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Influence of Dynamic Magnetic Field Exposure Duration on the Germination and Growth of Khao Dawk Mali 105 Rice Seed

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Abstract

Magnetic field (MF) priming provides a chemical-free alternative to conventional methods; however, static exposure approaches are often limited by spatial heterogeneity in field–seed interaction caused by fixed seed positioning, undermining both treatment uniformity and reproducibility. To address this, the present study investigated the effects of dynamic MF exposure on the germination and early growth of Khao Dawk Mali 105 (KDML 105) rice seeds. A novel MF testing apparatus was developed using a 150 mT permanent magnet and a vortex-based air injection system designed to continuously rotate and redistribute seeds, ensuring uniform exposure. Seeds were treated for 0, 5, 10, 15, and 20 min to evaluate effects on vigor, germination, and seedling growth. The results showed that 5 and 10 min exposures significantly enhanced seed vigor (93.00% and 94.67%, respectively) compared to the control (83.33%), with 10 min yielding the highest improvement ($p < 0.05$, DMRT). Shoot and root growth also increased by 14.21% and 99.59%, respectively. These findings suggest that moderate-duration dynamic MF exposure is an efficient, eco-friendly priming technique for improving seed vigor and early growth. Future research should explore long-term agronomic impacts, economic feasibility, and varietal responses. The apparatus's scalable design supports integration into industrial seed processing lines, advancing sustainable rice production.

Keywords: magnetic field; germination and growth; Khao Dawk Mali 105 rice; air injection technique; dynamic exposure

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1. Introduction

Agriculture plays a vital role in ensuring food security and economic stability in Thailand, with rice being the nation's most important economic crop. Khao Dawk Mali 105 (KDML 105) is a premium Thai rice variety renowned for its distinctive fragrance, enjoying high demand in both domestic and international markets. Consequently, improving the productivity and quality of KDML 105 has become a primary focus of contemporary agricultural research and development [1–3]. However, challenges posed by climate change, soil degradation, and the overuse of chemical treatments necessitate environmentally friendly technologies to support sustainable rice production [4–6].

Magnetic field (MF) technology has attracted considerable attention as a non-chemical method to promote seed germination and seedling vigor [7,8]. Studies indicate that expo-

sure to magnetic fields affects essential physiological processes such as enzymatic activity, cellular metabolism, and gene expression [9,10], resulting in improved water and nutrient uptake and enhanced resilience to stress [11,12].

Numerous studies have demonstrated its effectiveness across various crops. For instance, sunflower seeds exposed to a 50 mT MF for 45 min showed reduced germination time and enhanced seedling growth [13]. Similarly, MF priming in *Phaseolus vulgaris* L. significantly improved germination energy and vigor, along with notable increases in leaf fresh weight during specific growth stages [14]. In rice, exposure to a 343 mT MF for 72 h increased the germination rate to 90%, compared to 50% in the control group [15]. Moreover, MF intensities ranging from 7 mT significantly improved germination rate, root and shoot length, and total biomass in barley seeds [16].The effectiveness of MF priming is highly influenced by factors such as MF generation method, field intensity, exposure duration, and seed exposure pattern [15,17–21]. Most previous studies employed static MF exposure, where seeds remain stationary during treatment [15,17,19–23]. However, static exposure can result in non-uniform magnetic field distribution and inconsistent exposure due to spatial variations in magnetic flux density [24,25], leading to increased variability and reduced reproducibility. To overcome these limitations, dynamic MF exposure systems that induce continuous seed movement during treatment have emerged as a promising alternative.

This study introduces a novel dynamic magnetic field testing apparatus specifically developed for rice seed treatment. Unlike traditional static systems, this apparatus integrates a vortex-based air injection mechanism that continuously circulates rice seeds, ensuring uniform exposure to a stable 150 mT magnetic field. This dynamic system is designed to reduce spatial field variation and enhance exposure uniformity, thereby improving experimental reproducibility. The comparative mechanism of seed exposure under static and dynamic conditions is illustrated in Figure 1, which highlights how the vortex-based system promotes more uniform and reproducible seed treatment conditions. The primary objective of this study is to evaluate the effects of different magnetic field exposure durations (0, 5, 10, 15, and 20 min) on the germination, vigor, and early growth of KDML 105 rice seeds. The findings provide insights into optimizing dynamic MF priming for rice and contribute to the development of scalable, eco-friendly seed enhancement technologies.

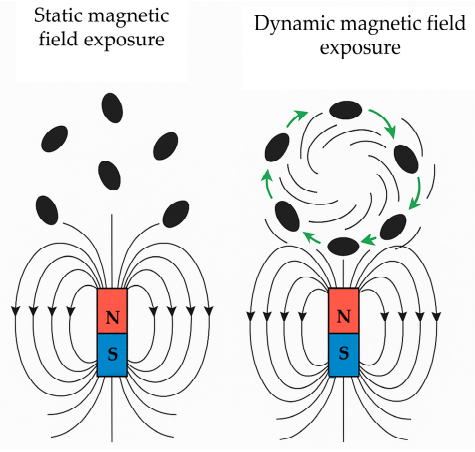


Figure 1. Schematic comparison of static vs. dynamic magnetic field exposure (vortex-based system) for rice seed treatment. The black arrows indicate the magnetic field lines, while the green arrows represent the turbulent vortex flow induced by air injection, which facilitates dynamic seed movement during treatment.

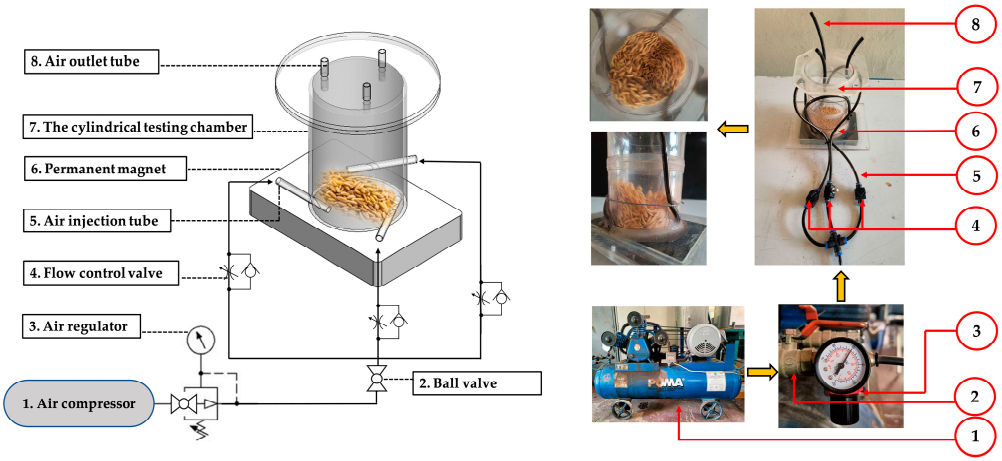
2. Materials and Methods

2.1. Rice Seed Samples

Paddy seeds (*Oryza sativa* L., cultivar Khao Dawk Mali 105, KDML 105) used in this study were harvested from a field located in Nakhon Phanom Province, Thailand. A single batch of seeds was obtained from the 2023 harvest season. Freshly harvested seeds were subjected to sun drying until they reached an optimal moisture content of approximately 14% on a wet basis [1]. After drying, the rice seeds were thoroughly cleaned to remove contaminants and inferior seeds [26], and subsequently stored in plastic containers under controlled conditions (25 ± 3 °C, 60 ± 10% relative humidity) for eight weeks. This storage period allowed for the natural release of dormancy and minimized its potential interference with germination performance. Seed dormancy was assessed following the method described in [27], where seed vigor and germination were evaluated to confirm the release of dormancy prior to magnetic field exposure and subsequent germination testing.

2.2. Magnetic Field Tester for KDML 105 Rice Seeds

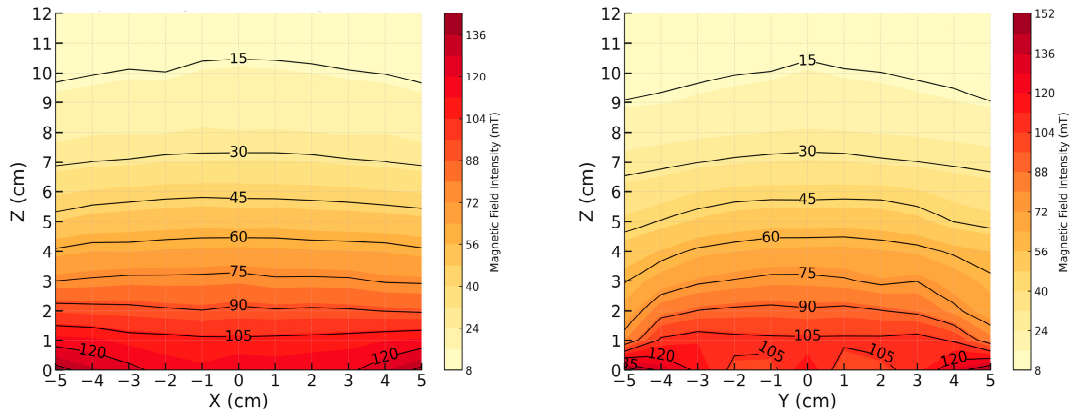
A magnetic field testing apparatus was newly developed to deliver precise and uniform magnetic field exposure to KDML 105 rice seeds while addressing the limitations of conventional static exposure methods (Figure 2). The system integrates several essential components to ensure effective and consistent seed treatment. At the core of the apparatus is a permanent ferrite magnet (6), measuring 150 mm in length, 100 mm in width, and 25 mm in thickness. It generates a maximum magnetic field intensity of 150 mT, which was quantitatively mapped and verified using a digital magnetometer (Tenmars TM-197, Tenmars Electronics Co., Taipei, Taiwan). A transparent cylindrical testing chamber (7), with a diameter of 100 mm and a height of 120 mm, is mounted directly above the magnet. This configuration allows real-time observation of seed movement and distribution during treatment. To ensure homogeneous exposure across the magnetic field, compressed air at 4 bars is introduced through three injection inlets (5) at the chamber base, generating a strong vortex motion that continuously circulates and redistributes the seeds across the magnetic field lines. Airflow is precisely regulated using a system comprising the air compressor (1), ball valve (2), air pressure regulator (3), and flow control valves (4). This setup prevents seed clustering, overexposure, and mechanical damage, ensuring uniform exposure throughout the treatment process.



(**a**) (**b**)

Figure 2. Schematic diagram (**a**) and actual photograph (**b**) of the magnetic field testing apparatus with air injection system for seed rotation.

The uniformity of the magnetic field within the exposure chamber was quantitatively assessed through detailed field mapping using the previously described magnetometer (TM-197). Measurements were taken along the radial (X and Y) and vertical (Z) axes at 10 mm intervals. The X-axis corresponded to the magnet's length (150 mm), the Y-axis to its width (100 mm), and the Z-axis to the vertical distance from the magnet surface to the top of the chamber. Mapping was performed on a central plane of the chamber, beginning with measurements at multiple XY positions directly on the magnet surface. Successive Z-axis measurements were then taken to capture the full vertical profile of the magnetic field distribution. The resulting data revealed a gradual attenuation in field intensity along the Z-axis, with excellent radial uniformity across both X and Y directions (Figure 3a,b).



(**a**) (**b**)

Figure 3. Mapping of the magnetic field in the magnetic field testing apparatus: (**a**) ZX plane; (**b**) ZY plane, showing the spatial distribution of magnetic flux density to assess field uniformity across the seed exposure region.

Although the initial seed layer had an approximate thickness of 20 mm, dynamic air injection during operation caused vigorous vertical seed movement, expanding the seed cloud to approximately 65 mm in height. The mapped magnetic field confirmed that flux density remained sufficiently uniform across this dynamic range, ensuring consistent seed exposure throughout the vortex circulation zone. All measurements were conducted under controlled laboratory conditions, with temperature and relative humidity maintained at 25 ± 2 °C and 60 ± 5% RH, respectively.

2.3. Investigation of Rice Seed Movement and Distribution in the Magnetic Field Testing Apparatus

Rice seed movement and spatial distribution were assessed to verify uniform magnetic field exposure, ensuring the validity of subsequent germination and growth results. For this assessment, rice seeds were dyed using food-grade dyes in four distinct colors (red, black, green, yellow). The dyed seeds were used solely for evaluating seed distribution and were not included in any germination or growth experiments. A total of 100 g of dyed seeds was loaded into the magnetic field testing chamber. The apparatus operated at a maximum magnetic field intensity of 150 mT with a 4-bar airflow to induce vortex motion. Seed distribution was evaluated at five time points: 1, 5, 10, 15, and 20 min. At each time point, the airflow was halted to stop seed movement, and the chamber was segmented into four radial quadrants. Seeds from each quadrant were carefully collected, separated by color, and weighed. The percentage of seed weight for each color within each quadrant was calculated to quantify spatial distribution and mixing efficiency.

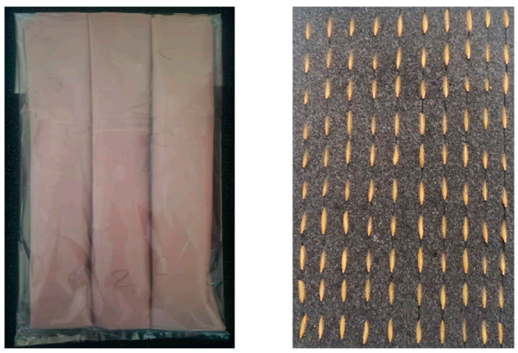
2.4. Effects of Magnetic Field Exposure on Seed Germination and Seedling Growth

Exposure durations of 0 (control), 5, 10, 15, and 20 min were selected based on preliminary trials and literature indicating that both the duration and intensity of magnetic field exposure critically influence seed vigor and seedling growth [17,28,29]. This range was chosen to encompass both short and extended exposures, enabling the identification of an optimal treatment window for KDML 105 rice seeds. To evaluate the effects of magnetic field exposure, untreated KDML 105 rice seeds (non-dyed) were exposed to a dynamic magnetic field with a maximum intensity of 150 mT, as characterized in Section 2.2. Germination performance was evaluated using the between paper (BP) method, following ISTA standards [30], with 100 seeds per treatment. The seeds were placed on moistened filter paper, covered with another layer of paper, and wrapped in plastic film to prevent moisture loss. The papers were then incubated at 25 ± 2 °C in a germination chamber and monitored for 14 days, with three replicates per treatment. Germination vigor was assessed at two time points: germination vigor on day 2 and day 5, reflecting the early growth potential of the seeds. The final germination percentage (G%) was determined on day 14 using the following equation [31].

$$\mathrm{G}\ (\%) = \frac{N_i}{\mathrm{N}} \times 100$$

where N_i is the number of normally germinated seeds and N is the total number tested. Normally germinated seeds were defined as those producing healthy seedlings with both a well-developed radicle and shoot, free from fungal contamination, necrosis, decay, or physical damage. Abnormal seedlings, dead seeds, and seeds exhibiting mold infection or morphological defects were excluded from the count.

To further investigate seedling growth, seed germination was conducted on 20 mm thick moist sponges to evaluate shoot and root development. Seeds were placed on the sponges inside transparent plastic boxes and incubated under laboratory conditions exposed to natural day/night light cycles. The light intensity and photoperiod were not actively controlled to mimic typical ambient laboratory conditions. All experiments were germinated simultaneously under identical environmental conditions for 14 days, with three replications per treatment. Shoot length was measured on days 6, 10, and 14, and root length on day 14. Fresh weights of shoots and roots were recorded immediately after harvest using a precision electronic balance (AND GF-300, A&D Company Ltd., Tokyo, Japan; accuracy ±0.001 g). Dry weights were determined after oven-drying at 80 °C for 48 h [18,22]. The two germination methods employed in this study, between paper and sponge medium, are illustrated in Figure 4.



(**a**) (**b**)

Figure 4. Germination methods used in this study for evaluating seed germination and seedling growth: (**a**) between paper method; (**b**) sponge medium method.

2.5. Statistical Analysis

All experimental data related to seed germination and seedling growth parameters were statistically analyzed using one-way analysis of variance (ANOVA) to determine significant differences among the treatment groups. Prior to the analysis, data were tested for normality and homogeneity of variances using the Shapiro–Wilk and Levene's tests, respectively, to ensure the validity of the assumptions. All statistical assumptions were verified before proceeding. Where significant differences were identified, Duncan's New Multiple Range Test (DMRT) was applied as a post hoc test to identify specific differences between treatment means at the 0.05 significance level. Results are reported as mean ± standard deviation (SD). Statistical analyses were conducted using IBM SPSS Statistics version 22.

3. Results

3.1. Evaluation of Rice Seed Distribution in the Magnetic Field Testing Apparatus

The uniformity of seed exposure within the magnetic field testing apparatus was evaluated by analyzing the distribution of rice seeds at four predefined sampling positions. During each test, seeds were circulated dynamically under the influence of the air vortex system. After magnetic field exposure, samples were collected from each designated position, and the percentage of seed weight at each location was determined to assess the spatial distribution of seed mass. As summarized in Table 1, the results indicated no significant differences in seed distribution across the four sampling positions ($p \geq 0.05$), confirming that the rice seeds were uniformly exposed to the magnetic field during dynamic operation. This finding validates the effectiveness of the vortex-based air injection system in promoting homogeneous seed mixing and ensuring consistent exposure across the entire seed batch.

Table 1. Seed weight percentages of colored rice seeds across sampling positions at different time points during dynamic magnetic field exposure. No statistically significant differences were observed among sampling positions ($p \geq 0.05$).

Position	Color	Spatial Distribution of Seed Weight (%)				
		1 min	5 min	10 min	15 min	20 min
1	Black	24.90 ± 1.44	25.75 ± 0.67	24.38 ± 1.97	24.55 ± 2.05	24.96 ± 0.74
	Red	25.62 ± 0.72	25.77 ± 0.31	25.06 ± 1.49	24.74 ± 1.09	24.31 ± 1.22
	Green	24.02 ± 0.48	24.94 ± 0.75	25.08 ± 1.01	25.36 ± 1.58	24.63 ± 1.77
	Yellow	25.46 ± 1.26	23.54 ± 0.63	25.47 ± 0.60	25.35 ± 1.58	25.69 ± 1.68
2	Black	25.37 ± 0.88	23.67 ± 1.46	26.04 ± 0.76	25.88 ± 1.06	26.03 ± 0.88
	Red	24.37 ± 0.88	26.06 ± 1.00	24.85 ± 0.44	25.00 ± 1.76	25.54 ± 1.02
	Green	25.38 ± 1.13	24.57 ± 1.39	24.15 ± 1.19	25.00 ± 1.48	24.35 ± 1.41
	Yellow	24.88 ± 0.94	25.70 ± 1.14	24.96 ± 1.82	24.13 ± 1.01	24.08 ± 1.18
3	Black	25.02 ± 1.46	25.10 ± 1.28	25.80 ± 1.64	24.12 ± 0.66	25.38 ± 2.07
	Red	25.03 ± 0.91	24.08 ± 1.38	24.51 ± 1.36	25.57 ± 1.03	23.91 ± 1.68
	Green	24.83 ± 1.67	25.79 ± 0.29	26.07 ± 1.22	24.90 ± 2.44	24.83 ± 1.64
	Yellow	25.12 ± 0.73	25.04 ± 1.57	23.61 ± 0.73	25.40 ± 2.30	25.88 ± 1.36
4	Black	24.07 ± 1.37	26.23 ± 1.35	25.32 ± 1.34	26.14 ± 0.40	25.27 ± 0.60
	Red	23.99 ± 1.29	23.56 ± 0.55	25.39 ± 0.89	24.94 ± 0.99	24.37 ± 0.43
	Green	25.74 ± 0.89	24.72 ± 2.29	24.50 ± 1.50	25.04 ± 0.67	25.97 ± 0.73
	Yellow	26.19 ± 0.68	25.48 ± 1.74	24.79 ± 2.16	23.88 ± 0.50	24.39 ± 1.69

3.2. Impact of Magnetic Field Treatment on Seed Vigor and Germination

The effects of magnetic field exposure on seed vigor and germination were evaluated to determine its potential in enhancing early seedling development. Figure 5 illustrates seed

vigor at days 2 and 5, as well as final germination percentage at day 14 across treatments. On day 2, the 10 min exposure yielded the highest seed vigor (94.67%), followed by the 5 min treatment (93.00%), both significantly greater than the control (83.33%) ($p = 0.008$). By day 5, vigor reached 100% for the 10 min treatment and 99.67% for the 5 min treatment, compared to 97.33% in the control group ($p = 0.010$). These results confirm that short-duration exposures (5–10 min) significantly improved seed vigor at both time points. Conversely, longer exposures (15 and 20 min) showed no additional benefits.

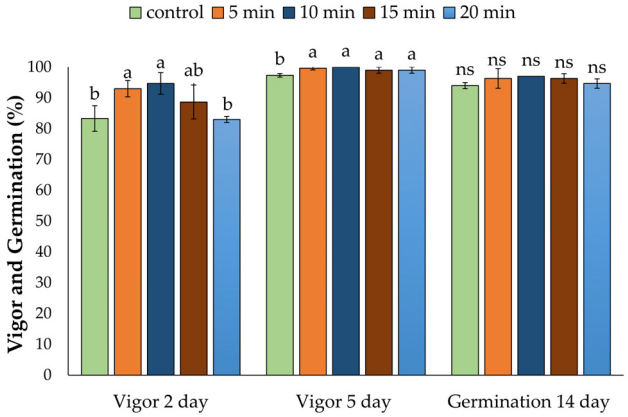


Figure 5. Effects of magnetic field exposure duration (0–20 min) on seed vigor and final germination percentage of KDML 105 rice seeds. Data represent mean ± SD. Different letters indicate significant differences ($p < 0.05$); ns = not significant.

For total germination at day 14, no significant differences were observed among treatments ($p = 0.271$), although slight variability in standard deviations was noted. These findings indicate that magnetic field exposure predominantly enhances early vigor rather than final germination rate. Therefore, moderate-duration exposure (5–10 min) may serve as an effective priming strategy for promoting rapid and uniform seedling establishment.

3.3. Effects of Magnetic Field Treatment on Shoot Length of Rice Seedlings

Figure 6 presents the effects of magnetic field exposure (0, 5, 10, 15, and 20 min) on shoot length measured at 6, 10, and 14 days post-germination. The results demonstrate that magnetic exposure prior to germination significantly promoted shoot elongation across all measured time points compared to the control group. At day 6, seedlings from all magnetic treatment groups exhibited significantly greater shoot lengths than the control ($p = 0.0001$). At day 10, a similar trend was observed: all magnetic exposure groups showed significantly longer shoots than the control ($p = 0.0106$), while no significant differences were detected among the treatments themselves. This consistency suggests that even short-duration exposure can positively influence shoot development during early growth. By day 14, significant differences among treatments were further accentuated ($p = 0.0072$). The 10 min exposure group exhibited the greatest shoot length, significantly surpassing both the control and the longer exposure groups (15 and 20 min). The 5 min treatment also maintained a significant advantage over the control, although it was slightly lower than the 10 min treatment. In contrast, the 15 and 20 min treatments did not confer additional benefits and, in some cases, resulted in reduced shoot length compared to the 10 min group. This suggests that while moderate magnetic field exposure (5–10 min) enhances early shoot growth, excessive exposure may not yield further improvements and could potentially limit elongation during later stages.

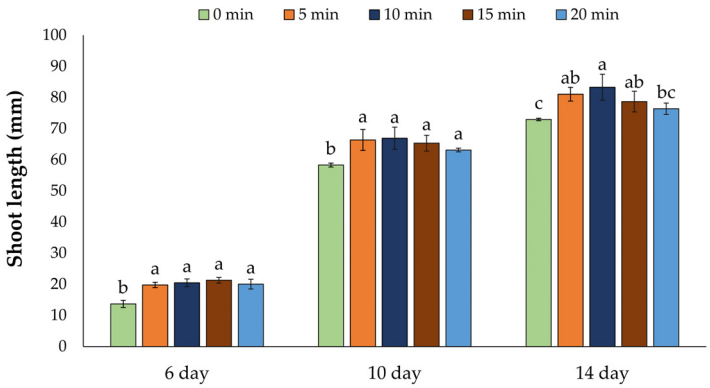


Figure 6. Effects of magnetic field exposure duration (0–20 min) on shoot length of KDML 105 rice seedlings. Different superscript letters above the bars indicate statistically significant differences ($p < 0.05$) within the same time point (days 6, 10, and 14). Bars sharing the same superscript letter are not significantly different.

3.4. Effects of Magnetic Field Treatment on Root Growth and Biomass Accumulation in Rice Seedlings

Table 2 presents the effects of magnetic field exposure (0, 5, 10, 15, and 20 min) on root length and biomass accumulation in KDML 105 rice seedlings at day 14. The results indicate that magnetic field treatment significantly influenced several growth parameters, particularly root elongation and shoot biomass accumulation, depending on exposure duration and the specific parameter assessed. Visual evidence of seedling morphology and root distribution is provided in Figures 7 and 8.

Table 2. Effects of magnetic field treatment on root length and biomass accumulation in KDML 105 rice seedlings at day 14. Different superscript letters within the same column indicate statistically significant differences ($p < 0.05$); values sharing the same letter are not significantly different. "ns" stands for "not significant".

Treatments	Root Length (mm)	Root Fresh Weight (mg)	Shoot Fresh Weight (mg)	Root Dry Weight (mg)	Shoot Dry Weight (mg)
Control	$16.90^{c} \pm 1.23$	$16.33^{a} \pm 1.90$	$36.26^{c} \pm 2.33$	$2.98^{b} \pm 0.22$	$6.45^{ns} \pm 0.40$
5 min	$27.78^{ab} \pm 7.53$	$14.93^{a} \pm 0.06$	$39.52^{b} \pm 0.75$	$3.11^{ab} \pm 0.11$	$6.48^{ns} \pm 0.07$
10 min	$33.81^{a} \pm 4.14$	$16.56^{a} \pm 0.56$	$42.67^{a} \pm 0.30$	$3.33^{a} \pm 0.11$	$6.52^{ns} \pm 0.07$
15 min	$26.41^{ab} \pm 2.39$	$12.70^{b} \pm 0.57$	$40.26^{b} \pm 0.34$	$3.04^{b} \pm 0.13$	$6.70^{ns} \pm 0.23$
20 min	$23.92^{bc} \pm 1.14$	$12.74^{b} \pm 1.27$	$40.33^{b} \pm 0.89$	$2.85^{b} \pm 0.06$	$6.56^{ns} \pm 0.00$

Root length was significantly enhanced by magnetic field exposure ($p = 0.006$). The 10 min treatment group exhibited the longest roots (33.81 mm), nearly doubling the root length of the control group (16.90 mm). The 5 min (27.78 mm) and 15 min (26.41 mm) groups also showed significant improvements over the control, though to a lesser extent. In contrast, the 20 min treatment resulted in a reduced root length (23.92 mm), suggesting that excessive exposure may hinder root elongation. This trend is visually supported by Figures 7 and 8, where the 10 min treatment clearly produced the most robust and well-developed root systems, whereas roots in the 20 min group appeared shorter and less extensive.

Root fresh weight also varied significantly among treatments ($p = 0.002$). The 10 min group exhibited the highest mean root fresh weight (16.56 mg), indicating that moderate magnetic exposure effectively promoted root biomass accumulation. However, prolonged exposures (15 and 20 min) led to significantly lower root fresh weights (12.70 mg and 12.74 mg, respectively). In terms of shoot fresh weight, the influence of magnetic treatment

remained evident (p = 0.001). The 10 min exposure led to the greatest shoot fresh weight, significantly exceeding that of the control. Moreover, both the 5 min and 15 min treatments also enhanced shoot fresh weight compared to the control, though to a lesser extent than the 10 min exposure.



Figure 7. Effects of magnetic field treatment on seedling growth and root development in KDML 105 rice at day 14.



Figure 8. Effects of magnetic field treatment on root distribution of KDML 105 rice seedlings grown on sponge medium at day 14.

Root dry weight exhibited significant variation (p = 0.01), with the 10 min group again recording the highest value (3.33 mg). This finding suggests that 10 min of magnetic exposure facilitates the accumulation of dry matter in roots. Notably, extended exposure (20 min) resulted in reduced root dry weight (2.85 mg), aligning with the observed reduction in root length and fresh weight. Shoot dry weight did not differ significantly among treatments (p = 0.634), indicating that while magnetic exposure enhanced root elongation and shoot fresh biomass accumulation, it had no measurable impact on shoot dry matter content at this stage.

4. Discussion

This study demonstrated that magnetic field priming, applied dynamically using a vortex-based system, can significantly enhance the early vigor and root growth of KDML 105 rice seedlings. The dynamic exposure approach employed herein overcomes the limitations associated with conventional static exposure methods by ensuring uniform seed movement and consistent magnetic field interaction. As illustrated in Figure 1, this vortex-based system facilitated homogeneous exposure, which was further supported by the seed distribution data presented in Table 1.

Among all tested durations, 5 and 10 min exposures yielded the most notable improvements in vigor and seedling growth. Both shoot and root elongation were significantly enhanced relative to the control. Although final germination percentages at day 14 were similar across all treatments, the distinct advantage in early vigor observed in the magnetically treated seeds may offer agronomic benefits by accelerating stand establishment and reducing susceptibility to environmental stress during early growth stages [9,32,33]. Growth parameter data (Table 2) further confirmed the efficacy of MF treatment, with 10 min exposure nearly doubling root length and significantly increasing shoot fresh weight. However, extended exposure (15–20 min) failed to provide additional benefits and in some cases even suppressed growth, consistent with earlier studies attributing such effects to oxidative stress and cellular disruption [7,34,35], although such mechanisms were not directly assessed in the present study.

The mechanisms through which magnetic fields influence plant growth are complex and multifaceted. Recent studies suggest that the beneficial effects of magnetic field priming on seedling development may result from a combination of physiological and biochemical responses initiated during the early stages of germination. In the present study, the observed enhancement in seed vigor and accelerated seedling growth under dynamic MF exposure may be partially attributed to improved water uptake, facilitated by increased membrane permeability, which promotes faster and more uniform germination [19,36–39]. Moreover, magnetic field stimulation has been reported to enhance ion transport and nutrient assimilation, thereby supplying essential resources for active cellular metabolism and growth [7,40,41]. Magnetic field exposure may also activate key metabolic pathways, enhancing energy metabolism and biosynthetic activity [9,10], while concurrently modulating phytohormone signaling networks particularly those involving gibberellins and auxins which are known to regulate root and shoot development [42]. In addition, magnetic priming may alter the expression of genes involved in stress tolerance and macromolecular synthesis (DNA/RNA), further contributing to enhanced seedling establishment [10,43,44]. The improved shoot biomass and root elongation observed in the 10 min exposure group align with these proposed mechanisms, although the present study did not directly examine molecular or transcriptomic responses. While no significant differences in shoot dry weight were detected among treatments [14], the observed increases in fresh biomass imply enhanced water absorption and cellular expansion during early growth, consistent with findings in soybean and other model species subjected to MF priming [38]. Thus, it can be seen that these effects collectively may contribute to the observed improvements in rice seedling performance under the dynamic magnetic field priming conditions employed in this study, supporting the potential utility of this technique in enhancing early crop establishment.

From an agricultural perspective, enhancing seed vigor, promoting robust root development, and accelerating tiller emergence are critical for successful field establishment and may ultimately contribute to yield improvement. For instance, the development of deeper root systems facilitates more efficient uptake of water and nutrients, offering particular advantages in drought-prone environments [45]. In this context, magnetic field priming represents a non-chemical, environmentally sustainable alternative to conventional seed coating or chemical priming methods. While seed coating can de-liver targeted protection or nutrient enhancement, it often incurs additional processing costs and raises environmental concerns due to residual chemicals. In contrast, the magnetic field approach requires no chemical input and is readily scalable, especially using the dynamic apparatus developed in this study. The effectiveness of short exposure durations further supports its feasibility for industrial applications.

Although 10 min exposure delivered the highest growth improvements, the 5 min treatment produced comparable results with reduced processing time, highlighting its potential as a time-efficient option for large-scale operations. Nevertheless, further research is needed to evaluate the long-term effects on yield and grain quality. Additionally, future studies should investigate varietal responses and construct a spatial model correlating magnetic flux density with seed positioning to optimize treatment uniformity. Field trials and economic feasibility assessments will also be crucial for practical adoption in commercial seed enhancement systems.

5. Conclusions

This study successfully developed a dynamic magnetic field testing apparatus that achieved uniform seed distribution using a 4-bar air injection system, effectively overcoming the limitations of static exposure methods. The system enhanced experimental precision and increased sample throughput, making it suitable for scalable agricultural applications. Exposure of KDML 105 rice seeds to a 150 mT magnetic field for 5 and 10 min significantly improved germination vigor and early seedling development. The 10 min treatment produced the highest vigor (94.67%), representing an 11.34% increase compared to the control, along with 14.21% and 99.88% increases in shoot and root growth, respectively. Notably, the 5 min treatment yielded comparable results while offering the advantage of reduced processing time, indicating its potential as a more time-efficient and practical option for large-scale implementation.

These findings highlight the potential of magnetic field technology as a chemical-free and eco-friendly approach to enhancing seed vigor, accelerating early growth, and improving resource efficiency in sustainable agriculture. The system demonstrates broad applicability across various crop types, including cereals and vegetables, serving as a flexible tool for seed quality enhancement. In comparison to conventional priming methods such as hydropriming, osmopriming, and chemical priming, this magnetic field-based approach offers clear advantages as a dry, rapid, and residue-free process that eliminates the need for chemical agents and post-treatment drying, facilitating seamless integration into scalable commercial seed enhancement systems.

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