Agrotrop : Journal on Agriculture Science, 16(3): 298-311 (2026)
ISSN: 2654-4008 (Online), 2088-155X (Print)
URL: https://ejournal2.unud.ac.id/index.php/agrotrop
DOI: https://doi.org/10.24843/AJoAS.2026.v16.i03.p09
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The Influence of Ferrite and Neodymium Induced Magnetic Fields on the Growth of Yellow Dragon Fruit (*Selenicereus megalanthus*) Seeds

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ABSTRACT

This study aimed to analyze the effects of ferrite and neodymium magnetic fields on the germination and early growth of yellow dragon fruit (Selenicereus megalanthus) seeds. Conducted over 28 days, the research employed a non-factorial Completely Randomized Design (CRD) with three treatments: a control without a magnetic field (PK), a 1500 µT ferrite magnetic field (PF), and a 2200 µT neodymium magnetic field (PN), each comprising 10 replicates (30 experimental units). Parameters included the number of germinated seeds, germination rate, germination capacity, root length, and shoot length on days 7, 14, 21, and 28. Data were analyzed using One-Way ANOVA (α=0.05), followed by Tukey's HSD test. Results demonstrated that magnetic field treatments exerted a highly significant effect on all observed parameters ($p<0.001$). The PN treatment produced the highest responses: an average of 3.70 germinated seeds, 92.50% germination capacity, 0.868 cm root length, and 2.437 cm shoot length by day 28. The PF treatment yielded 2.60 germinated seeds, 65.00% germination capacity, 0.593 cm root length, and 1.665 cm shoot length. The control exhibited the lowest values. Tukey's HSD confirmed significant differences among all groups, reflecting a response pattern of PN > PF > PK. The 2200 µT neodymium magnetic field proved most effective in enhancing germination and early growth. These findings highlight magneto-priming as a viable, non-chemical physical approach for efficient seedling production. The consistent growth response under neodymium treatment indicates enhanced seedling vigor throughout the observation period. Future research should assess varying intensities and exposure durations to optimize treatments. This study provides an experimental foundation for integrating magnetic field-based seed treatments into sustainable horticulture.

Keywords: yellow dragon fruit, Selenicereus megalanthus, magnetic field, magneto-priming, ferrite, neodymium, germination, early growth

INTRODUCTION

Agriculture constitutes a highly dominant sector regarding public income in Indonesia, as the majority of the population is engaged in farming (Wiryanata and Owa, 2021). The enhancement of seedling productivity and quality represents a crucial aspect of horticultural cultivation practices. The adequate availability of superior seedlings is an indispensable prerequisite for achieving maximal and sustainable production yields (Dewi *et al*., 2025). This

applies to high-economic-value species, such as the yellow dragon fruit (*Selenicereus megalanthus*). Yellow dragon fruit exhibits substantial potential as an agricultural commodity, driven by its superior nutritional profile and the continuous surge in global market demand. One of the primary obstacles that must be overcome in intensive cultivation is the procurement of high-quality seeds. These seeds are required to demonstrate rapid and uniform germination rates, accompanied by optimal initial vigor immediately following sowing. Ensuring premium seed quality from the outset is paramount for establishing a uniform and healthy plant population, ultimately yielding abundant and high-quality fruit harvests. Furthermore, nutrient absorption efficiency remains a focal point in organic plant breeding (Wiryanata, 2024).

The evolution of modern agricultural systems has introduced various innovative solutions capable of enhancing efficiency, productivity, and sustainability in food production (Wiryanata, 2025). Innovative non-chemical approaches are currently gaining traction as promising solutions to address seed quality challenges within sustainable agricultural systems. Elevated activity of the α-amylase enzyme, which is involved in carbohydrate mobilization as an energy source for seeds, can accelerate the process of dormancy breaking and germination without the requisite of chemical agents (Prasetyo, 2020). Phytohormones such as gibberellins (GA) and auxins (IAA) play a pivotal role in regulating seed dormancy and accelerating its termination. Gibberellins are frequently utilized to break seed dormancy while simultaneously stimulating synchronous flowering, thereby resulting in uniform harvest times (Wiryanata *et al.,* 2026). Magnetic fields can modify this hormonal balance, leading to an enhanced initial growth rate and more effective seed dormancy breaking. Such hormonal modulation influences germination velocity as well as the quality of early-stage growth. Consequently, plants exposed to magnetic fields tend to exhibit more uniform and accelerated growth, alongside improvements in vegetative parameters such as plant height, leaf number, and biomass. The physiological processes modified by magnetic fields confer significant advantages in improving plant growth efficiency, holding substantial potential for augmenting overall agricultural yields (Ramadhani *et al*., 2022).

A physical technology known as pre-sowing magnetic field treatment, frequently referred to as magneto-priming, is emerging as a potential method to improve seed characteristics and promote robust early plant growth. This relatively simple yet sophisticated treatment involves exposing seeds to magnetic fields of specific intensities prior to sowing, with the objective of triggering beneficial metabolic and physiological processes within the seed embryo. This technique offers an eco-friendly alternative to the application of chemical substances, rendering it a highly relevant strategy for enhancing the germinability and vigor of yellow dragon fruit seedlings, thereby contributing directly to the efficiency and output of sustainable agricultural cultivation. Magnetic fields represent a physical phenomenon capable of influencing molecular structures and physiological processes within biological systems. Empirical evidence suggests that exposing seeds to specific magnetic field intensities prior to sowing can alter the imbibition process, augment the activity of enzymes responsible for mobilizing seed food reserves, and stimulate initial seed metabolism; thus accelerating and improving both germination outcomes and early plant growth. Previous studies have demonstrated that exposure to Extremely Low Frequency (ELF) magnetic fields affects the vegetative growth of crops such as tomatoes, mustard greens, edamame,

and mushrooms by enhancing growth parameters including plant height, leaf number, and biomass which vary contingent upon the field intensity and exposure duration (Ramadhani *et al.,* 2022).

Research on seeds indicates the impact of magnetic fields on germination duration and velocity. A study on mung bean sprouts reported that magnetic field exposure accelerates seed water absorption and stimulates α-amylase enzyme activity, which is crucial for germination and early growth processes, without the need for external chemicals (Prasetyo, 2020). Magneto-priming experiments conducted on tomato seeds have shown that the application of magnetic fields from neodymium magnets significantly increases the germination rate, shoot and root lengths, as well as tolerance to stress conditions such as salinity. These results indicate that permanent magnetic fields with specific polarities and intensities elicit distinct physiological responses in seeds during their initial growth phases (Abhary *et al.,* 2023). Prior research on rice has also indicated that low intensity magnetic fields can influence the generative growth parameters of the plants, although these effects are similarly modulated by the exposure duration and the applied field intensity (Qudsiyah *et al*., 2025). This underscores the complexity of plant responses to magnetic fields and highlights the necessity for comparative studies across various seed types, including yellow dragon fruit, which physiologically possesses unique germination characteristics. Meanwhile, research on red pomegranate seeds concluded that the duration of exposure and the strength of the electromagnetic field influence dormancy breaking and seed germination, demonstrating that magnetic field parameters—such as exposure duration and field magnitude—must be meticulously considered in the design of seed growth studies (Rahmawati *et al*., 2023).

Ferrite magnets are ceramic magnets possessing a moderate magnetic field, whereas neodymium magnets are known as rare-earth magnets with exceptionally strong magnetic fields; thereby providing distinct field variations to stimulate seeds under controlled conditions. The objective of this study is to determine the differences and the effects of magnetic fields generated by ferrite and neodymium magnets on the growth of yellow dragon fruit seeds. Research concerning the effects of ferrite and neodymium magnetic field treatments on yellow dragon fruit seed growth is imperative to definitively identify whether magnetic field interventions can exert a significant influence on accelerating the germination process and early growth stages. Furthermore, it aims to comprehensively compare the effects generated by these two distinct types of permanent magnetic field sources on various seed growth parameters, and to provide valid recommendations regarding practical and efficient non-chemical physical nursery techniques for broader implementation within the tropical fruit agribusiness sector.

MATERIALS AND METHODS

The research materials consisted of yellow dragon fruit (Selenicereus megalanthus) seeds obtained from mature, healthy, and morphologically uniform fruits sourced from a reliable supplier. The seeds were thoroughly washed, air-dried, and carefully selected to ensure uniformity in size and physical condition prior to treatment. Four yellow dragon fruit seeds were directly sown in rockwool, with magnets attached to both sides of the rockwool, and subsequently placed inside a plastic container. Plant moisture was maintained by regular irrigation using mineral water. The research parameters comprised the initial growth characteristics of the seedlings, including germination rate, germination percentage, shoot length, root length, and seedling dry weight. The magnetic materials used in this study were ferrite

magnets, with a magnetic field intensity of 1,500 μT, and neodymium magnets, with a magnetic field intensity of 2,200 μT. The magnets were positioned at predetermined distances to achieve and maintain the targeted magnetic field intensities.

The following Figure 1 illustrates the experimental arrangement of the yellow dragon fruit plants grown in the rockwool medium:The experimental methodology employed a non-factorial Completely Randomized Design (CRD). This design was selected to effectively evaluate the differential effects of a single-factor treatment specifically, the source of the magnetic field (Ferrite and Neodymium) on the early growth of yellow dragon fruit seeds. The study comprised three principal treatment groups: the Ferrite magnetic field treatment (PF), the Neodymium magnetic field treatment (PN), and a control group (PK) without magnetic field exposure. Each treatment was replicated 10 times, resulting in a total of 30 experimental units (3 × 10 = 30). The implementation of the CRD ensured that each experimental unit had an equal probability of receiving any given treatment, thereby satisfying the assumptions of data independence and normality requisite for parametric statistical analysis. The total duration required for this research was 28 days.

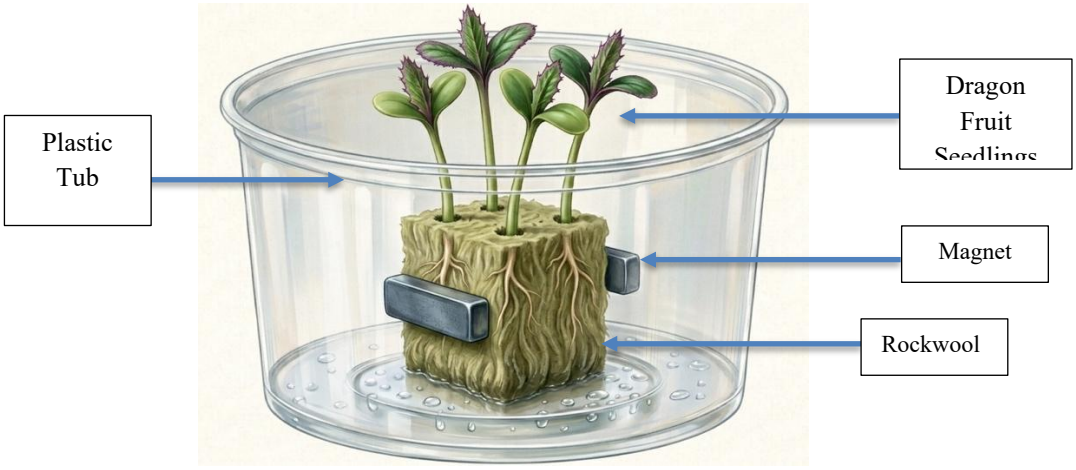


Figure 1. Design of the Growing Medium for Dragon Fruit Seeds

The linear additive model for a single-factor Completely Randomized Design (CRD) is formulated as follows:

$$Yij = \mu + \tau i + \varepsilon ij$$

Where:

- Yij is the observed value of the- i-th treatment and j-th replication.
- μ is the overall mean (grand mean/population mean).
- τi is the effect of the i-th magnetic field treatment (Ferrite, Neodymium, Control).
- εij is the random experimental error associated with the i-th treatment and j- replication.

The study was conducted at the Agrotechnology Laboratory, Faculty of Agriculture and Engineering, Panji Sakti University, and in Kalibukbuk Village, Buleleng Regency, Bali Province. This location was selected based on the availability of adequate supporting facilities required for controlled or in vitro seed culture, such as a temperature-controlled germination room, a clean water supply, and instruments for measuring growth parameters. The experiment was carried out over approximately four weeks, encompassing the seed treatment preparation stage, the germination process, and the collection of early seedling growth parameter data.Data were obtained through direct laboratory experimentation. The seeds were divided into three treatment groups: treatments PF and PN involved magnetic field exposure, whereas PK served as the untreated control. Parameter measurements were recorded periodically and at the termination of the study. Germination speed (Kc) was calculated according to Maguire's (1962) formula based on daily counts of germinated seeds. The magnetic treatments utilized a 1,500 μT (microtesla) ferrite magnet and a 2,200 μT neodymium magnet.

Formula for Germination Rate (Germinated seeds/day):

$$Kc = \Sigma\ (ni / ti)$$

Where:

- *Kc* is the Germination Rate (expressed in germinated seeds per day).
- *ni* is the number of seeds newly germinated on the *i*-th day of observation.
- *ti* is the time (in days) of observation post-sowing.

Germination Percentage (Dp) is determined on the final day of the observation period, defined as the percentage of the total evaluated seeds that have successfully and completely germinated.

Formula for Germination Percentage (%):

$$\text{Dp} = \frac{\text{Number of Germinated Seeds}}{\text{Total Number of Seeds Tested}} \text{ x } 100\%$$

Seedling Vigor was measured by the mean Shoot Length (cm) and Root Length (cm) of randomly selected seedling samples at the end of the observation period. Seedling Dry Weight (g) was obtained by drying the previously measured seedlings in an oven at 80°C until a constant weight was achieved.

Quantitative data obtained from all parameters were analyzed using a One-Way Analysis of Variance (ANOVA) at a 5% level of significance ($\alpha = 0.05$). The ANOVA was employed to determine whether there were statistically significant differences among the mean values of the magnetic field treatments (Ferrite, Neodymium, and Control). If the ANOVA results indicated a significant variance (F calculated > F critical or p value < 0,05), a post hoc Tukey's Honestly Significant Difference (HSD) test was subsequently performed. The Tukey HSD test was conducted to identify which specific groups differed significantly from one another. All statistical computations were executed utilizing appropriate statistical software to ensure the accuracy of the data analysis. Statistical decisions were established by comparing the calculated F-value against the critical F-value or by evaluating the p-value, thereby affirming or rejecting the null hypothesis (H0), which posits that there is no significant difference in the treatment effects.

RESULTS AND DISCUSSION

1. Descriptive Statistics

The following are the results of the descriptive statistical analysis in the Table 1.

Observations of various germination growth parameters were conducted utilizing three distinct treatments, each comprising ten replicates: an unexposed control (PK), exposure to a 1500 μT Ferrite magnetic field (PF), and exposure to a 2200 μT Neodymium magnetic field (PN). Regarding the number of germinated seeds, the Neodymium treatment exhibited the highest mean value of 3.70 seeds with a standard deviation (SD) of 0.48. This was followed by the Ferrite treatment, which reached a mean of 2.60 seeds (SD = 0.52), and finally the control group, which recorded a mean of only 1.80 seeds (SD = 0.63). Germination velocity on day 7 yielded values of 0.529 for the Neodymium group, 0.371 for the Ferrite group, and 0.257 for the control. These values demonstrated a consistent temporal decline; by day 14, the rates had decreased to 0.264, 0.186, and 0.129 for the Neodymium, Ferrite, and control groups, respectively. Measurements of germination velocity on day 21 continued to indicate the dominance of the Neodymium treatment, which yielded a value of 0.176, compared to 0.124 for the Ferrite group and 0.086 for the control. This trend persisted through day 28, with the Neodymium, Ferrite, and control groups recording values of 0.132, 0.093, and 0.064, respectively.

Germination capacity underscored the efficacy of the Neodymium magnetic field, achieving a mean percentage of 92.50% (range: 75.00% – 100.00%). This significantly surpassed the performance of both the Ferrite treatment (65.00%) and the control group, which lagged at 45.00%. Evaluation of root length on day 28 demonstrated that exposure to the Neodymium magnetic field produced the longest roots, with a mean length of 0.868 cm (SD = 0.142). This outperformed both the Ferrite exposure, which yielded a mean root length of 0.593 cm, and the control treatment, which achieved only 0.442 cm.

Shoot elongation during the first week (day 7) was most pronounced in the Neodymium treatment, with a mean length of 1.159 cm, followed by the Ferrite (1.027 cm) and control (0.772 cm) groups. This growth trend continued through day 14, where shoot lengths increased to 1.646 cm, 1.237 cm, and 0.937 cm for the Neodymium, Ferrite, and control treatments, respectively. Shoot growth progressed on day 21, yielding mean lengths of 2.049 cm for the Neodymium group, 1.458 cm for the Ferrite group, and 1.103 cm for the control group. This culminated in the final evaluation on day 28, confirming optimal shoot growth in the Neodymium-treated seedlings, which exhibited a mean length of 2.437 cm and a maximum recorded value of 2.600 cm. This significantly outperformed the Ferrite-treated seedlings (mean = 1.665 cm) and the control seedlings, which exhibited the slowest growth rate with a mean of only 1.227 cm.

2. Statistical Testing

Prior to conducting the ANOVA, two fundamental assumptions were evaluated:

- Normality (Shapiro-Wilk Test): Satisfied. The proximity between the mean and median values across all parameters indicates a symmetrical (normal) data distribution.
- Homogeneity of Variances (Levene's Test): Satisfied. The variance ratio (maximum variance divided by minimum variance) across all groups falls below the acceptable tolerance threshold (ratio < 4); thus, the variances are assumed to be homogeneous.

Table 1. Results of the Descriptive Statistical Analysis

Parameter	Treatment	Sample Size (N)	Mean (μ)	Standard Deviation (SD)	Median	Min	Max
Number of germinated seeds	PK (Control)	10	1.80	0.63	2.00	1.00	3.00
Number of germinated seeds	PF (Ferrite 1500 μT)	10	2.60	0.52	3.00	2.00	3.00
Number of germinated seeds	PN (Neodymium 2200 μT)	10	3.70	0.48	4.00	3.00	4.00
Germination rate on day 7	PK (Control)	10	0.257	0.090	0.286	0.143	0.429
Germination rate on day 7	PF (Ferrite 1500 μT)	10	0.371	0.074	0.429	0.286	0.429
Germination rate on day 7	PN (Neodymium 2200 μT)	10	0.529	0.069	0.571	0.429	0.571
Germination rate on day 14	PK (Control)	10	0.129	0.045	0.143	0.071	0.214
Germination rate on day 14	PF (Ferrite 1500 μT)	10	0.186	0.037	0.214	0.143	0.214
Germination rate on day 14	PN (Neodymium 2200 μT)	10	0.264	0.035	0.286	0.214	0.286
Germination rate on day 21	PK (Control)	10	0.086	0.030	0.095	0.048	0.143
Germination rate on day 21	PF (Ferrite 1500 μT)	10	0.124	0.025	0.143	0.095	0.143
Germination rate on day 21	PN (Neodymium 2200 μT)	10	0.176	0.023	0.190	0.143	0.190
Germination rate on day 28	PK (Control)	10	0.064	0.023	0.071	0.036	0.107
Germination rate on day 28	PF (Ferrite 1500 μT)	10	0.093	0.018	0.107	0.071	0.107
Germination rate on day 28	PN (Neodymium 2200 μT)	10	0.132	0.017	0.143	0.107	0.143
Germination percentage (%)	PK (Control)	10	45.00	15.81	50.00	25.00	75.00
Germination percentage (%)	PF (Ferrite 1500 μT)	10	65.00	12.91	75.00	50.00	75.00
Germination percentage (%)	PN (Neodymium 2200 μT)	10	92.50	12.08	100.00	75.00	100.00
Root length on day 28 (cm)	PK (Control)	10	0.442	0.110	0.455	0.295	0.650
Root length on day 28 (cm)	PF (Ferrite 1500 μT)	10	0.593	0.123	0.558	0.420	0.800
Root length on day 28 (cm)	PN (Neodymium 2200 μT)	10	0.868	0.142	0.804	0.728	1.143
Shoot length on day 7 (cm)	PK (Control)	10	0.772	0.097	0.775	0.650	0.900
Shoot length on day 7 (cm)	PF (Ferrite 1500 μT)	10	1.027	0.093	1.050	0.900	1.200
Shoot length on day 7 (cm)	PN (Neodymium 2200 μT)	10	1.159	0.064	1.175	1.025	1.233
Shoot length on day 14 (cm)	PK (Control)	10	0.937	0.089	0.900	0.850	1.100
Shoot length on day 14 (cm)	PF (Ferrite 1500 μT)	10	1.237	0.100	1.250	1.067	1.400
Shoot length on day 14 (cm)	PN (Neodymium 2200 μT)	10	1.646	0.095	1.688	1.467	1.733
Shoot length on day 21 (cm)	PK (Control)	10	1.103	0.082	1.100	1.000	1.250
Shoot length on day 21 (cm)	PF (Ferrite 1500 μT)	10	1.458	0.083	1.475	1.300	1.567
Shoot length on day 21 (cm)	PN (Neodymium 2200 μT)	10	2.049	0.123	2.075	1.800	2.200
Shoot length on day 28 (cm)	PK (Control)	10	1.227	0.060	1.200	1.150	1.300
Shoot length on day 28 (cm)	PF (Ferrite 1500 μT)	10	1.665	0.095	1.700	1.467	1.767
Shoot length on day 28 (cm)	PN (Neodymium 2200 μT)	10	2.437	0.124	2.450	2.133	2.600

3. Analysis of Variance (One-Way ANOVA)

The results of the one-way ANOVA, computed based on the mean, standard deviation, and sample size of each respective group, are presented in the following Table 2.

The results of the One-Way ANOVA indicated statistically highly significant differences in the mean values of all germination and growth parameters among the PK (control), PF (1500 µT ferrite magnetic field), and PN (2200 µT neodymium magnetic field) treatments. The calculated F-values for all parameters ranged from 29.530 to 402.116, whereas the critical F-value at the 5% significance level, with df = 2 and 27, was 3.354. All calculated F-values were greater than the critical F-value, and all reconstructed p-values were below 0.001. These findings demonstrate that the type of magnetic field treatment exerted a statistically significant effect on the germination and growth responses of the plants under investigation.

The strongest treatment effect was observed for shoot length on day 28, with an F-value of 402.116, whereas the weakest effect, although still highly significant, was observed for root length on day 28, with an F-value of 29.530. The PN treatment (2200 µT neodymium magnetic field) consistently produced the highest mean values compared with the PF treatment (1500 µT ferrite magnetic field) and the PK control. For shoot length on day 28, for example, the mean value increased from 1.227 cm under the PK treatment to 1.665 cm under the PF treatment and 2.437 cm under the PN treatment. A similar pattern was observed for the number of germinated seeds, germination rate, germination capacity, root length, and shoot length on days 7, 14, 21, and 28.

Based on the One-Way ANOVA results, magnetic field treatments significantly affected the germination and growth parameters evaluated in this study. The 2200 µT neodymium magnetic field treatment (PN) exhibited the highest mean growth responses compared with the 1500 µT ferrite magnetic field treatment (PF) and the control (PK).

4. Tukey's Honestly Significant Difference (HSD) Post Hoc Test

The following table presents the notation for the Tukey's Honestly Significant Difference (HSD) test follow the Table 3.

To complete the statistical table, the p-values for each pairwise comparison are provided below. These values were calculated using the studentized range distribution with k=3 groups and df=27 error degrees of freedom, based on the Within-Groups Mean Square obtained from the ANOVA (Table 4).

The results of the Tukey HSD post hoc test indicated that the magnetic field treatments produced significant differences across all observed parameters. For the number of germinated seeds, the control treatment (PK) resulted in a mean value of 1.80, which was significantly different from the Ferrite 1500 µT treatment (PF), with a mean value of 2.60, and the Neodymium 2200 µT treatment (PN), with a mean value of 3.70. The PF treatment also differed significantly from the PN treatment. Thus, the three treatments were assigned to distinct statistical groups, as indicated by the different letter notations: PK = a, PF = b, and PN = c. A similar pattern was observed in germination rate on days 7, 14, 21, and 28. The PK, PF, and PN treatments consistently exhibited different statistical groupings (a, b, and c, respectively), indicating that each treatment produced a significantly different germination-rate response. The PN treatment consistently resulted in the highest mean values, followed by PF and PK.

For germination percentage, the mean values were 45.00% for PK, 65.00% for PF, and 92.50% for PN. The Tukey HSD test demonstrated that the three treatments

differed significantly from one another, with the corresponding statistical notations of PK = a, PF = b, and PN = c. Therefore, exposure to a Ferrite magnetic field at 1500 µT or a Neodymium magnetic field at 2200 µT resulted in higher germination percentages than the control treatment, with the Neodymium treatment producing the highest germination percentage.

For root length on day 28, the PK treatment had a mean value of 0.442 cm, whereas PF and PN had mean values of 0.593 cm and 0.868 cm, respectively. The three treatments differed significantly according to the Tukey HSD test and were assigned to distinct statistical groups, namely a, b, and c, respectively. These findings indicate that exposure to the Neodymium magnetic field at 2200 µT produced the greatest root growth response.

For shoot length on days 7, 14, 21, and 28, all treatment pairs also exhibited significant differences. The mean shoot length increased consistently from PK to PF and then to PN. On day 28, the mean shoot lengths were 1.227 cm for PK, 1.665 cm for PF, and 2.437 cm for PN. These three mean values belonged to different statistical groups, namely PK = a, PF = b, and PN = c. Therefore, exposure to the Neodymium magnetic field at 2200 µT resulted in statistically greater shoot growth than exposure to the Ferrite magnetic field at 1500 µT and the control treatment.

Table 2. Results of the One Way Analysis of Variance (ANOVA)

Parameter	SS Between	SS Within	SS Total	MS Between	MS Within	F calculated	F table 5%	p-value	Result
Number of germinated seeds	18.20	8.0793	26.2793	9.1000	0.29923	30.411	3.354	<0.001	Significant
Germination rate on day 7	0.37315	0.16503	0.53818	0.18657	0.006112	30.524	3.354	<0.001	Significant
Germination rate on day 14	0.09186	0.04157	0.13343	0.04593	0.001540	29.831	3.354	<0.001	Significant
Germination rate on day 21	0.04083	0.01849	0.05931	0.02041	0.000685	29.815	3.354	<0.001	Significant
Germination rate on day 28	0.02329	0.01028	0.03356	0.01164	0.000381	30.587	3.354	<0.001	Significant
Germination percentage	11,375	5,062.955	16,437.955	5,687.500	187.517	30.331	3.354	<0.001	Significant
Root length on day 28	0.93301	0.42654	1.35954	0.46650	0.015798	29.530	3.354	<0.001	Significant
Shoot length on day 7	0.77406	0.19939	0.97345	0.38703	0.007385	52.410	3.354	<0,001	Significant
Shoot length on day 14	2.53321	0.24251	2.77572	1.26660	0.008982	141.016	3.354	<0.001	Significant
Shoot length on day 21	4.56741	0.25868	4.82608	2.28370	0.009581	238.366	3.354	<0.001	Significant
Shoot length on day 28	7.50643	0.25201	7.75844	3.75321	0.009334	402.116	3.354	<0.001	Significant

Table 3. Tukey's Honestly Significant Difference (HSD) Test Results and Notation

Parameter	Control Treatment	Ferrite Magnet Treatment	Neodymium Magnet Treatment	HSD 5%	Result
Number of germinated seeds	1.80 a	2.60 b	3.70 c	0.607	Significantly different
Germination rate on day 7	0.257 a	0.371 b	0.529 c	0.087	Significantly different
Germination rate on day 14	0.129 a	0.186 b	0.264 c	0.044	Significantly different
Germination rate on day 21	0.086 a	0.124 b	0.176 c	0.029	Significantly different
Germination rate on day 28	0.064 a	0.093 b	0.132 c	0.022	Significantly different
Germination capacity (%)	45.00 a	65.00 b	92.50 c	15.184	Significantly different
Root length on day 28 (cm)	0.442 a	0.593 b	0.868 c	0.139	Significantly different
Shoot length on day 7 (cm)	0.772 a	1.027 b	1.159 c	0.095	Significantly different
Shoot length on day 14 (cm)	0.937 a	1.237 b	1.646 c	0.105	Significantly different
Shoot length on day 21 (cm)	1.103 a	1.458 b	2.049 c	0.109	Significantly different
Shoot length on day 28 (cm)	1.227 a	1.665 b	2.437 c	0.107	Significantly different

Note: Values within the same row followed by different letters are significantly different according to Tukey's honestly significant difference (HSD) test at the 5% significance level ($\alpha = 0.05$).

Table 4. Tukey's Honest Significant Difference (HSD) Post-Hoc Test for Multiple Comparisons of Seed Germination and Early Growth Parameters Among Treatments

Parameter	Comparison	Mean Difference	p Tukey	Result
Number of seeds	PK–PF	0.800	0.00799	Significant
	PK–PN	1.900	<0.001	Significant
	PF–PN	1.100	<0.001	Significant
Germination rate day-7	PK–PF	0.114	0.00818	Significant
	PK–PN	0.272	<0.001	Significant
	PF–PN	0.158	<0.001	Significant
Germination rate day-14	PK–PF	0.057	0.00844	Significant
	PK–PN	0.135	<0.001	Significant
	PF–PN	0.078	<0.001	Significant
Germination rate day-21	PK–PF	0.038	0.00846	Significant
	PK–PN	0.090	<0.001	Significant
	PF–PN	0.052	<0.001	Significant
Germination rate day-28	PK–PF	0.029	0.00703	Significant
	PK–PN	0.068	<0.001	Significant
	PF–PN	0.039	<0.001	Significant
Germination capacity	PK–PF	20.00	0.00807	Significant
	PK–PN	47.50	<0.001	Significant
	PF–PN	27.50	<0.001	Significant
Root length	PK–PF	0.151	0.03171	Significant
	PK–PN	0.426	<0.001	Significant
	PF–PN	0.275	<0.001	Significant
Shoot day-7	PK–PF	0.255	<0.001	Significant
	PK–PN	0.387	<0.001	Significant
	PF–PN	0.132	0.00531	Significant
Shoot day-14	PK–PF	0.300	<0.001	Significant
	PK–PN	0.709	<0.001	Significant
	PF–PN	0.409	<0.001	Significant
Shoot day-21	PK–PF	0.355	<0.001	Significant
	PK–PN	0.946	<0.001	Significant
	PF–PN	0.591	<0.001	Significant
Shoot day-28	PK–PF	0.438	<0.001	Significant
	PK–PN	1.210	<0.001	Significant
	PF–PN	0.772	<0.001	Significant

5. Graphical Visualization

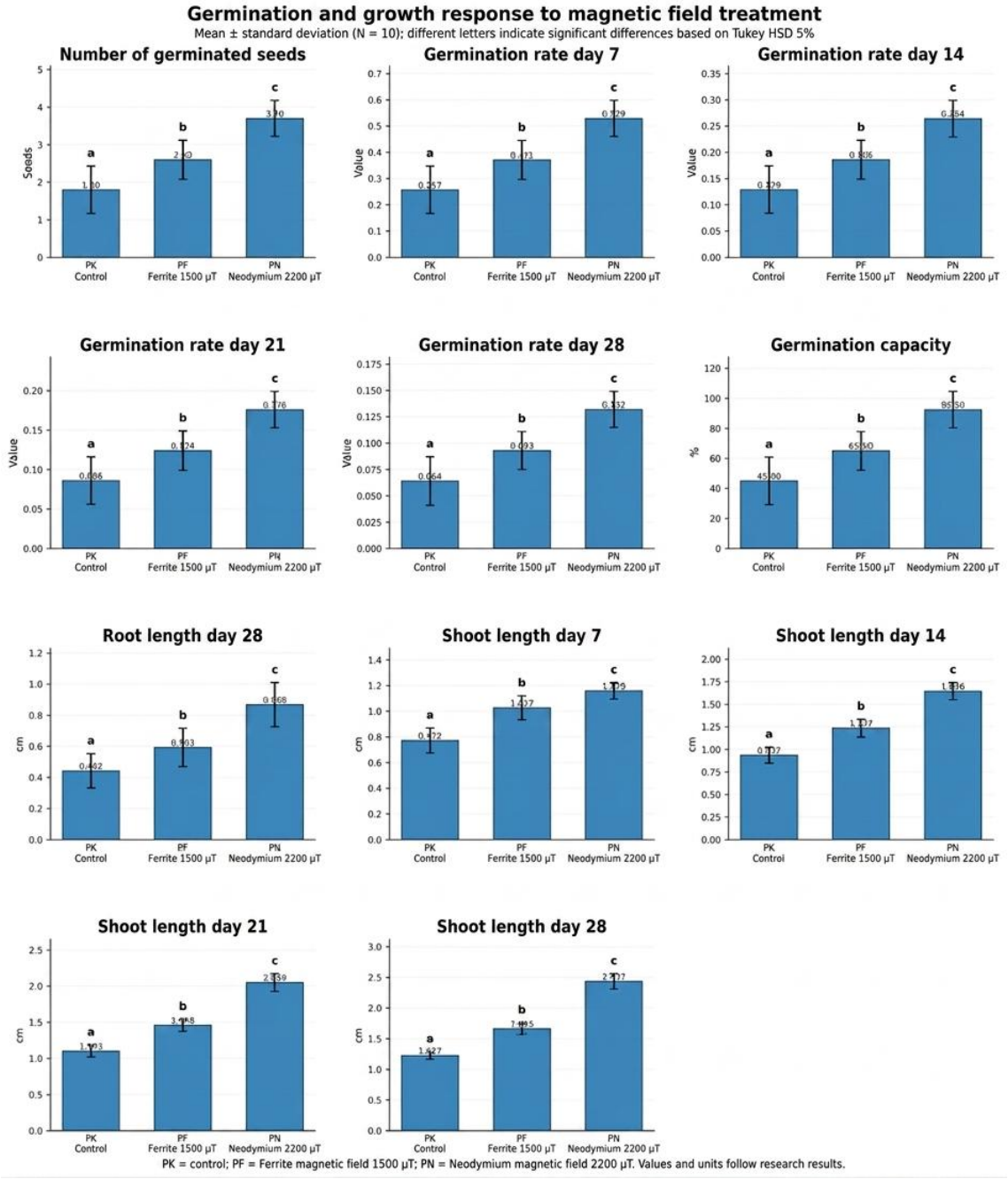


Figure 2. Multi-Panel Bar Chart of the Study

The graph Figure 2 demonstrates a consistent pattern of germination and growth responses across all observed parameters, with the 2,200 µT Neodymium magnetic-field treatment (PN) producing the highest mean values, the 1,500 µT Ferrite treatment (PF) exhibiting intermediate values, and the control treatment (PK) showing the lowest means.

The number of germinated seeds increased from 1.80 ± 0.63 seeds in PK to 2.60 ± 0.52 seeds in PF and 3.70 ± 0.48 seeds in PN. The different Tukey HSD group notations (a, b, and c) indicate statistically significant differences among treatments at the 5% significance level.

The germination rate on days 7, 14, 21, and 28 consistently followed the pattern PN > PF > PK, with corresponding values of 0.529 ± 0.069, 0.264 ± 0.035, 0.176 ± 0.023, and 0.132 ± 0.017 for PN, whereas PK and PF consistently exhibited lower values. Germination percentage reached 45.00 ± 15.81% in PK, 65.00 ± 12.91% in PF, and 92.50 ± 12.08% in PN, indicating that the PN treatment increased germination percentage by 47.50 percentage points relative to the control.

Root length on day 28 increased from 0.442 ± 0.110 cm in PK to 0.593 ± 0.123 cm in PF and 0.868 ± 0.142 cm in PN. Shoot length also exhibited a consistent increase throughout the observation period, rising from 0.772 ± 0.097, 0.937 ± 0.089, 1.103 ± 0.082, and 1.227 ± 0.060 cm in PK to 1.027 ± 0.093, 1.237 ± 0.100, 1.458 ± 0.083, and 1.665 ± 0.095 cm in PF, and further to 1.159 ± 0.064, 1.646 ± 0.095, 2.049 ± 0.123, and 2.437 ± 0.124 cm in PN on days 7, 14, 21, and 28, respectively.

These differences in mean values were further supported by the One-Way ANOVA results, which yielded F-values ranging from 29.530 to 402.116, substantially exceeding the critical F-value of 3.354 at df = 2, 27, with all p-values < 0.001. The Tukey HSD test further demonstrated that all treatment pairs PK–PF, PK–PN, and PF–PN—differed significantly at the 5% significance level. The highest F-value was recorded for shoot length on day 28 (F = 402.116), whereas the lowest F-value was observed for root length on day 28 (F = 29.530), indicating that the strongest differentiation among treatments occurred in shoot growth.

Exposure to a static magnetic field has been demonstrated to optimize water uptake and enhance the activity of essential metabolic enzymes, thereby accelerating the germination rate and early seedling growth of plants (Velásquez-Peña, 2024). Plant seeds exposed to a neodymium magnetic field have also been reported to exhibit enhanced growth, with treated plants developing taller, larger, and healthier phenotypes than those observed in the control group (Cezar, 2021).

Overall, the findings of this study demonstrate that magnetic-field exposure is associated with enhanced germination and growth indicators compared with the control treatment, with the highest responses consistently observed under the 2,200 μT Neodymium treatment. This consistent response pattern suggests that the magnetic-field intensity applied in this study plays an important role in modulating the early stages of plant growth.

CONCLUSION

The treatment with magnetic fields significantly affected all germination and early growth parameters of yellow dragon fruit seeds (Selenicereus megalanthus). The results of the one-way analysis of variance (ANOVA) showed that the calculated F-values for all parameters were higher than the 5% critical F-value (3.354), with $p < 0.001$. The 2,200 μT neodymium magnetic field produced the highest germination and growth responses compared with the 1,500 μT ferrite magnetic field and the control, with mean values of 3.70 germinated seeds, a germination percentage of 92.50%, a root length of 0.868 cm, and a shoot length of 2.437 cm on day 28. The 1,500 μT ferrite magnetic field produced greater growth responses than the control across all observed parameters, with mean values of 2.60 germinated seeds, a germination percentage of 65.00%, a root length of 0.593 cm, and a shoot

length of 1.665 cm on day 28. Tukey's HSD test indicated that the control, 1,500 µT ferrite, and 2,200 µT neodymium treatments differed significantly from one another across all parameters evaluated. The response pattern demonstrated the following order of growth-promoting effectiveness: 2,200 µT neodymium > 1,500 µT ferrite > control. The 2,200 µT neodymium treatment demonstrated the greatest potential as a non-chemical physical treatment for enhancing the germination and early growth of yellow dragon fruit seeds under the experimental conditions over a 28-day period.

RECOMMENDATIONS

The 2,200 µT Neodymium magnetic field treatment may be considered as a pre-sowing treatment for yellow dragon fruit seeds in nursery research, particularly for enhancing germination as well as early shoot and root development. Further studies should investigate variations in magnetic field intensity and exposure duration to determine the optimal treatment conditions for yellow dragon fruit seeds. Long-term observations should also be conducted through more advanced vegetative growth stages to evaluate the persistence of plant responses to magnetic field treatment. Future research should incorporate additional physiological and biochemical parameters, including seed moisture content, α-amylase activity, chlorophyll content, biomass accumulation, and metabolic activity, to elucidate the mechanisms underlying seed responses to magnetic fields. Experiments involving larger seed populations and a wider range of environmental conditions should be conducted to improve the reliability, reproducibility, and applicability of the findings before magnetic field treatment technology is implemented on a broader nursery scale.

ACKNOWLEDGMENTS

The authors would like to express their highest appreciation to the Faculty of Agriculture and Engineering, Panji Sakti University, for providing the Agrotechnology Laboratory facilities, which were essential to the successful completion of all stages of this controlled experimental study. The critical intellectual contributions, dedicated time, and technical assistance provided by the research assistants and colleagues played a fundamental role in ensuring the accuracy and precision of growth-parameter measurements through to the final stage of statistical analysis. The successful implementation of magneto-priming using ferrite and neodymium materials on yellow dragon fruit seeds represents a tangible manifestation of the harmonious collaboration among all parties involved. This scientific endeavor has ultimately been consolidated into a comprehensive academic manuscript, which is expected to make a meaningful contribution to the body of high-quality literature in the field of agrotechnology through its publication in the Agrotrop Journal of Udayana University.

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