular coils aligned along a common axis, with the separation between them equal to their radius, and are connected in parallel so that the same current flows through both in the same direction. This configuration ensures the creation of a uniform magnetic field in the region between the coils. The magnetic field strength was calculated using Biosavar's law, as shown in Equation 1:

$$B_z = \frac{\mu_0 NI}{2} \times \frac{R^2}{(R^2+Z)^{32}} \quad (1)$$

where B_z denotes the magnetic field intensity (T), R is the coil radius (m), N is the number of turns per coil, I is the current (A), and μ_0 represents the vacuum permeability.

The two coils were positioned at a fixed distance apart, with their planes parallel and the coordinate system origin located midway between them. Denoting the distance between the coils as 'a', the total magnetic field in the region between them is the sum of the individual fields generated by each coil, as expressed in Equation 2 (Pastena, Grassi, 2002):

$$B = \frac{\mu_0 NIR^2}{2} \times \left(\frac{1}{((Z+\left(\frac{a}{2}\right))^2+R^2)^{32}} + \frac{1}{((Z+\left(\frac{a}{2}\right))^2+R^2)^{32}} \right) \quad (2)$$

The circular coils were constructed using non-ferromagnetic materials such as aluminum, polyvinyl chloride (PVC), and wood. Coated copper wires with a diameter of 0.8 mm were used for winding the coils, as this gauge is capable of safely carrying approximately 2 A in accordance with established standards. Each coil was wound with 1000 turns. The magnetic field intensity was measured with a TES-1394 Triaxial ELF magnetic field meter, which offers a resolution of 0.001 mT and an accuracy of ±3%. A DAZHENG PS-303D direct current (DC) digital power supply, adjustable to 32 V and 3 A, was used to generate the magnetic field.

2.2 Laboratory testing of magnetic field effects on weed seed germination

The impact of magnetic fields on the germination of weed seeds was evaluated by exposing the seeds of two weed species, *Chenopodium album* and *Echinochloa crus-galli*, to magnetic fields of 10, 20, and 25 mT for exposure durations ranging from 1 to 10 minutes, with intervals of 1 minute (Figure 1a). Magnetic field intensities of 10, 20, and 25 mT were achieved by applying electric currents of 0.55, 1.11, and 1.38 A, corresponding to voltages of 12.2, 24.22, and 30.32 V, respectively. A control group of seeds was included, which was not exposed to the magnetic field. Prior to testing, all seeds, including those in the control group, were disinfected by soaking in a 5% hypochlorite solution followed by rinsing with distilled water. For each treatment, 25 seeds were placed in sterile containers on filter paper, with three replicates per treatment (Figure 1b). The seeds, along with the filter paper, were moistened with distilled water, and the containers were placed in a germinator. The germinator was set to a 12-hour light and 12-hour dark cycle, maintaining a constant temperature of 25 ± 1°C for 14 days. During the experiment, the number of germinated seeds was recorded daily. After 14 days, the Petri dishes were removed from the germinator, and germination parameters were calculated, including the average germination time (AGT), germination percentage (GP), and germination rate (GS), using the equations below (Burnett et al., 2005):

$$\text{AGT} = \frac{\Sigma\,(\text{F.X})}{\Sigma\,\text{F}} \quad (3)$$

$$\text{GP} = \frac{n_g}{\text{N}} \times 100" \quad (4)$$

$$\text{GS} = \Sigma \frac{n_i}{X_i} \quad (5)$$

where F represents the number of newly germinated seeds on the X-th day, n_g is the total number of germinated seeds, and N is the total number of seeds in the sample.

2.3 Field experiment to assess the effects of magnetic fields on weed seed germination

The field experiment was conducted by planting weed seeds at a depth of 1 cm in farm soil and subjecting them to magnetic field treatments using the optimal intensity and duration determined from the laboratory tests (Figure 2). Each treatment was replicated three times, and the results were compared to a control group that was not exposed to the magnetic field. The optimal magnetic field intensity and duration for *Echinochloa crus-galli* and *Chenopodium album* were found to be 22.46 mT for 7.22 minutes and 25 mT for 10 minutes, respectively. Seedling emergence was recorded over a 14-day period following planting, and parameters such as seedling emergence percentage, average time of seedling emergence (Equation 3), and seedling emergence speed (Equation 5) were calculated. The soil at the experimental site was characterized as clay loam. According to climatic data, the mean air temperature during the summer months (June–August) in Mazandaran Province ranged from 27.2°C to 31.5°C, while the average relative

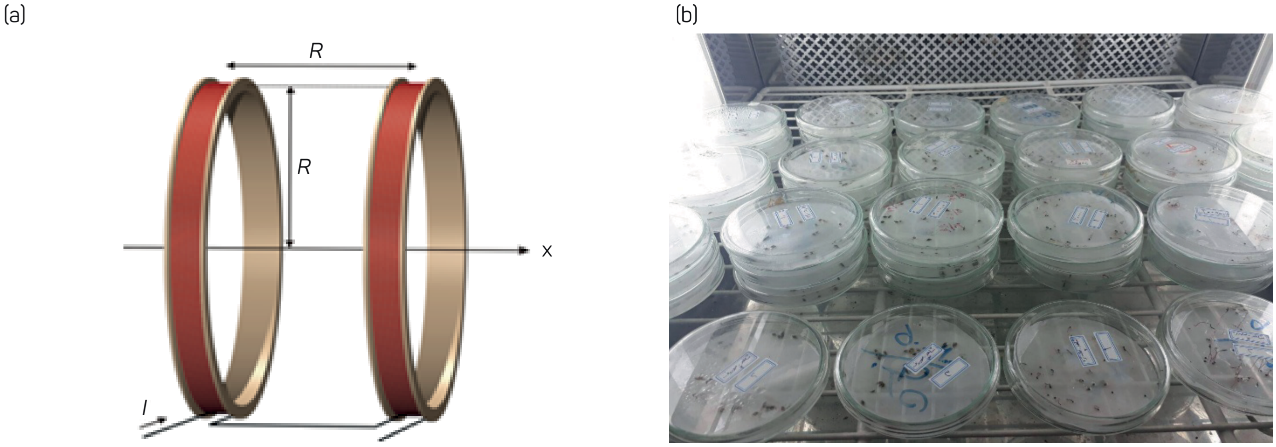


Figure 1 - schematic diagram of the Helmholtz coil (a) and experimental setup for seed germination tests (b)

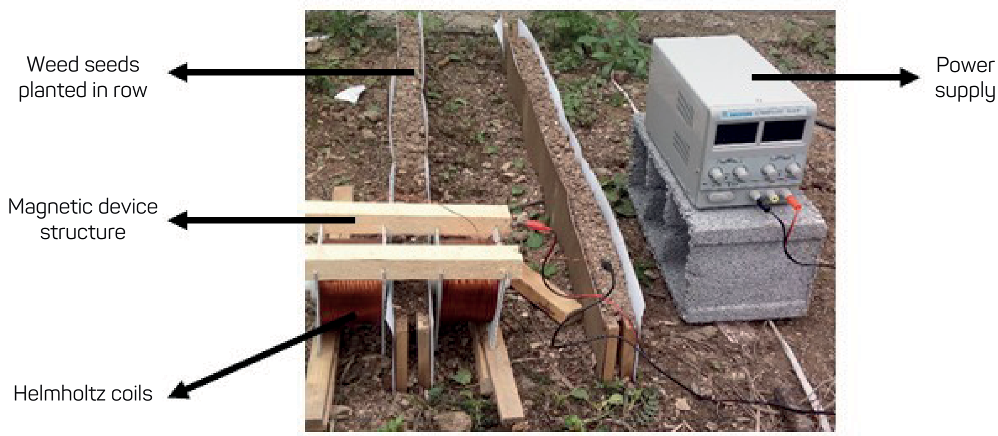


Figure 2 - Components of the experimental setup for field tests assessing the effects of magnetic fields on weed seed germination

humidity was approximately 80%, with peak morning values exceeding 90%.

2.4 Statistical analysis for magnetic field effects on weed seed germination

Response Surface Methodology (RSM) is a powerful statistical approach used to optimize and analyze complex systems across various fields. In this study, RSM was employed to examine the effects of magnetic fields on weed seed germination. The independent variables in the experiment were magnetic field intensity and exposure duration, while the response variables included seedling emergence percentage, average time of seedling emergence, and seedling emergence speed. RSM allowed the identification of the optimal combination of magnetic field intensity and duration, which maximized seedling emergence percentage, minimized average emergence time, and enhanced emergence speed. The main advantage of RSM lies in its efficiency, as it enables the determination of optimal conditions with a minimal number of experimental trials, thus reducing both time and cost. This makes RSM an invaluable tool for optimizing the germination process and improving weed control strategies. In this section, the materials and methods used for RSM analysis and the investigation of magnetic field effects on weed seed germination are detailed (Khuri, 2006).

The study aimed to explore the relationship between independent variables—magnetic field intensity (at 10, 20, and 25 mT) and exposure duration (at 0, 1, 5.5, and 10 minutes)—and response variables, including average germination time (AGT), germination percentage (GP), and germination rate (GS), using various regression models. In this study, a full second-order (quadratic) regression model (Equation 6) was employed to describe the relationship between the independent variables and the germination response. This model comprises the intercept (β_0), linear terms (β_1, β_2), interaction term (β_{12}), and quadratic terms (β_{11}, β_{22}). Simpler models can be derived from this comprehensive form by systematically excluding specific terms: the linear model includes only the intercept and linear coefficients (β_0, β_1, β_2); the two-factor interaction (2FI) model adds the interaction term (β_{12}) to the linear structure; and the reduced quadratic model retains the intercept, linear, and quadratic terms (β_0, β_1, β_2, β_{11}, β_{22}) but omits the interaction term when it is found to be statistically insignificant.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon \quad (6)$$

Where y denotes the response variable (i.e., the germination parameter), and β_0, β_1, β_2, β_{12}, β_{11}, and β_{22} are the model coefficients. The terms x_1 and x_2 correspond to the independent variables—exposure duration (min) and magnetic field intensity (mT), respectively—while ε accounts for the random error.

To assess the efficacy of the regression models, two statistical measures were employed: the coefficient of determination (R^2) (Equation 7) and the adjusted coefficient of determination (R^2_{adj}) (Equation 8). These measures were calculated using Minitab software for data analysis and regression model evaluation. Additionally, the independent variables were fitted using a genetic algorithm in MATLAB software. An F-test was conducted using Minitab to compare the experimental results from the control and treatment groups, assessing the significance of differences in germination parameters.

$$R^2 = \frac{SS_R}{SS_T} \quad (7)$$

$$R^2_{adj} = 1 - \frac{n-1}{n-p} \times \frac{SS_E}{SS_T} \quad (8)$$

Where SS_E is the sum of squares for the residuals, SS_T is the total sum of squares, nnn is the number of replicates, and p is the number of parameters in the model.

The R^2value indicates how well the independent variables explain the variation in the dependent variable, while R^2_{adj} adjusts for the number of independent variables in the model, penalizing unnecessary terms. Both values range from 0 to 1, with higher values indicating better model fit.

2.5 Optimizing magnetic treatment conditions using genetic algorithm

Genetic algorithms (GAs) are optimization techniques inspired by the principles of natural selection and genetics. They have been widely utilized across various fields to solve complex optimization problems. In recent years, GAs have seen increasing application in agricultural research. There are two primary types of genetic algorithms: Single-Objective Genetic Algorithms (SOGA) and Multi-Objective Genetic Algorithms (MOGA). SOGA focuses on optimizing a single objective function, while MOGA seeks to optimize multiple objective functions simultaneously. In this study, both SOGA and MOGA were employed to identify the optimal magnetic treatment conditions for controlling two weed species, *Chenopodium album* and *Echinochloa crus-galli*. The magnetic treatment experiment involved exposing weed seeds to a static electromagnetic field with varying field intensities and exposure durations. The objective functions used in the genetic algorithms included germination percentage (GP), average germination time (AGT), and germination speed (GS). The aim was to determine the optimal values of magnetic field intensity (MF) and exposure duration (T) that would maximize GP and GS while minimizing AGT.

The genetic algorithms were implemented in MATLAB to optimize the magnetic treatment conditions for weed control. The algorithms were based on the regression models developed for each germination parameter of the weed seeds. The optimization process was set to run for 100 generations, with a population size of 50 individuals. The crossover and mutation probabilities were set at 0.8 and 0.02, respectively. Additionally, the elitism parameter was set at 0.15 to ensure that the best individual from each generation was preserved. The optimization process concluded when either the maximum number of generations was reached or the convergence criterion was satisfied. The values of the genetic algorithm parameters were determined through a trial-and-error approach and validated by analyzing the quality and distribution of the solutions along the Pareto front.

3. Result and discussion

This section presents the results of the investigation into the effects of magnetic fields on weed seed germination, employing response surface methodology (RSM). The selection of the most appropriate regression model is discussed, along with the application of a multi-objective genetic algorithm to optimize the levels of the independent variables. The findings provide important insights into potential methods for weed control and contribute to a deeper understanding of the influence of magnetic fields on seed germination.

3.1 Results of laboratory experiments

3.1.1 *Selection of the best regression model*

To accurately estimate the germination parameters, including average germination time (AGT), germination percentage (GP), and germination rate (GS), four regression models were employed: linear regression, two-factor interaction regression, quadratic regression, and reduced quadratic regression. These models were evaluated using two independent variables: duration (x_1) and magnetic field intensity (x_2). The results of this analysis, including the coefficients of determination (R^2) and adjusted coefficients of determination (R^2_{adj}) for each regression model applied to the two weed species, *Echinochloa crus-galli* and

Chenopodium album, are summarized in Table 2. The models with the highest fit are indicated in bold.

The ideal model selection criterion is based on maximizing both R^2 and R^2_{adj} values, ideally approaching unity. As presented in Table 2, the reduced quadratic regression model was selected for the dependent variables GP and GS for *Echinochloa crus-galli*, while the quadratic regression model was chosen for AGT. A similar pattern was observed for *Chenopodium album*. The R^2 values for the selected models were 83% and 86% for the two weed species, respectively, indicating a moderate predictive power for these variables. For all other dependent variables, R^2 values exceeded 96%, signifying that the regression models effectively explained the variability in the response variables and provided a strong fit to the observed data.

To enhance model efficiency and prediction accuracy, a stepwise regression approach was applied to eliminate less significant variables. This refinement resulted in a more streamlined model that maintained its predictive ability for estimating the germination parameters of the weed species under investigation.

3.1.2 *Analysis of variance of the regression model*

The analysis of variance (ANOVA) is a statistical method used to evaluate the significance of explanatory variables within a regression model. A significant F-statistic indicates that a variable contributes meaningfully to the model's overall fit. Table 3 presents the ANOVA results for the regression models selected using the stepwise method, applied to the three dependent variables: average germination time (AGT), germination rate (GS), and germination percentage (GP) for the two weed species, *Echinochloa crus-galli* and *Chenopodium album*. The table includes the sum of squares (SS) values for each selected factor, along with their significance levels at the 1% and 5% thresholds. Factors that were excluded from the models are marked with dashes.

The results indicate that all selected factors were significant at either the 1% or 5% level, which underscores

Table 2 - Comparison of regression models for estimating germination parameters

Weed species	Regression model	GP		GS		AGT	
		R^2	R^2_{adj}	R^2	R^2_{adj}	R^2	R^2_{adj}
Echinochloa crus-galli	Linear	0.88	0.87	0.88	0.87	0.51	0.49
	Two-factor interaction	0.90	0.89	0.89	0.88	0.51	0.49
	Reduce quadratic	0.98	0.98	0.98	0.97	0.71	0.67
	Quadratic	0.98	0.98	0.98	0.97	0.86	0.83
Chenopodium album	Linear	0.95	0.95	0.96	0.96	0.89	0.88
	Two-factor interaction	0.96	0.95	0.97	0.97	0.90	0.89
	Reduce quadratic	0.99	0.99	0.99	0.99	0.92	0.92
	Quadratic	0.99	0.99	0.99	0.99	0.97	0.96

Table 3. Analysis of variance for the selected regression model in estimating germination parameters

		AGT		GS		GP	
	Degrees of freedom	Ech.	Che.	Ech.	Che.	Ech.	Che.
Regression	5	526.11^{**}	1313.92^{**}	2.00^{**}	15.85^{**}	0.25^{**}	1.16^{**}
x_1 (min)	1	198.09^{**}	314.35^{**}	1.02^{**}	11.70^{**}	0.05^{**}	1.04^{**}
x_2 (mT)	1	273.40^{**}	947.73^{**}	0.78^{**}	3.76^{*}	0.11^{**}	0.03^{*}
x_1^2	1	5.04^{**}	36.41^{**}	0.05^{**}	0.23^{**}	-	0.07^{**}
x_2^2	1	49.58^{**}	15.43^{**}	0.16^{**}	0.16^{**}	0.09^{**}	0.01^{*}
$x_1 x_2$	1	-	-	-	-	0.00^{**}	0.02^{**}
Error	24	9.93	12.45	0.05	0.08	0.04	0.03
Lack-of-fit (LOF)	5	1.77^{ns}	10.23^{ns}	0.02^{ns}	0.06^{**}	0.01^{ns}	0.01^{ns}
Pure error	19	8.16	2.22	0.03	0.02	0.03	0.02
Total	29	536.03	1326.36	2.05	15.93	0.30	1.20

Note: **, * and ns denote statistical significance at p-values of 0.01 and 0.05, and non-significance, respectively. *Ech* and *Che* represent *Echinochloa crus-galli* and *Chenopodium album*, respectively.

AGT , GS and GP represent average germination time, germination rate, and germination percentage, respectively their importance in predicting the response variables. The lack of fit (LOF) factor in the ANOVA tests whether there is a significant difference between the predicted and experimental observed values. A significant LOF suggests that the model does not adequately fit the data, while a non-significant LOF implies that the model is a good fit and there is no significant discrepancy between the predicted and observed values.

Based on these findings, it can be concluded that, except for the GS variable in *Chenopodium album*, the LOF was not statistically significant for the regression models. This suggests that the models developed in the previous steps can be considered reliable. However, for the model where LOF was significant, despite high R^2 and adjusted R^2 values (99%), the reliability of the estimates can only be partially assured.

3.1.3 *Coefficients of the fitted regression model*

Regression analysis is used to develop a model that predicts the values of a dependent variable based on the values of independent variables. The goal of regression analysis is to estimate the coefficients of the independent variables that best describe the variation in the dependent variable. These coefficients represent the change in the dependent variable for a unit change in the corresponding independent variable, while holding all other independent variables constant. The coefficients may be either positive or negative, indicating a positive or negative relationship between the dependent and independent variables.

Table 4 presents the values of the regression coefficients for the models developed to estimate the dependent variables in two weed species, *Echinochloa crus-galli* and *Chenopodium album*. These coefficients allow for the estimation of the three dependent variables—average germination time (AGT), germination rate (GS), and germination percentage (GP)—based on the duration (x_1) and magnetic field intensity (x_2). Additionally, the presence of a non-zero intercept coefficient ($\beta_0 \neq 0$) suggests that factors other than the two independent variables investigated may have influenced the observed changes in the dependent variables.

Figure 3 presents the percentage contribution (PC) of the independent variables—magnetic field duration (T) and intensity (MF)—to the variation in seed germination parameters, including germination percentage (GP), germination speed (GS), and average germination time (AGT). The results reveal clear species-specific responses to magnetic field exposure in *Echinochloa crus-galli* and *Chenopodium album*, likely arising from inherent physiological differences such as seed coat permeability, enzymatic response thresholds, or dormancy regulation mechanisms. For *E. crus-galli*, MF intensity had a more pronounced effect on GP and AGT, whereas duration played a larger role in influencing GS. In contrast, *C. album* showed stronger sensitivity to magnetic field duration, particularly for AGT, where T accounted for approximately 93% of the observed variation, while MF contributed only 4.5%. These findings underscore the need for species-specific calibration of magnetic treatment parameters in practical applications. The underlying biological mechanisms by which magnetic fields influence seed behavior are not yet fully understood, but several hypotheses have been proposed. Previous studies suggest that magnetic exposure may enhance membrane permeability, enabling faster water uptake (Flórez et al., 2007), as well as stimulate the activity of key enzymes such as α-amylase, protease, and dehydrogenase, which are crucial for energy mobilization during germination. In addition, magnetic treatment has been linked to the modulation of reactive oxygen species (ROS) signaling and hormonal balance, particularly gibberellins and abscisic acid, which regulate dormancy and germination (Radhakrishnan, Ranjitha Kumari, 2012). Given these multifaceted effects, the interaction of MF intensity and exposure time appears to influence a complex network of physiological and biochemical processes. Further molecular-level studies, including transcriptomic and metabolomic profiling, are recommended to clarify the mechanisms by which magnetic fields exert their influence on different seed types. These insights will be essential for designing effective, non-chemical weed control systems that are biologically informed and field-adaptable.

Table 4 - Regression model coefficients for estimating germination parameters

	AGT		GS		GP	
Coef.	**Ech.**	**Che.**	**Ech.**	**Che.**	**Ech.**	**Che.**
β_0	59.69	72.52	3.95	5.45	4.26	3.81
β_1	1.49	-0.34	0.11	7.28×10^{-2}	-3.85×10^{-2}	-6.57×10^{-2}
β_2	-0.33	0.33	-1.97×10^{-2}	9.99×10^{-3}	2.17×10^{-2}	8.88×10^{-3}
β_{11}	-0.09	0.09	-6.62×10^{-3}	6.36×10^{-3}	-	4.68×10^{-3}
β_{22}	0.02	0.02	1.33×10^{-3}	1.43×10^{-3}	-1.23×10^{-3}	4.23×10^{-3}
β_{12}	-	-	-	-	1.64×10^{-3}	-1.71×10^{-3}

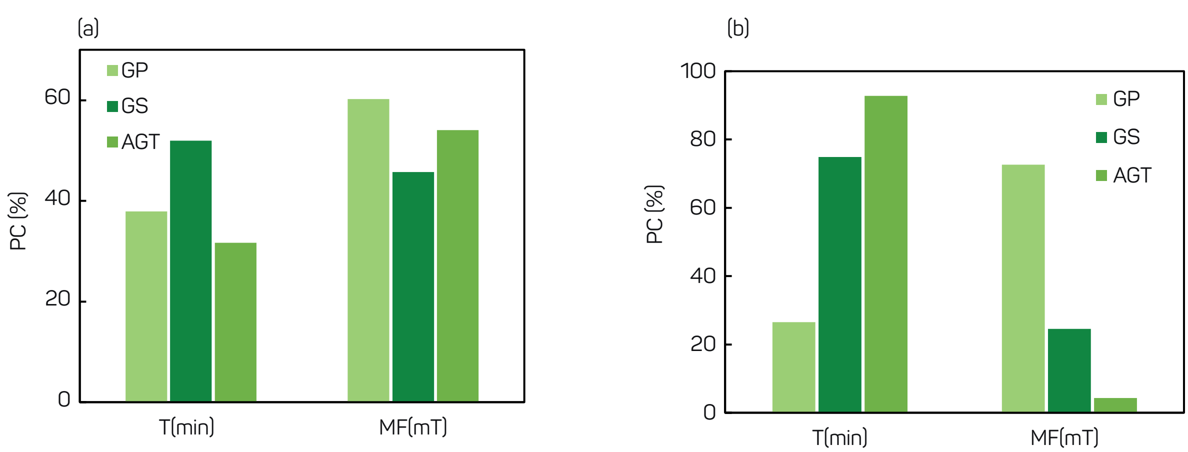
Note: *Ech* and *Che* represent *Echinochloa crus-galli* and *Chenopodium album*, respectively.
AGT, GS and GP represent average germination time, germination rate, and germination percentage, respectively

3.1.4 *Evaluating the validity and reliability of regression models*

Regression models are powerful tools for prediction, but their validity must be verified through diagnostics. This study applied standard diagnostic tests—residual plots, normality tests, homoscedasticity tests, and multicollinearity assessments—to ensure the models were sound. Results of normality and homoscedasticity tests for average germination time (AGT) in *Echinochloa crus-galli* and *Chenopodium album* confirmed that key assumptions were met (Figure 4). Additionally, all variance inflation factor (VIF) values were below 10, indicating no multicollinearity. A 99% agreement between predicted and observed lab values validated model accuracy across all test cases. These outcomes confirm the regression models are both valid and reliable, providing a solid foundation for the study's findings and subsequent analyses.

3.1.5 *Response surface graphs for germination parameters*

Response surface plots (Figure 5) were used to visualize the effects of magnetic field duration (T) and intensity (MF) on germination parameters—average germination time (AGT), germination speed (GS), and germination percentage (GP)—for *Echinochloa crus-galli* and *Chenopodium album*. The x- and y-axes represent T and MF, respectively, while the z-axis shows the model-predicted response. Distinct patterns were observed between the two species, indicating species-specific responses to magnetic field treatments. The findings for *Echinochloa crus-galli*, presented in Figure 5(a), show that the lowest values of GP and GS occur at the lowest values of T and MF. In contrast, the highest values of GP and GS are observed with the highest values of T and MF. However, for AGT, the maximum value is found within the range of MF values between approximately 10 and 20 milliTesla and the lowest value of T. For *Chenopodium album*, the results presented in Figure 5(b) indicate that the highest values for all three germination parameters (GP, GS, and AGT) are achieved with the highest values of T and MF, except for AGT, where the lowest T value produces the highest result. Conversely, the lowest values for these parameters are associated with the lowest values of T and MF, and the highest value of AGT corresponds to the lowest MF. These results provide valuable insights into how the duration and intensity of magnetic field exposure influence the germination parameters of weed seeds. The observed species-specific responses underscore the need for targeted strategies in weed control. Previous studies have reported that increasing magnetic field exposure from 87 to 226 mT led to a linear increase in the germination parameters of



AGT: Average Germination Time; GS: Germination Rate; and GP: Germination Percentage, represent the respective germination parameters

Figure 3 - The Percentage of Contribution (PC) of the duration (T(min)) and the magnetic field intensity (MF(mT)) on germination parameters of (a) *Echinochloa crus-galli* and (b) *Chenopodium album* seeds

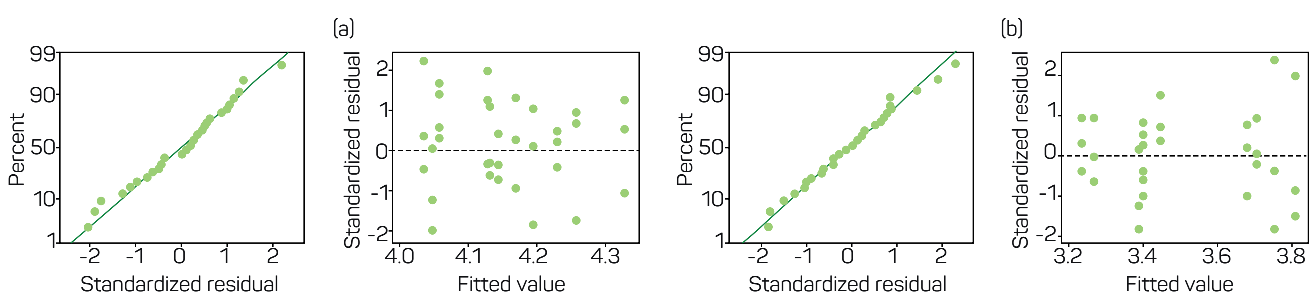


Figure 4 - Results of diagnostic techniques for regression models of (a) *Echinochloa crus-galli* and (b) *Chenopodium album*

bean seeds. Similarly, exposure to a magnetic field of 50 to 250 mT for 1 to 4 hours has been shown to increase the germination percentage and germination rate of sunflower seeds by 5 to 11% and 1 to 9%, respectively (Vashisth, Nagarajan, 2010). The present study further demonstrates that magnetic field exposure significantly affects the germination parameters of weed seeds, suggesting that this approach could be a promising non-chemical method for weed control. The following section will present optimization results that will provide additional insights into the potential practical applications of these findings and guide future research and the development of magnetic field exposure as a viable weed control strategy.

3.1.6 *Optimization of magnetic field exposure for weed control using genetic algorithm*

This study employed a genetic algorithm (GA) to optimize the duration (T) and intensity (MF) of magnetic field exposure for two weed species, *Echinochloa crus-galli* and *Chenopodium album*, in order to evaluate their effects on germination parameters, including germination percentage (GP), germination rate (GS), and average germination time (AGT). Initially, a single-objective genetic algorithm was applied to assess the relationship between the duration and intensity of magnetic field exposure and each of the individual germination parameters. The objective was to identify the optimal values of T and MF that would maximize GP and GS, while minimizing AGT. The GA was utilized to explore various combinations of T and MF to optimize each of the three germination parameters individually. Through iterative evaluations of different parameter sets, the GA converged on the optimal T and MF values that would maximize GP and GS, and minimize AGT for each weed species. It is important to note that the fitness and cost functions used in this study were the same regression models developed in previous sections. This approach ensured consistency and accuracy throughout the optimization process and enabled the derivation of meaningful conclusions regarding the impact of magnetic field exposure on the germination parameters of weed seeds. The results of the single-objective optimization are summarized in Table 5. The findings indicate that the optimal magnetic field intensity (MF) was 25 milliTesla (mT) for all cases, except for GP of *Chenopodium album*, which exhibited a different optimal value. For *Echinochloa crus-galli*, the optimal duration (T) was 10 minutes for GP and GS, while

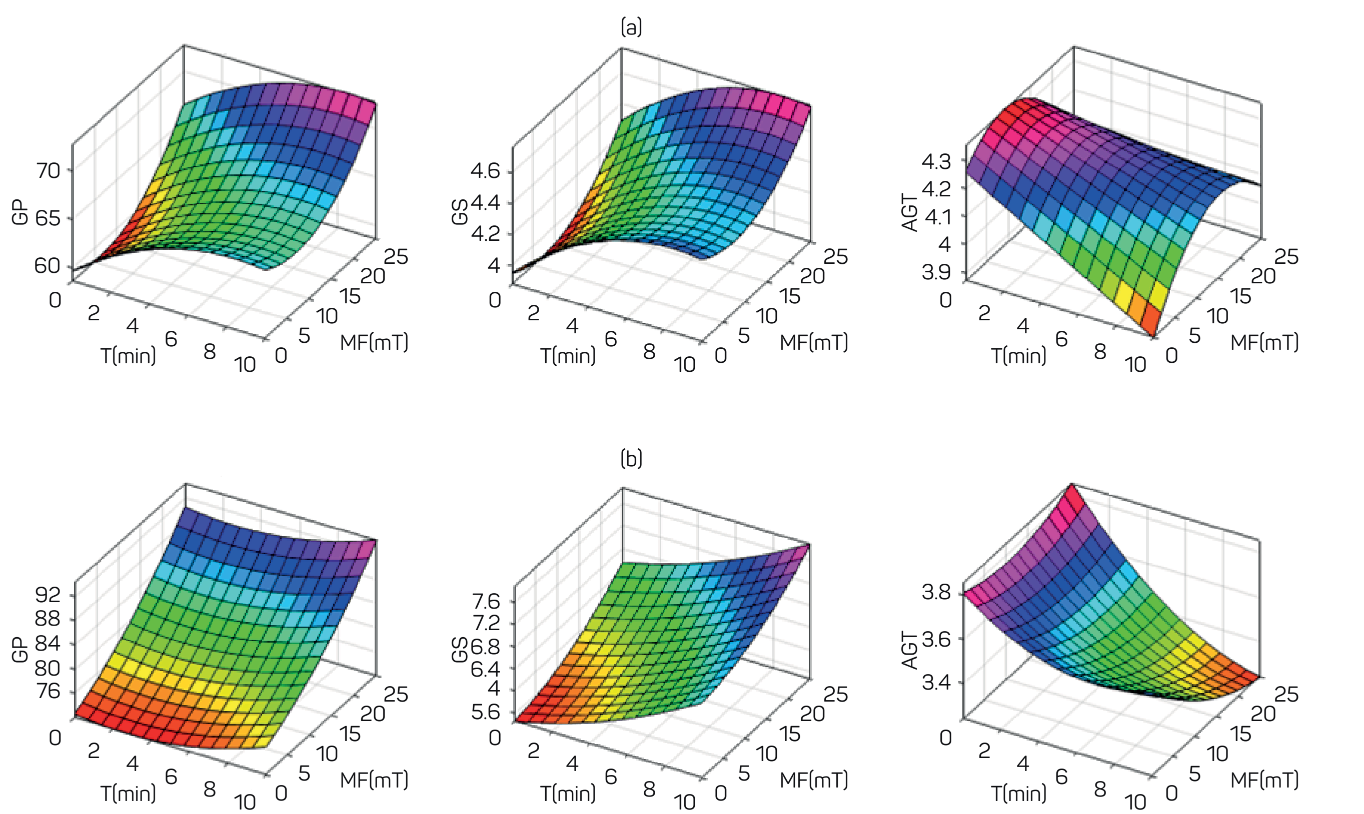


Figure 5 - Response surface graphs for germination percentage (GP), germination rate (GS), and average germination time (AGT) based on the duration (T) and intensity (MF) of the magnetic field for (a) *Echinochloa crus-galli* and (b) *Chenopodium album*

it was 8.41 minutes for AGT. In contrast, for *Chenopodium album*, the optimal values of T were 0, 8.47, and 10 minutes for GP, GS, and AGT, respectively. These results reveal that the optimal values for each weed species and germination parameter were not consistent and, in some cases, even contradictory. For instance, the optimal values of T and MF for GP of *Chenopodium album* differ from those of the other two germination parameters for this species. Overcoming the limitation of inconsistent optimal values across multiple objectives is a key goal of this study. To address this, a multi-objective genetic algorithm is being implemented to identify a unified set of optimal values for all objectives. This multi-objective optimization approach will enable the simultaneous optimization of multiple parameters, allowing the determination of a fixed optimal set of T and MF values that will achieve the desired germination parameters for each of the weed species under investigation.

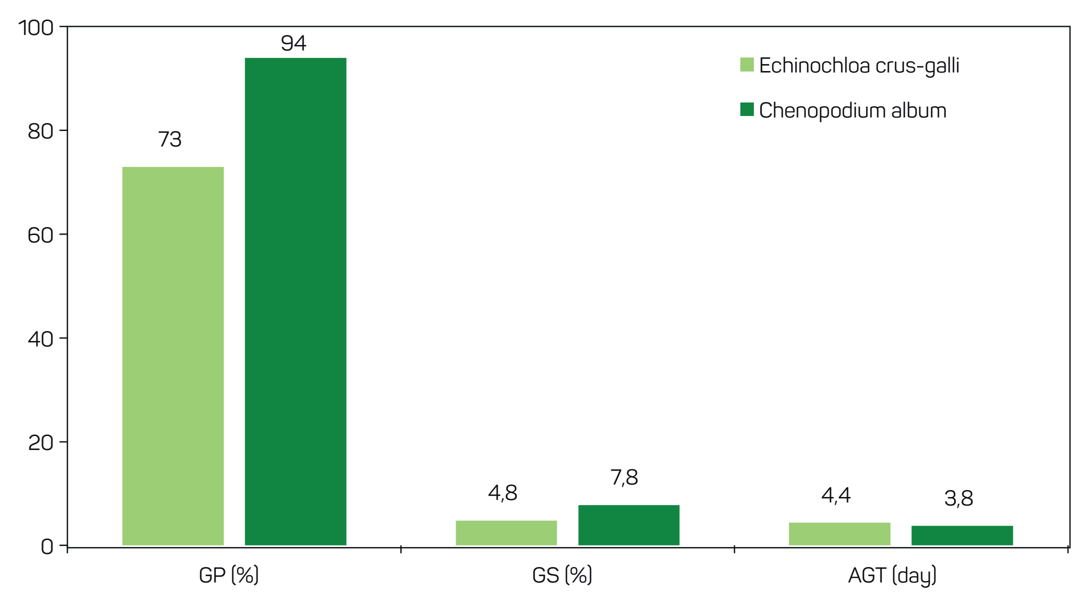
The optimal values for the duration (T) and intensity (MF) of the magnetic field were determined using the regression models outlined in Table 5. The results, shown in Figure 6, reveal that for *Echinochloa crus-galli*, the highest values of germination percentage (GP) and germination rate (GS), along with the lowest average germination time (AGT), were 73%, 4.8%, and 4.4 days, respectively. In contrast, for *Chenopodium album*, the corresponding values were 94%, 7.8%, and 3.8 days. These findings indicate significant differences in the germination behavior of the two weed species, emphasizing the need to carefully select the appropriate T and MF levels for effective weed management.

In line with the previously discussed rationale, a multi-objective genetic algorithm (MOGA) approach was employed to determine the optimal values for the duration (T) and intensity (MF) of the magnetic field for each weed species. This method provided a comprehensive analysis of the interaction between T and MF for each species, with the goal of maximizing germination percentage (GP) and germination rate (GS), while minimizing average germination time (AGT). To illustrate the feasible solutions obtained from the MOGA, the Pareto-front method was utilized. The resulting set of solutions is presented in Figure 7. The Pareto-optimal front comprises solutions that cannot be improved for one objective without compromising the performance of another objective. Through the analysis of the Pareto-optimal front, it was possible to identify the optimal trade-offs among the objectives, enabling the selection of the most appropriate solution for the study's objectives. The

Table 5 - Optimization of magnetic field exposure for weed germination parameters using genetic algorithm: identification of optimum values

	Echinochloa crus-galli			Chenopodium album		
Independent variables	**GP**	**GS**	**AGT**	**GP**	**GS**	**AGT**
Duration of magnetic field (T, min)	10	10	8.41	0	8.47	10
Magnetic field intensity (MF, mT)	25	25	25	0	25	25

AGT: Average Germination Time; GS: Germination Rate; and GP: Germination Percentage, represent the respective germination parameters



GP, GS, and AGT: respectively represent Germination Percentage, Germination Rate and Average Germination Time
Figure 6 - Identification of optimal values for weed germination parameters using genetic algorithm.

optimal values identified from this analysis are summarized in Table 6. For *Echinochloa crus-galli*, the optimal values were found to be 7.22 minutes for duration and 22.46 milli-tesla for magnetic field intensity, while for *Chenopodium album*, the optimal values were 10 minutes for duration and 25 milli-tesla for intensity. These findings indicate the most effective magnetic field exposure conditions for each weed species. Although the optimal values for both species are somewhat similar, they should not be generalized.

3.2 Results of field trial experiments

In the final phase of the study, field trials were conducted to validate the laboratory findings on the optimal values for duration (T) and intensity (MF) of the magnetic field for each weed species, as shown in Table 6. Germination characteristics of Echinochloa crus-galli and Chenopodium album were evaluated with and without magnetic field treatment. ANOVA results, summarized in Table 7, revealed significant differences in average germination time (AGT), germination rate (GS), and germination percentage (GP) between the two conditions, suggesting magnetic treatment can significantly impact germination. Figure 8 shows the average GP, GS, and AGT values under different conditions. A similar study on tomato seeds indicated that magnetic treatments reduced germination time (Martinez et al., 2009). However, discrepancies between laboratory and field results were noted, likely due to differences in controlled versus field conditions and potential incompatibility of the magnetic system with field settings. The study concludes that magnetic treatment can be effective in the field, but optimal parameters should be determined using

Table 6 - Optimization of magnetic field exposure for weed germination parameters using multi-objective genetic algorithm: identification of optimum values

	Echinochloa crus-galli			Chenopodium album		
Independent variables	**GP**	**GS**	**AGT**	**GP**	**GS**	**AGT**
Duration of magnetic field (T, min)		7.22			10	
Magnetic field intensity (MF, mT)		22.46			25	
	70.60	4.65	4.12	94.36	7.90	3.71

AGT: Average Germination Time; GS: Germination Rate; and GP: Germination Percentage, represent the respective germination parameters

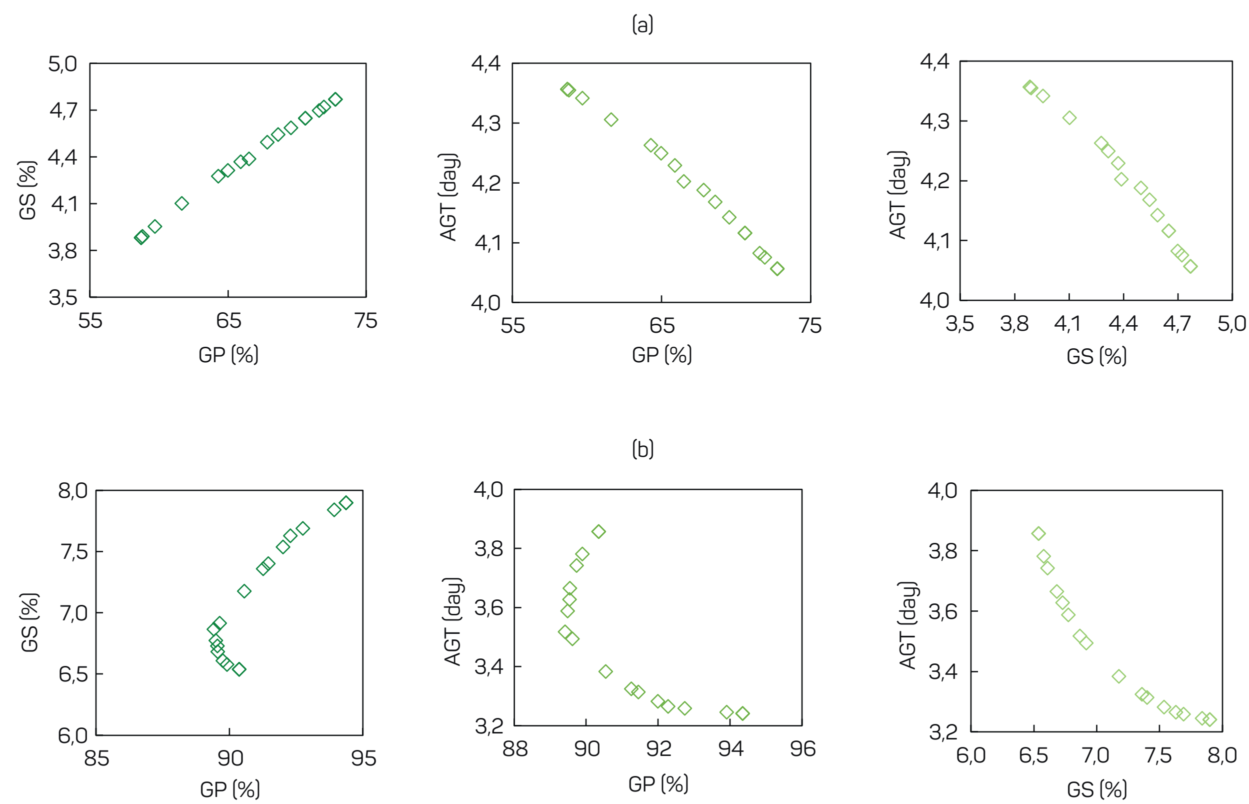


Figure 7 - Trade-off analysis of germination percentage (GP), germination rate (GS), and average germination time (AGT) using Pareto-front method for two weed species: (a) *Echinochloa crus-galli* and (b) *Chenopodium album*

the proposed approach, with further research needed for practical weed management applications.

4. Conclusion

This study investigated the effects of static magnetic field (SMF) treatments on the germination behavior of two weed species, *Chenopodium album* and *Echinochloa crus-galli*, under controlled laboratory conditions. SMF intensities of 10, 20, and 25 mT applied for 1–10 minutes produced species- and intensity-dependent responses.

1. Quadratic and reduced quadratic regression models provided the best fit, with R^2 values exceeding 0.96 for germination parameters across both species.
2. ANOVA confirmed the significance of all key factors at the 1% or 5% level, with non-significant lack-of-fit in most models, indicating strong model validity except for germination rate in *Chenopodium album*.
3. Magnetic field intensity contributed up to ~65% of the variance in germination parameters for *Echinochloa crus-galli*, whereas duration accounted for up to ~93% of the variation in average germination time for *Chenopodium album*.
4. Regression models showed 99% predictive accuracy and met all key assumptions of normality, homoscedasticity, and multicollinearity.
5. Optimal magnetic treatment increased germination rate from 3.8 to 4.75 and germination percentage from 60% to 74%, while reducing average germination time from 4.4 to 3.8 days in *Echinochloa crus-galli*. For *Chenopodium album*, germination rate rose from 5.5 to 7.65, germination percentage from 75% to 93%, and average germination time decreased from 3.85 to 3.3 days.

Table 7 - Variance analysis of germination characteristics of two types of weed in field conditions with and without magnetic treatment using optimal parameters of duration and intensity of magnetic field.

	Echinochloa crus-galli			Chenopodium album		
Source of variation	**GP**	**GS**	**AGT**	**GP**	**GS**	**AGT**
Treatment	384^{*}	1.22^{*}	3.48^{*}	42.66^{**}	1.189^{**}	6.59^{**}
Error	149.33	0.29	1.94	117.33	0.05	1.13
Coefficient of variation (%)	10.65	13.79	9.10	8.45	5.50	6.52

AGT: Average Germination Time; GS: Germination Rate; and GP: Germination Percentage, represent the respective germination parameters

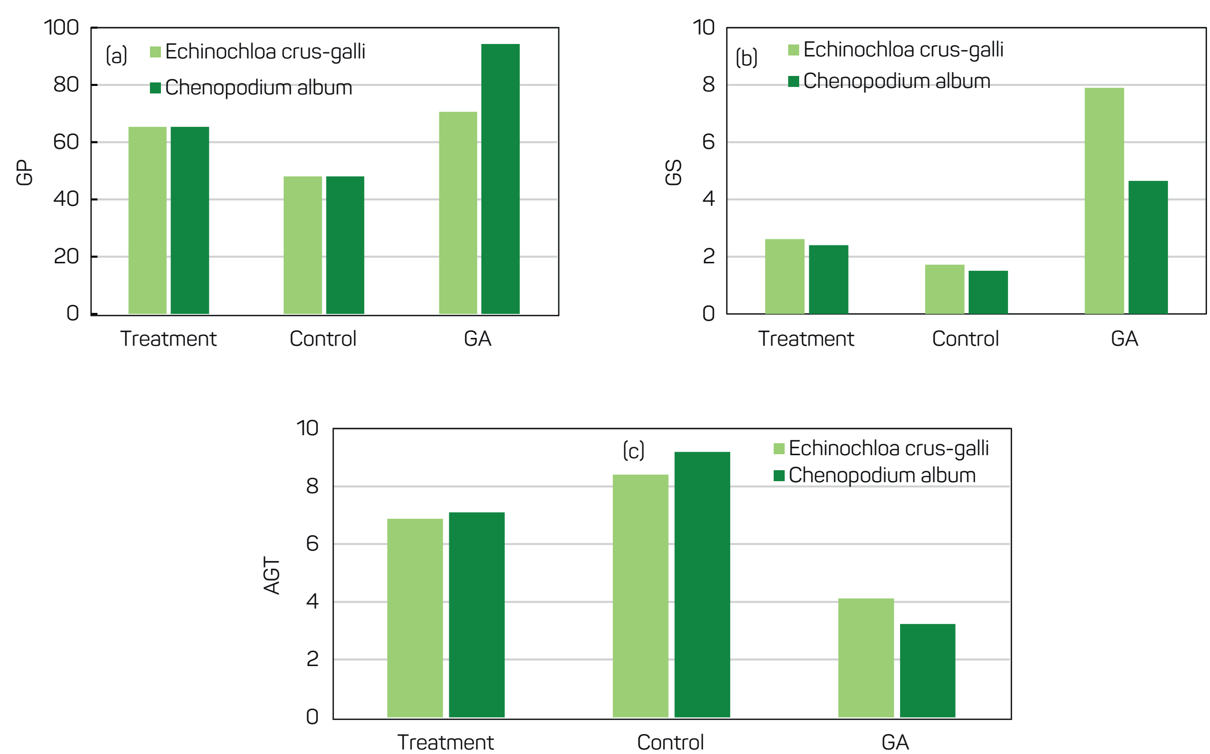


Figure 8 - A comparative analysis of germination characteristics of *Echinochloa crus-galli* and *Chenopodium album* weeds: Field experimentation with magnetic and control treatments, and genetic algorithm

6. Genetic algorithm optimization identified species-specific optimal SMF exposure conditions: 7.2 minutes and 22.5 mT for *Echinochloa crus-galli* (70.6% germination, 4.65 germination rate, 4.12 days AGT), and 10 minutes and 25 mT for *Chenopodium album* (94.4% germination, 7.9 germination rate, 3.7 days AGT), underscoring the necessity of tailored magnetic treatments for effective weed control.
7. Field trials validated the laboratory findings, showing significant increases in germination percentage (from 60% to 73% for *Echinochloa crus-galli*, and 75% to 94% for *Chenopodium album*), along with enhanced germination rate and reduced germination time, though some discrepancies with lab predictions highlight the need for further field optimization.

For practical implementation, future research should focus on long-term field evaluation of magnetic treatments under diverse environmental conditions, integration with sustainable weed management practices, and elucidation of the physiological mechanisms underlying species-specific responses. Additionally, expanding optimization studies to a broader range of weed species will enhance the applicability and robustness of magnetic treatment as a sustainable weed control strategy in agriculture.

Author's contributions

All authors read and agreed to the published version of the manuscript. MAF, AR, and MHA: conceptualization of the manuscript and development of the methodology. MAF: data collection and curation. AR: data analysis. AR, and DG: data interpretation. MHA: supervision. MAF, AR, anf DG: writing the original draft of the manuscript.

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References

Afzal I, Saleem S, Skalicky M, Javed T, Bakhtavar MA, ul Haq Z et al. Magnetic field treatments improves sunflower yield by inducing physiological and biochemical modulations in seeds. Molecules. 2021;26(7):1-14. Available from: https://doi.org/10.3390/molecules26072022

Al-Akhras MAH, Al-Quraan NA, Abu-Aloush ZA, Mousa MS, AlZoubi T, Makhadmeh GN et al. Impact of magnetized water on seed germination and seedling growth of wheat and barley. Res Eng. 2024;22:1-11. Available from: https://doi.org/10.1016/j.rineng.2024.101991

Bajwa AA, Jabran K, Shahid M, Ali HH, Chauhan BS. Eco-biology and management of Echinochloa crus-galli. Crop Prot. 2015;75:151-62. Available from: https://doi.org/10.1016/j.cropro.2015.06.001

Bukhari SA, Tanveer M, Mustafa G, Zia-Ud-Den N. Magnetic field stimulation effect on germination and antioxidant activities of presown hybrid seeds of sunflower and its seedlings. J Food Qual. 2021;2021:1-9. Available from: https://doi.org/10.1155/2021/5594183

Burnett SE, Pennisi SV, Thomas PA, Van Iersel MW. Controlled drought affects morphology and anatomy of Salvia splendens. J Am Soc Hortic Sci. 2005;130(5):775-81. Available from: https://doi.org/10.21273/JASHS.130.5.775

Cao X, Li M, Li J, Song Y, Zhang X, Yang D et al. Co-expression of hydrolase genes improves seed germination of *Sinopodophyllum hexandrum*. Ind Crops Prod. 2021;164. Available from: https://dx.doi.org/10.1016/j.indcrop.2021.113414

Cecchetti D, Pawełek A, Wyszkowska J, Antoszewski M, Szmidt-Jaworska A. Treatment of winter wheat (*Triticum aestivum* L.) seeds with electromagnetic field influences germination and phytohormone balance depending on seed size. Agronomy. 2022;12(6):1-19. Available from: https://doi.org/10.3390/agronomy12061423

Chen D, Yuan Z, Wei Z, Hu X. Effect of maternal environment on seed germination and seed yield components of *Thlaspi arvense*. Ind Crops Prod. 2022;181. Available from: https://doi.org/10.1016/j.indcrop.2022.114790

Dziergowska K, Lewandowska S, Mech R, Pol M, Detyna J, Michalak I. Soybean germination response to algae extract and a static magnetic field treatment. Appl Sci. 2021;11(18):1-18. Available from: https://doi.org/10.3390/app11188597

Ercan I, Tombuloglu H, Alqahtani N, Alotaibi B, Bamhrez M, Alshumrani R et al. Magnetic field effects on the magnetic properties, germination, chlorophyll fluorescence, and nutrient content of barley (*Hordeum vulgare* L.). Plant Physiol Biochem. 2022;170:36-48. Available from: https://doi.org/10.1016/j.plaphy.2021.11.033

Erez ME, Özbek M. Magnetic field effects on the physiologic and molecular pathway of wheat (*Triticum turgidum* L.) germination and seedling growth. Acta Phys Plant. 2023;46(1). Available from: https://doi.org/10.1007/s11738-023-03631-7

Flórez M, Carbonell MV, Martínez E. Exposure of maize seeds to stationary magnetic fields: effects on germination and early growth. Environ Exp Bot. 2007;59(1):68-75. Available from: https://doi.org/10.1016/j.envexpbot.2005.10.006

Gantait S, Mukherjee E, Bandyopadhyay P, Bhattacharyya S. M-bridge-and elicitor-assisted enhanced post-storage germination of Rauvolfia serpentina synthetic seeds, their genetic fidelity assessment and reserpine estimation. Industr Crops Prod. 2022;180. Available from: https://doi.org/10.1016/j.indcrop.2022.114732

Hossain M. Recent perspective of herbicide: review of demand and adoption in world agriculture. J Bangl Agric Univ. 2015;13(1):13-24. Available from: https://doi.org/10.22004/ag.econ.211172

Khuri AI. Response surface methodology and related topics. In: Khuri AI. Response surface methodology and related topics. Singapore: World Scientific; 2006. p. 13 - 24.

Kniss AR. Long-term trends in the intensity and relative toxicity of herbicide use. Nat Commun. 2017;8(1):1-7. Available from: https://doi.org/10.1038/ncomms14865

Luo X, Li D, Tao Y, Wang P, Yang R, Han Y. 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. 2022;383. Available from: https://doi.org/10.1016/j.foodchem.2022.132392

Martinez E, Carbonell MV, Florez M, Amaya J, Maqueda R. Germination of tomato seeds (*Lycopersicon esculentum* L.) under magnetic field. Int Agrophys. 2009;23(1):45-9.

Pastena M, Grassi M. Optimum design of a three-axis magnetic field simulator. IEEE Trans Aerosp Electron Syst. 2002;38(2):488-501. Available from: https://doi.org/10.1109/TAES.2002.1008981

Radhakrishnan R, Ranjitha Kumari BD. Pulsed magnetic field: a contemporary approach offers to enhance plant growth and yield of soybean. Plant Physiol Biochem. 2012;51:139-144. Available from: https://doi.org/10.1016/j.plaphy.2011.10.017

Sagvand M, Esfahani MN, Hadi F. Pre-sowing enrichment of Echinacea angustifolia seeds with macronutrients improved germination performance and early seedling growth via stimulating the metabolism of reserves. Ind Crops Prod. 2022;188:115614. Available from: https://doi.org/10.1016/j.indcrop.2022.115614

Sahin H, Yalınkılıc M. Using electric current as a weed control method. Eur J Eng Technol Res. 2017;2(6):59-64. Available from: https://doi.org/10.24018/ejeng.2017.2.6.379

Schuster CL, Shoup DE, Al-Khatib K. Response of common lambsquarters (Chenopodium album) to glyphosate as affected by growth stage. Weed Sci. 2007;55(2):147-51. Available from: https://doi.org/10.1614/WS-06-130.1

Semerdjieva I, Atanasova D, Maneva V, Zheljazkov V, Radoukova T, Astatkie T et al. Allelopathic effects of juniper essential oils on seed germination and seedling growth of some weed seeds. Ind Crops Prod. 2022;180. Available from: https://doi.org/10.1016/j.indcrop.2022.114768

Ureta-Leones D, García-Quintana Y, Vega-Rosete S, Pérez-Morell L, Bravo-Medina CA, Arteaga-Crespo Y. Effect of pre-germination treatment with direct magnetic field exposure: a systematic review and meta-analysis. Eur J For Res. 2021;140(5):1029-38. Available from: https://doi.org/10.1007/s10342-021-01400-0

Vashisth A, Nagarajan S. Effect on germination and early growth characteristics in sunflower (*Helianthus annuus*) seeds exposed to static magnetic field. J Plant Physiol. 2010;167(2):149-56. Available from: https://doi.org/10.1016/j.jplph.2009.08.011

Wang H, Huang Y, Zhao K, Liu W, Wang J. Greenhouse and field evaluation of the novel herbicide qyc101 for weed control in maize (*Zea mays* L.) in China. Crop Prot. 2019;124. Available from: https://doi.org/10.1016/j.cropro.2019.04.012

Wang S, Zhang X, Fan Y, Wang Y, Yang R, Wu J et al. Effect of magnetic field pretreatment on germination characteristics, phenolic biosynthesis, and antioxidant capacity of quinoa. Plant Physiol Biochem. 2024;212. Available from: https://doi.org/10.1016/j.plaphy.2024.108734

Wu X, Aravecchia S, Lottes P, Stachniss C, Pradalier C. Robotic weed control using automated weed and crop classification. J Field Robot. 2020;37(2):322-40. Available from: https://doi.org/10.1002/rob.21938