International Journal of Agriculture and Biosciences 2025 14(6): 1271-1277.
https://doi.org/10.47278/journal.ijab/2025.103

RESEARCH ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

Synergistic Impacts of Optimal Doses of Gamma Irradiation (Gy) and Magnetically Treated Water to Enhance Biophysical Parameters of Maize Seeds

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ABSTRACT

Maize production in Pakistan faces ongoing challenges, including low germination percentages and restricted seedling growth, which ultimately reduce crop yields. This study investigated the synergistic effects of gamma irradiation and magnetically treated water on the germination and early seedling growth of maize seeds. Tap water was magnetized using a 211mT magnetic field for durations of 20, 30, 40, and 50 minutes. Simultaneously, maize seeds were subjected to gamma irradiation at doses of 50, 100, 150, and 200Gy. Principal Component Analysis and heatmap visualization analysis were used to assess treatment efficacy. Results showed that the highest gamma dose (200 Gy) significantly decreased germination to 33% in T_4 and negatively affected seedling growth. In contrast, lower doses (50, 100, 150Gy) combined with magnetic water treatments enhanced germination percentages to 66, 86, and 73% in T_1, T_2, and T_3, respectively and improved growth compared to control. The best result (86%) observed under 100 Gy gamma irradiation and 30min magnetic treatment. This integrated approach using an optimal dose of gamma irradiation along with magnetically treated water presents a promising, eco-friendly strategy to improve maize germination and vigor, ultimately contributing to sustainable agricultural productivity.

Keywords: Maize seeds, Magnetically treated water, Gamma irradiation, Dose optimization

Article History
Article # 25-233
Received: 05-May-25
Revised: 10-Jun-25
Accepted: 20-Jun-25
Online First: 11-Jul-25

INTRODUCTION

Maize (*Zea mays L.*) is one of the most important cereal crops globally, providing essential nutrients for human consumption, animal feed, and raw material for industrial use (Leite et al., 2021; Ali et al., 2024). In countries like Pakistan, maize holds significant value for food security and income generation from farming. However, its productivity is often constrained by various biological and environmental factors that reduce its potential yield. Some of the major challenges include high temperatures, not enough water, and low germination rates, especially in regions severely affected by climate change (Chen et al., 2023; Cui et al., 2024). These limitations make it harder for seedlings to develop, biomass to build up, and yields to be large, which make the farm less profitable. To address these challenges, researchers and farmers are searching new ways to better seed growth and crop resilience under stress conditions.

Chemical seed treatments, fertilizers, and insecticides have transformed farming practices. However, the excessive use of these substances has led to unintended consequences. According to (Ahumada-Flores et al. (2021) and Balakrishnan et al. (2022), excessive pesticide usage may harm agricultural land, taint water supplies, diminish biodiversity, and raise production costs. These are only few pesticide side effects. Since chemicals are conceivable, they may have caused this environmental damage. These treatments are being examined further due to their long-term usage (Kiani et al., 2022; Thounaojam, 2024). Because they pose a danger to human and environmental health. There is growing interest in ecologically responsible, cost-effective solutions that reduce their environmental impact and increase agricultural output. This heightened interest stems from the demand for green solutions. Besides these procedures, long-term physical seed treatments like gamma ray irradiation and magnetic field water treatment are becoming more common. Due to their chemical-free procedure, these techniques are environmentally beneficial.

Gamma irradiation is a form of ionizing radiation that changes the DNA of seeds by exposing them to different doses of gamma rays (Al_Raheem et al., 2024). It is extensively utilized to make changes in the body and genes

Cite this Article as: Ali KA, Adeelanjum and Zia-ul-Haq, 2025. Synergistic impacts of optimal doses of gamma irradiation (Gy) and magnetically treated water to enhance biophysical parameters of maize seeds. International Journal of Agriculture and Biosciences 14(6): 1271-1277. https://doi.org/10.47278/journal.ijab/2025.103

A Publication of Unique Scientific Publishers

that can improve seed performance and make them more resistant to stress. Gamma radiation may change the structure and metabolic functions of cells, which can help seeds to germinate, seedlings to develop faster, and plants become more resistant to abiotic challenges (Afram et al., 2024). When used in appropriate amounts, gamma irradiation may cause beneficial mutations that increase enzyme activity, chlorophyll content, and yield potential in crops like chili (Samarah et al., 2021). The effects of gamma irradiation depend on the dose. Low doses can help better growth of plants, while excessive doses might harm DNA and can stop working of cells. Also, gamma radiation has been demonstrated to be able to improve the genetics of crops, which makes them more resistant to climatic stress and help farmers to get the optimized land production.

Magnetically treated water is a novel, non-chemical way for improving seed germination and plant growth. When water passes through a magnetic field, it causes changes in its physical and chemical characteristics, such as its dielectric constant, viscosity, and pH (Ercan et al., 2022; Putti et al., 2023). These changes make it easier for the water to get through the seed coats, which helps enhancing hydration and nutritional absorption. Magnetically treated water boosts activity of enzymes like amylase, protease, and lipase. These enzymes are vital in the early phases of seed germination. These enzymes are very important for mobilize stored nutrients that are necessary for the development of plants. As a consequence, several crop such as cotton have shown better seedling vigor, root development, plant growth, and chlorophyll synthesis (Kishore et al., 2022; Yi et al., 2023).

Although the individual benefits of gamma irradiation and magnetically treated water have been well documented, limited studies have examined their combined effects. Theoretically, a synergistic interaction could exist between these two treatments, gamma irradiation can stimulate internal biochemical pathways and genetic mechanisms, while magnetically treated water could enhance external physiological processes such as hydration and nutrient uptake. Together, they may significantly improve germination rates, seedling establishment, stress resilience, and ultimately crop yield. Yet, the scientific validation of this hypothesis, especially in maize, remains unexplored. Pakistan's agricultural sector, particularly maize production, could greatly benefit from such innovative approaches. The increasing pressure from climate change, population growth, and resource limitations, it is crucial to explore integrated and environmentally sustainable strategies that enhance crop performance. Implementing combined physical treatments like gamma irradiation and magnetically treated water offers farmers a low-cost, scalable solution that reduces reliance on chemical inputs and supports climate-resilient agriculture.

The synergistic potential of gamma irradiation and magnetically treated water offers a promising avenue for enhancing the growth of maize (Zea *mays* L.), yet remains largely unexplored. Although both treatments have independently shown positive effects on seed germination, plant growth, and physiological attributes, but limited research has assessed their combined impact on maize. This study aimed to fill this critical knowledge gap by evaluating the effects of gamma irradiation (at 50 and 100Gy) and magnetically treated water for 30 minutes on maize seed germination, growth parameters and chlorophyll content in maize. The integration of these treatments could significantly enhance seedling resistance to environmental stress, optimize growth performance, and enhance crop yield. Additionally, this eco-friendly and cost effective approach has the potential to serve as a viable alternative to traditional agricultural methods, especially in climate-affected regions like Pakistan. This strategy could be useful for farmers to promote sustainable agriculture and contribute to increase food security and environmental conservation.

MATERIALS & METHODS

Seed Sampling

Maize seeds (Malka 2016 variety) were obtained from Ayub Agriculture Research Institute, Faisalabad. Healthy, uniform seeds were washed with distilled water, dried using a solar dehydrator. The seeds were then divided into five treatment groups: T_0 (control) and T_1-T_4, each with three replicates (R_1, R_2, and R3).

Effect of Gamma Irradiation on Maize Seeds

Maize seeds were exposed to gamma radiation doses of 50, 100, 150 and 200Gy for varying durations of 12, 25, 37 and 50min using a Cobalt-60 gamma source. The effects of these treatments on various parameters were compared to the control group (un-treated seeds).

Hydro-magnetic Device

A hydro-magnetic device, with 26 permanent magnets (13 on each side) producing a 211mT magnetic field was used to treat water. Water flowed slowly through a polyvinyl chloride pipe (12.7mm diameter, 87cm length) passed through the magnets. Magnetic field intensity, measured with a flux meter, was highest at the center and lowest at the edges. Water was magnetized for 20, 30, 40, and 50 minutes, and then collected in bottles for supply.

Agronomic Practice and Sowing

Seeds were sown in pots. Each treatment, including the control, was replicated. Seeds were soaked for 24 hours in freshly magnetized water (Atchaya et al., 2023). Five healthy seeds were planted per pot, with fifteen seeds per treatment at equal intervals. After sowing, 500mL of tap water was applied to each pot, which were then placed in natural sunlight and irrigated regularly until germination. After germination, three plants per pot were selected and tagged for further growth and other parameter analysis (El-Sayed et al., 2024). The experimental setup for treatments is shown in Table 1.

Germination Kinetics and Morphological Parameters

Fresh leaf samples were collected and transported to the lab using ice packs and avoiding direct sunlight to preserve their water content and chemical composition of the tissues. Seed germination was recorded on days 5, 7, and 10. Germination percentage (GP) was calculated using the following formula:

$$Final\ Germination\ Percentage = \left\{\frac{Number\ of\ germinated\ seeds\ after\ n\ days}{Total\ number\ of\ seeds}\right\} \times 100 \quad (1)$$

Table 1: Experimental setup for treatments

Treatments	Gamma radiation (Gy)	Time exposure of gamma radiation (mints)	Magnetic field strength (mT)	Time exposure of treated water (mints)
T_0	Control	……	……..	………
T_1	50	12	211	20
T_2	100	25	211	30
T_3	150	37	211	40
T_4	200	50	211	50

Table 2: Combined ANOVA Summary: Effects of Treatment on Germination, Growth, and Plant Weight Parameters

Source	Response Variable	Df	Sum Sq	Mean Sq	F value	Pr(>F)	Significance
Treatment	Germination Percentage	4	3835.0	958.8	107.60	5.47e-07	Highly Significant
Day (5,7,10)	Germination Percentage	2	1654.0	827.1	92.80	2.92e-06	Highly Significant
Treatment	Root & shoot length (cm), plant height (cm)	4	494.0	123.4	11.57	0.00208	Significant
Parameter	Root & shoot length (cm), plant height (cm)	2	3303.0	1651.7	154.84	4.02e-07	Highly Significant
Treatment	Leaf Length (cm), leaf width(cm), leaf area (cm^2), no. of leaves	4	240.2	60.1	3.26	0.0500	Marginally Significant
Parameter	Leaf Length (cm), leaf width (cm),leaf area (cm^2), no. of leaves	3	1229.3	409.8	22.23	3.44e-05	Highly Significant
Treatment	Root fresh and dry weight (g), shoot fresh and dry weight (g)	4	8.22	2.06	5.28	0.0109	Significant
Parameter	Root fresh and dry weight (g), shoot fresh and dry weight (g)	3	70.39	23.46	60.24	1.66e-07	Highly Significant
Treatment	Chlorophyll	4	17.49	4.37	10.92	0.00251	Significant
Parameter	Chlorophyll	2	208.20	104.10	260.02	5.27e-08	Highly Significant

Leaf length, leaf width, plant height, roots and shoot lengths, fresh and dry weights were measured after 28 days. Leaf area was calculated with a planimeter. The fresh and dry weights of shoots and roots were measured using an electronic balance. The dry weight was taken after drying the samples at 70℃. Seed vigor indices I and II were calculated according to Abdul-Baki & Anderson (1973). Chlorophyll contents were directly measured with the help of a chlorophyll meter.

Statistical Analysis

Data from five treatments were analyzed using R software (version 4.4.0) with ANOVA, and differences among means were tested, as shown in Table 2. Principal Component Analysis (PCA) and heatmap analysis were conducted using R Studio version 2024.12.0+467 to visualize treatment responses.

RESULTS

The effects of gamma irradiation and magnetically treated water on maize seed germination percentage after 5, 7, 10 days, as well as the effects on plant height, root length, shoot length, fresh and dry weight are shown in (Fig. 1). Among all treatments, T_2 (100Gy gamma irradiation with 30 minutes magnetic water) showed the most favorable outcomes, with the highest germination percentage recorded at 86%, a 20% increase over the untreated control group (T_0), which showed 66%. In contrast, T_4 displayed the lowest germination rate at 33%, indicating a 33% decrease relative to T_0. Treatments T_1 and T_3 showed germination percentage of 66 and 73%, respectively. These variations are shown in (Fig. 1a).

Root length was also affected, with all treated groups showing reductions compared to the control (17cm). Specifically, root lengths were 13.5cm in T_1, 13cm in T_2, 11cm in T_3 and 8cm in T_4, showing the negative impact of higher radiation doses (Fig. 1b). Shoot length slightly increased in T_1 (44cm) and T_2 (44.5cm) relative to the control (43cm) but decreased significantly in T_3 (36cm) and T_4 (25cm), indicating a dose-dependent inhibitory response at higher irradiation levels. Plant height followed a similar trend; T1 and T2 showed slight improvements (52.5cm and 53cm, respectively) compared to the control group (52cm). In contrast, significant decreases were noted in T_3 (46cm) and T_4 (34cm) (Fig. 1b). Leaf area initially increased in T_1 (24.98cm^2) and T_2 (31.02cm^2), which were 26.5 and 41% higher than the control (28cm^2), respectively. However, T_3 (14.04cm^2) and T_4 (7.12cm^2) showed substantial reductions (31% and 158%) in leaf area than T_0, as shown in (Fig. 1c). Regarding the number of leaves, the maximum count was observed in T_2 (six leaves) followed by T_1 (five leaves) and T_0 (four leaves), while the lowest (three leaves) was recorded in T_4. T_2 exhibited a 33.3% increase, while T_4 exhibited a 33.3% decrease in leaf number relative to the control (Fig. 1c). Biomass data demonstrated that root fresh weight increased in T_1 (14.8%) and T_2 (25%) compared to the control (1.5g), but T_3 and T_4 showed reductions of 33.9 and 294%, respectively (Fig. 1d). Similarly, shoot fresh weight increased by (5.3%) in T_1 and (11.9%) in T_2, but declined in T_3 (13.14%) and T_4 (127%) relative to the control (5.68g) (Fig. 1d). The root dry weight also reflected this trend, with increases of 4 and 7.7% in T_1 and T_2, respectively, but sharp reductions of 84.6 and 166.7% in T_3 and T_4 when compared with the control (0.24g) (Fig. 1d). In terms of seedling vigor index, T_2 again outperformed all other groups. Vigor index I values were 3996 (T_0), 3830 (T_1), 4976 (T_2), 3431 (T_3), and 1099 (T_4). Compared to T_0, this represents a 4.3% decrease in T_1, a 19.7% increase in T_2, a 16.5% decrease in T_3, and a 263% decrease in T_4. Vigor index II showed similar trends with values 116 (T_0), 128 (T_1), 176 (T_2), 75 (T_3), and 11 (T_4). Compared to T_0, this showed a 9.4% increase in T_1, 34.1% in T_2, 54.7% decrease in T_3, and 91% decrease in T_4. Finally, chlorophyll content was highest in T_2 (17.78mg/L), showing a 20.4% increase compared to the control (14.15mg/L). Moderate increases were noted in T_1 (14.99mg/L; 5.6%) and T_3 (14.53mg/L; 2.16%), while T_4 showed the lowest chlorophyll content value at 12.87mg/L, showing a 9.95% decrease (Fig. 2). The application of 100Gy gamma irradiation and 30 minutes of magnetic water exposure (T_2) significantly enhances maize seed germination, growth parameters, and physiological traits. Conversely, T_4 involving a higher dose, had adverse effects across all measured traits. These results highlight the potential of optimized magneto-radiation treatment in improving crop performance.

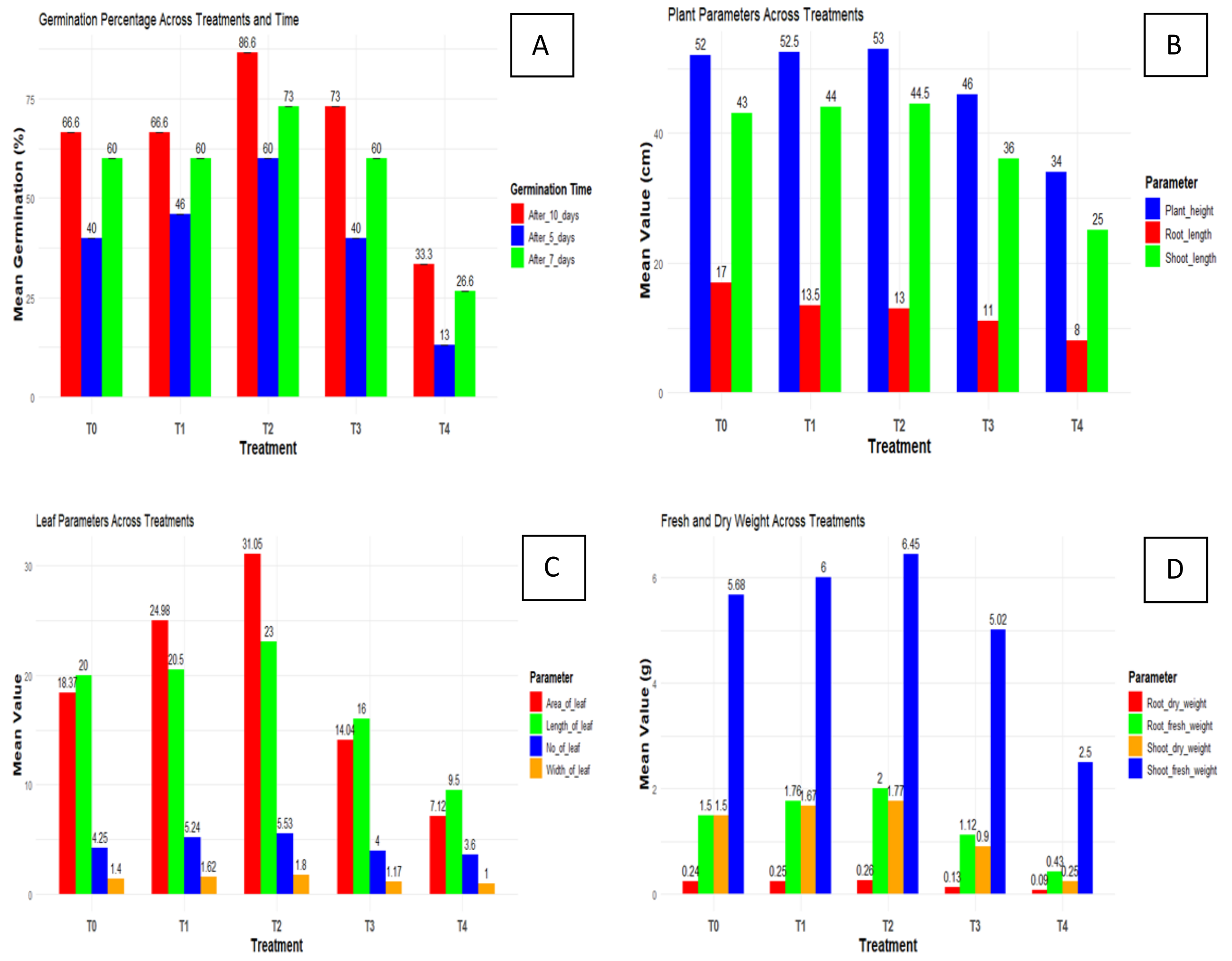

Fig. 1: Effect of gamma irradiation and magnetically treated water on maize germination percentage, shoot and root length, plant height, leaf number, leaf area, leaf length, leaf width, root/shoot fresh and dry weight, root dry weights.

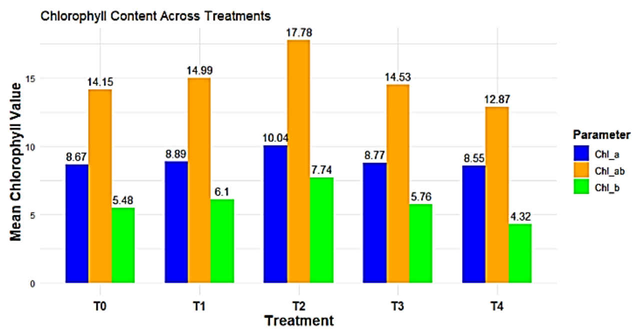

Fig. 2: Effect of gamma radiation and magnetically treated water on chlorophyll content (mg/L).

PCA (Principal Component Analysis)

The PCA biplot (Fig. 3) illustrates the relationship between different treatments (T0-T4) and plant growth and chlorophyll content. PC1 explains 86.06% of the total variance, T_4, which shows poor performance in most parameters. PC2, (9.45% variance) distinguishes T1, which had generally low values but a relatively higher root length. Treatments T_0, T_2, and T_3 shows moderate response. The direction and length of the vectors indicate the strength and influence of each parameter on treatment variation.

Heatmap Analysis

The heatmap (Fig. 4) shows that treatment T_4 (dark-purple pellet) had the lowest values for all growth and chlorophyll parameters, indicating a strong negative effect on plant development. T_2 showed high values (green-yellow pellet). Hierarchical clustering also separated T_4 from the other treatments, highlighting its reduced performance.

DISCUSSION

As an emerging agricultural irrigation technique, magnetized water technology has shown promise in improving crop production and water quality in recent years (Kishore et al., 2023). Magnetic treatment significantly influences the physiochemical properties of water by altering its molecular structure, reducing surface tension, and forming smaller, more active molecular clusters. These changes increase better solubility and cellular permeability, which speeds up cell metabolism. Magnetic fields may increase water molecule mobility by strengthening their transition dipole moments and polarizing characteristics. This has been proven by researchers. This influence may be seen in water molecules. (Al-Akhras et al., 2024) suggest that

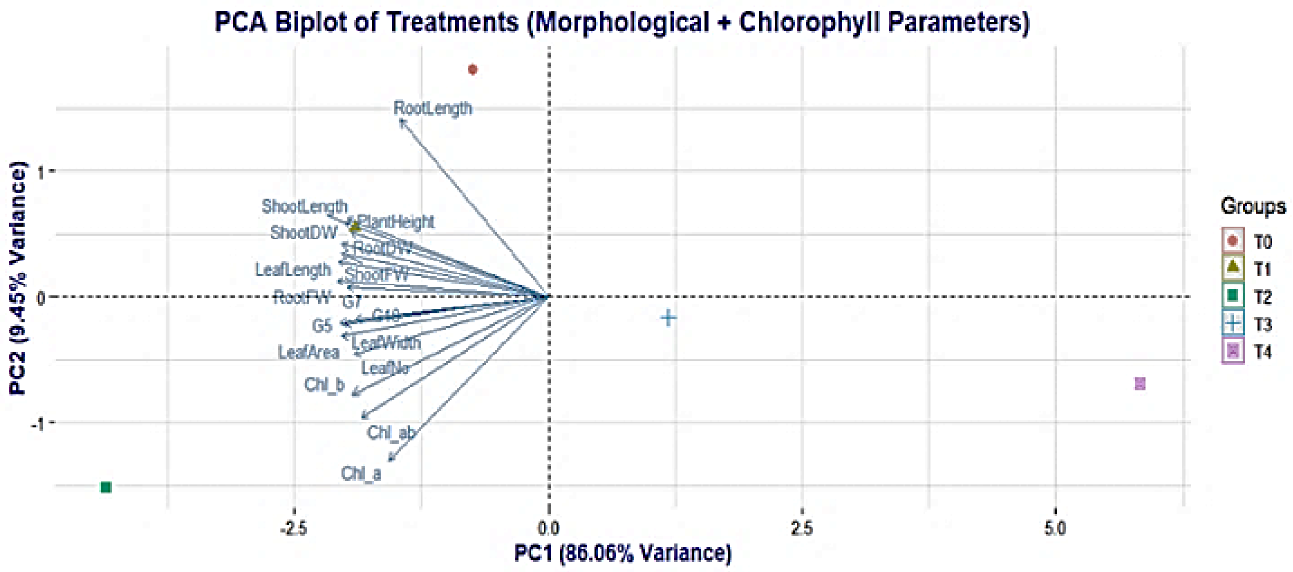

Fig. 3: Principal Component Analysis (PCA) of germination, growth parameters.

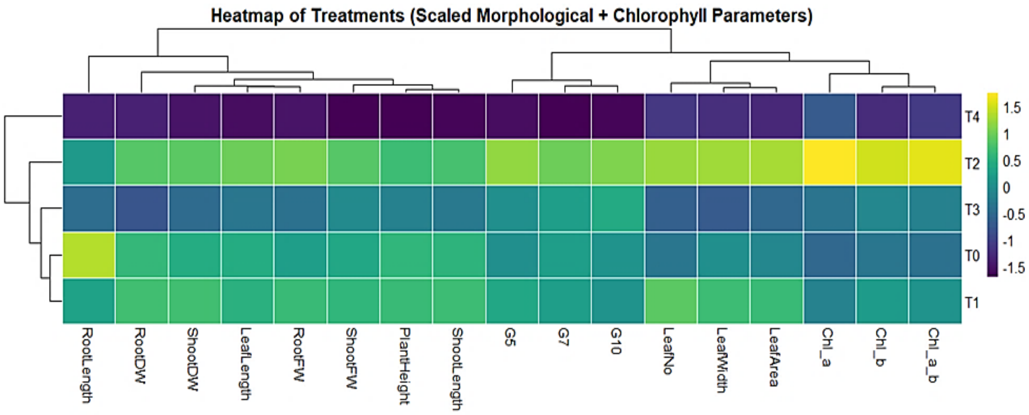

Fig. 4: Cluster heatmap of various parameters across five treatments.

atom repositioning and magnetic moments between water molecules cause this phenomenon. Researchers found that magnetic field therapy may enhance water pH. This was proven by water pH rise (Jiang et al., 2024). Magnetic fields influence ion mobility in water. Lorentz forces cause this transformation. This changes the water's electrical conductivity and total dissolved solids (TDS), creating the discrepancy. Proton spin alignment is a key element in the creation of smaller water molecule clusters to speed up their synthesis. Hydrogen bonding forms these clusters, which lower surface tension and promote water absorption. According to Zhou et al. (2022), these changes facilitate water and nutrient absorption by seeds, accelerating germination and seedling development. This research shows that magnetic fields affect water pH, electrical conductivity, and total dissolved solids. This is because magnetic fields significantly affect their characteristics. (Yang et al., 2023) found that magnetized irrigation water increased leaf development when administered in the right quantity. This happened when water was utilized efficiently. Growing leaves cools the soil, reducing evaporation. This may be done by shading the soil and limiting direct sunlight. According to (Meng et al., 2022) environmental changes may affect biodegradable film-breaking microorganisms. According to (Zhou et al., 2024), magnetized water irrigation enhances soil moisture retention and reduces wind erosion on soil foundations. Magnetic treatment alters water viscosity, surface tension, and other properties. See these variations in water molecules. These changes may have been caused by treatment. In (Ma et al., 2022) found that magnetic field-treated water reduces soil salinity, slows water evaporation, and boosts rice seedling germination and growth. After magnetic fields are applied to water, researchers found that plants absorb more nutrients. This is because plants absorb more nutrients. According to (Medeiros et al., 2023), these nutrients include nitrogen, phosphorus, and sulfur, which plants need to grow. (Yang et al., 2023) study found that it enhances rice seedling biomass and maize soluble sugar and protein. Magnetized irrigation improves rice nutrition in salty and alkaline conditions by upregulating nitrogen absorption genes such OSNRT and OSAMT (Ma et al., 2022). This increases rice's nutritional efficiency. The enzymes' main functions were binding metal ions, oxidoreductase activity, galactose metabolism, amino acid synthesis, and starch and sucrose metabolism. (Wu et al. 2024) found that these metabolic pathways affect crop growth and development. These metabolic activities promote sugar accumulation, carb conversion, protein synthesis, and membrane integrity, which boost lettuce yields. By binding metal ions and activating oxidoreductase, crop cell membranes become more robust. The amount of damage to chromosomes and the kind of mutations affect how well plants survive. An increase in chromosomal damage is observed with higher levels of radiation exposure, which may account for the reduced plant growth and survival. These findings align with previous studies (Shabani et al., 2022). The results of the present study indicate that gamma radiation and magnetically treated water enhanced seed germination percentage, vigor indices I and II, and several biophysical parameters, such as root and shoot length, fresh and dry weight of root and shoot, number of leaves, plant height, and leaf area. Furthermore, both treatments also improved photosynthetic pigment levels and mineral content. Such improvements are associated with increased leaf membrane integrity and changes in several endogenous hormone levels (Bezerra et al., 2023). However, while these parameters improved at moderate levels, they declined at higher doses of gamma radiation and prolonged exposure of magnetically treated water. However, present study suggests that appropriate doses of gamma radiation and magnetically treated water can effectively enhance germination rate, seedling growth, chlorophyll content, mineral ion concentration and antioxidant activity. For broader agricultural application, further evaluation under field conditions is necessary, with the hope that farmers will compare real-world findings with those obtained in laboratory settings. Since, it is cost-effective, and environment friendly technique holds promise for promoting sustainable agricultural practices.

Conclusion

Gamma radiation and magnetically treated water significantly influenced the germination percentage and seedling growth of maize. The highest germination percentage was observed in seeds treated with 100Gy of gamma radiation combined with 30min of magnetically treated water exposure, while the lowest germination percentage was recorded at the highest gamma dose (T_4 treatment). Root length, shoot length, plant height, and the fresh and dry weights of both roots and shoots decreased with increasing gamma radiation doses and prolonged magnetic water exposure times. The best germination and growth parameters were achieved at 100Gy gamma radiation combined with 30min of magnetic water treatment, while the lowest values were recorded under 200Gy irradiation combined with 50 minutes of magnetic water exposure, compared to the control.

DECLARATIONS

Funding: There is no funding support from any organization.

Acknowledgement: The authors thank Mr. Zia-Ul-Haq (Department of Physics, University of Agriculture, Faisalabad, Pakistan) for his expertise in this field.

Conflicts of Interest: The authors declared no conflict of interest in this research paper.

Data Availability: The data will be made available upon receipt of an appropriate request.

Ethics Statement: The authors declare that this study was conducted per the principles of ethical research practices. All plant-related procedures were performed in accordance with standard laboratory guidelines. The study did not involve any endangered plant species, and no ethical approval was required.

Author's Contribution: ZUH designed the experiment, KA worked on the proposed research in consultation with IA, while AA conceived the statistical idea. All authors finally approved the present research work.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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