



Effect of various electroculture materials on seed germination and growth of chilies (*Capsicum annuum*)

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Abstract

Chili (*Capsicum annuum*) production is frequently constrained by low germination rates and weak seedling growth, necessitating sustainable, non-chemical strategies to enhance crop establishment. This study evaluated the effects of electroculture on seed germination and early growth of chili under field conditions. Seed germination ranged from 57.50% in control plants to 67.50% under silver treatment, with iron treatment and magnetic treatment achieving 70.00% and 65.00%, respectively. Days to germination were slightly reduced under magnetic exposure (7.25 days) compared with control plants (7.75 days), indicating a modest acceleration in emergence. Electroculture significantly enhanced vegetative growth, with Magnetic treatment producing the highest plant height (36.16 cm), number of leaves per plant (33.75), branches (10.25), flowers per plant (12.00), and shoot biomass (9.93 g). Metallic treatments such as silver and iron primarily improved germination but had limited effects on subsequent vegetative growth, whereas copper treatment exhibited moderate effects across both germination and early growth traits. Statistical analysis revealed significant differences ($P < 0.05$) for vegetative and reproductive traits, while germination percentage and time to germination were less sensitive to treatments. Overall, the findings demonstrate that magnet-based electroculture promotes sustained vegetative and reproductive growth, providing a practical, eco-friendly approach to improve chili productivity. The results highlight the potential of electroculture as a low-input, sustainable strategy for vegetable production, reducing reliance on chemical inputs, improving crop performance, and supporting resilient agricultural systems. These findings provide a foundation for further research on the physiological and biochemical mechanisms underlying electroculture-mediated growth enhancement in chili.

1. Introduction

Chili (*Capsicum annuum* L.) is a globally important vegetable and spice crop, valued for its culinary, nutritional, and industrial uses. Domesticated in the Americas, chili is now cultivated worldwide and plays a key role in supporting

smallholder incomes and regional food systems, with global production surpassing 40 million tonnes in recent decades (Rani et al., 2023). Beyond food applications, chili bioactives such as capsaicinoids and carotenoids underpin pharmaceutical and nutraceutical uses, including analgesic and antioxidant formulations (Lata & Sharma, 2022).

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Nutritionally, chilies are rich in vitamins A and C and a range of minerals and phenolic compounds, which collectively contribute to human health and enhance market value (Ganguly et al., 2017). Despite its economic and nutritional importance, chili (*Capsicum annuum* L.) production faces persistent constraints during the crop establishment stage. Low seed vigor, uneven germination, and early seedling stress limit stand establishment, ultimately reduces yield (Attri et al., 2021; Walia et al., 2021). Seed quality is therefore critical to productivity, and various seed enhancement technologies have received considerable attention (Hufnagel et al., 2020; Clémence-Aggy et al., 2021). Conventional seed treatments often rely on chemical agents, which may have environmental trade-offs and exhibit variable efficacy under field conditions, motivating research into sustainable alternatives (Mansoori, 2017).

Electroculture, the application of electric and electromagnetic fields to seeds or growing plants, has recently reappeared in the literature as an eco-friendly strategy to improve germination, seedling vigor, and resource-use efficiency. Historical experiments reported growth stimulation following electrical exposure, and contemporary studies have linked electric and magnetic treatments to accelerated germination, modulated enzyme activity, enhanced membrane permeability, and improved water and nutrient uptake (Mamluc et al., 2021). Electromagnetic treatments have also been associated with shifts in hormone balance and rhizosphere microbial dynamics; these changes can increase stress tolerance during early establishment (Singeorzan et al., 2022; Dziwulska-Hunek et al., 2023).

Magnetic fields and magnetized water represent practical applications of electroculture. Controlled magnetic exposure has been reported to influence photoreceptor-mediated pathways (cryptochrome/phytochrome), biological rhythms, and photosynthetic performance, with positive effects on germination and growth in diverse crops (Dhiman & Galland, 2018). Studies employing magnetized water and direct magnet treatments have demonstrated improvements in growth parameters in chili and other horticultural crops, although responses are often species- and dose-dependent (Alattar et al., 2021).

Concurrently, nanotechnology and metallic particle treatments (nanopriming) are increasingly explored for seed invigoration. Metal-based nanoparticles (MNPs) such as ZnO, Cu, Ag, and TiO₂ have produced both beneficial and adverse outcomes in *Capsicum* species. Zinc oxide nanoparticles enhanced phenolic synthesis and antioxidant capacity during chili germination, although higher concentrations sometimes inhibited root growth (Mushtaq et al., 2025). Copper and silver nanoparticles applied as seed

priming or foliar sprays improved physiological traits and reduced pest pressure in chili in some studies (Gupta et al., 2022; Mawale et al., 2024), whereas other reports noted phytotoxicity, delayed flowering, or reduced germination depending on dose and application method (Allegra et al., 2019; Akdemir, 2021). Seed invigoration studies and theses on nanoparticle priming have reported tangible improvements in seed yield and storability for chili, reinforcing the practical potential of nanopriming (Riya Mary, 2020; Gupta et al., 2022). Meta-analytic and crop-specific reviews further underscore mixed responses and emphasize the need for species-tailored optimization (Van Nguyen et al., 2022; Díaz-Parra et al., 2025).

Overall, the literature reveals two critical gaps. First, while both magnetic or electric treatments and metallic nanoparticles show promise, experimental results are inconsistent across species and protocols, and direct comparative studies are limited (Shotbolt et al., 2025). Second, electroculture research in chili remains limited compared with investigations in cereals and industrial crops, leaving uncertainties about the relative benefits and risks of different electroculture materials (Ayesha et al., 2023). Given the increasing interest in sustainable, chemical-free seed enhancement approaches, there is an urgent requirement for controlled, comparative evaluations of common electroculture materials (magnetic fields, copper, silver, iron) under standardized conditions (Mansoori, 2017; Nandini et al., 2023).

Therefore, the present study aimed to evaluate the comparative effects of magnetic, copper, silver, and iron electroculture materials on seed germination and early growth of chili (*Capsicum annuum* L.). Specifically, we aimed to (1) compare germination percentage, germination speed, and early seedling vigor across treatments, (2) examine physiological and biomass responses, and (3) assess potential trade-offs (e.g., germination vs. biomass). We hypothesize that electroculture treatments will improve germination and early growth relative to controls, but that effects will be material-dependent, with magnetic exposure and optimized metallic treatments providing the most consistent benefits (Mawale et al., 2024; Alam et al., 2025). The study aims to fill a critical knowledge gap in sustainable chili seed management and provide guidance for practical electroculture applications for improved crop establishment.

2. Materials and Methods

The field experiment was carried out during the winter season of 2024 at the Department of Horticulture, Sindh Agriculture University, Tandojam, to evaluate the effect of different electroculture materials on seed germination and early growth of chili (*Capsicum annuum* L.). The experiment was arranged in a completely randomized design (CRD) with four

replications to ensure reliability of statistical inference. The local chili variety 'Ghotki' was used as the test material. A total of five treatments were applied, including: T_1 = Control, T_2 = Magnetic treatment (Four magnets of 4.5 cm per pot), T_3 = Copper wires (Two 2-ft wires per pot), T_4 = Silver wires (Two 2-ft wires per pot), T_5 = Iron wires (Two 2-ft wires per pot) (Figure 5).

2.2. Crop Husbandry

Seeds were sown in medium-sized earthen pots (25–30 cm in diameter) filled with a uniform soil:sand;farmyard manure (FYM) mixture (2:1:1). Pots were irrigated as required to maintain optimal moisture levels and were kept under natural field conditions. Standard agronomic practices were followed, and no chemical fertilizers or pesticides were applied to avoid interference with treatment effects.

2.3. Data Collection

Seed germination (%), days to germination, plant height (cm), number of leaves per plant, number of branches per plant, days to flower initiation, number of flowers per plant, fresh biomass of root (g), and fresh biomass of shoot (g) were recorded (Figure 1).

2.4. Procedure

2.4.1. Seed germination (%):

The number of seeds that germinated from a known total was counted, and the percentage was calculated.

2.4.2. Days to seed germination:

The number of days from sowing to the appearance of the first visible sprout was recorded.

2.4.3. Number of leaves per plant:

The number of leaves on each randomly selected plant was counted, and the mean value was calculated.

2.4.4. Plant height (cm):

Plant height was recorded at crop maturity using a measuring tape from the base to the tip of randomly selected plants in each treatment, and the average was calculated in centimeters.

2.4.5. Number of branches per plant:

The number of branches on each randomly selected plant was counted, and the mean value was calculated.

2.4.6. Days to flower initiation:

The number of days from sowing to the appearance of the first flower bud was recorded.

2.4.7. Number of flowers per plant:

The number of flowers on each randomly selected plant was counted, and the mean value was calculated.

2.4.8. Fresh biomass of root (g):

Plants were gently uprooted, roots were washed, and their fresh weight was measured immediately using a digital balance.

2.4.9. Fresh biomass of shoot (g):

Plants were gently uprooted, shoots were washed, and their fresh weight was measured immediately using a digital balance.

2.5. Statistical design:

Data was analyzed using Statistix 8.1 (Statistix, 2006) for analysis of variance (ANOVA). Treatment means were compared using the Least Significant Difference (LSD) test at the 5% probability level ($P \leq 0.05$).



Figure 1. Visual representation of the applied treatments (Magnetic, Iron, Silver and Copper) during the experimental phase.

3. Results

3.1. Germination and early growth

3.1.1. Seed germination (%):

The findings on seed germination (%) as influenced by different electroculture treatments are presented in (Figure 2) with the corresponding analysis of variance in (Table 1). Data showed a clear trend from maximum to minimum effectiveness. Copper treatment recorded the highest

germination at 75.00%, indicating its superior ability to stimulate seed germination. This was followed by iron treatment, which achieved a germination percentage of 70.00%, and silver treatment at 67.50%. Magnetic treatment resulted in 65.00% germination, while the control exhibited the lowest germination percentage at 57.50%. Comparisons among treatments showed no significant differences in

both averaging 7.50 days. The control exhibited the longest germination time at 7.75 days. Although magnetic treatment showed a slight trend toward earlier germination compared to the others, the differences among treatments were statistically non-significant ($P = 0.5437$; $P > 0.05$), and the LSD value of 0.7536.

3.1.3. Number of leaves per plant:

Table 1. Analysis of variance for seed germination, days to germination and number of leaves per plant

Level of Significance	Seed germination (%)	Days to seed germination	Number of leaves per plant
SE	7.4722	0.3536	3.2869
LSD @ 5%	15.927	0.7536	7.0058
P value	0.3841	0.5437	0.0320

germination ($P = 0.3841$; $P > 0.05$), with an LSD value of 15.927. Although treatments such as copper and iron had higher mean germination compared with the control, these differences did not exceed the LSD threshold.

3.1.2. Days to germination:

The findings on days to seed germination as influenced by different electroculture treatments are presented in (Figure 2) with the corresponding analysis of variance in (Table 1). Days to germination varied slightly among treatments, with only minor differences observed. Magnetic and iron treatments resulted in the earliest germination, averaging 7.25 days. This was followed by copper and silver treatments,

The effect of different electroculture treatments on chilies was investigated, and the results for the number of leaves per plant are presented in (Figure 2) with the corresponding analysis of variance in (Table 1). The analysis of variance revealed a significant effect ($P < 0.05$) of electroculture treatments on the number of leaves per plant of chilies. Magnetic treatment produced the highest number of leaves per plant (33.75), followed by iron treatment (30.50), copper treatment (29.00), and silver treatment (28.25). The control had the lowest number of leaves per plant (23.00).

3.2 Vegetative and reproductive growth

3.2.1. Plant height (cm):

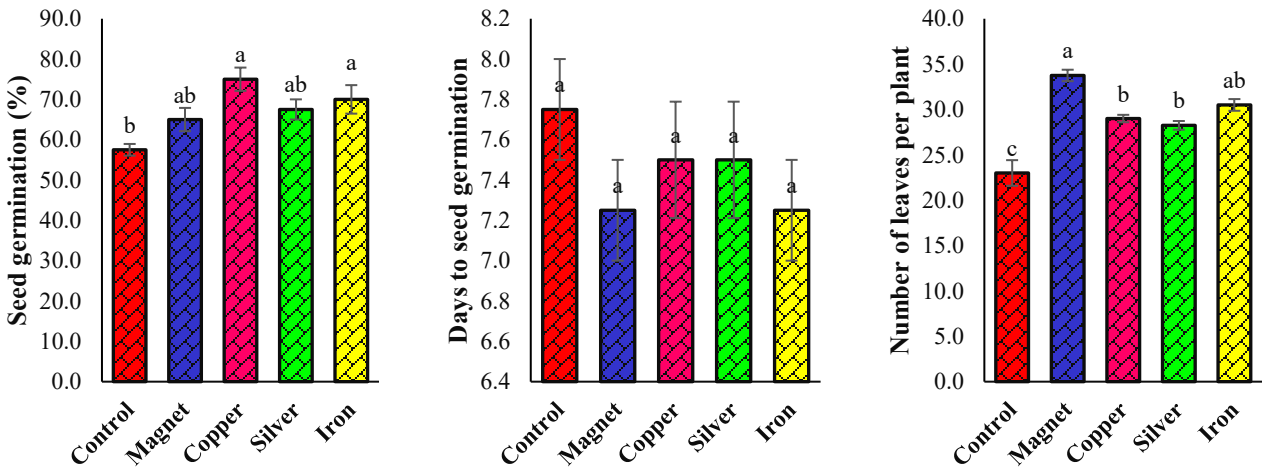


Figure 2. Effect of different electroculture treatments on seed germination (%), days to germination, and number of leaves per plant in chili (*Capsicum annuum* L.). Bars show mean $\pm$ SE. Bars sharing the same letter(s) are statistically similar at the 5% level of probability under Tukey's HSD test.

The effect of different electroculture treatments on the plant height of chili showed notable variation, with the magnetic treatment exhibiting the greatest influence and the findings are shown in (Figure 3). Among the five treatments, magnetic treatment recorded the highest plant height (36.16 cm), followed by iron treatment (33.83 cm), copper treatment (30.83 cm), and silver treatment (24.50 cm). The control group recorded the lowest height (22.50 cm). The analysis of variance revealed statistically significant differences among treatments ($P = 0.0011$, $LSD = 6.01$, $P < 0.05$). Copper treatment also demonstrated a significant increase compared with the control, whereas the difference between silver and control was not statistically significant, as it did not exceed

indicated a significant effect ($P < 0.05$) of electroculture treatments on the number of branches. Magnetic and silver treatments produced the highest branch count (10.25 branches per plant), followed by iron treatment (9.50 branches per plant) and copper treatment (8.50 branches per plant). The control had the lowest number of branches (6.50 branches per plant). Differences among treatments were statistically significant, as the P -value was 0.0039 ($P < 0.05$). The difference between magnetic treatment (T_2) and the other treatments exceeded the LSD value (2.76), indicating a significant effect of the magnet treatment.

3.2.3. Days to flower initiation:

Table 2. Analysis of variance for seed germination, days to germination and number of leaves per plant

Level of Significance	Plant height (cm)	Number of branches per plant	Days to flower initiation
SE	2.8213	1.2964	14.926
LSD @ 5%	6.0134	2.7633	31.814
P value	0.0011	0.0039	0.1776

the LSD threshold.

3.2.2. Number of branches per plant:

The impact of various electroculture treatments on the number of chili branches was examined, and the results are presented in (Figure 3). Analysis of variance (Table 2)

The influence of various electroculture treatments on the days to flower initiation in chilies was assessed, with the results summarized in (Figure 3). The analysis of variance (Table 2) revealed a non-significant ($P = 0.1776$, $P < 0.05$) effect of electroculture on flower initiation. Among the treatments silver treatment and iron treatment exhibited the longest

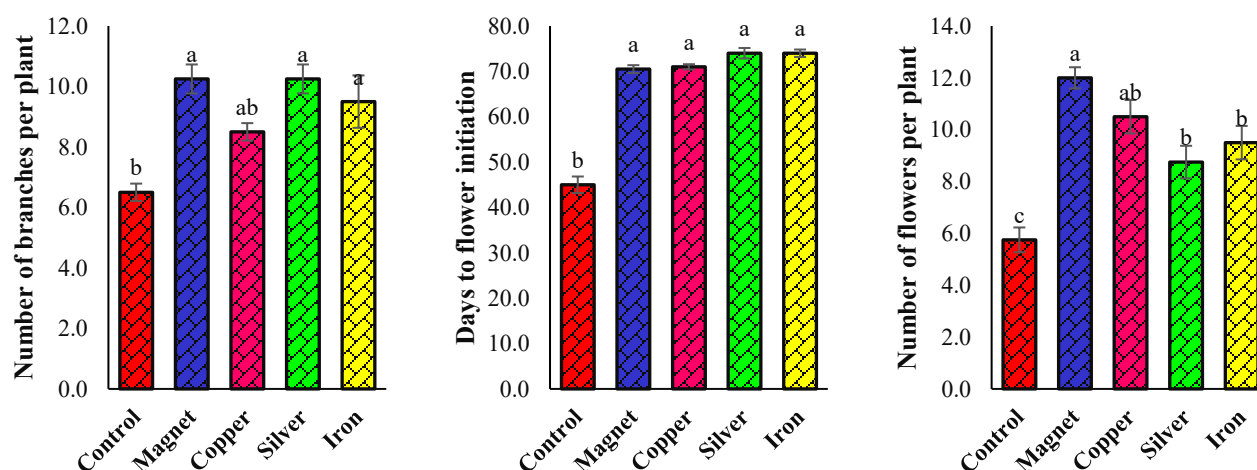


Figure 3. Effect of different electroculture treatments on number of flowers per plant, number of branches per plant, and days to flower initiation in chili (*Capsicum annuum* L.). Bars show mean $\pm$ SE. Bars sharing the same letter(s) are statistically similar at the 5% level of probability under Tukey's HSD test.

period for flower initiation, averaging 74.00 days followed by copper treatment (71.00 days) and magnetic treatment (70.50 days). The control had the shortest time to flower initiation (40.75 days). Differences among treatments were statistically non-significant, as indicated by the P-value exceeding the 0.05 threshold.

3.3 Yield and Biomass:

3.3.1. Number of flowers per plant:

The results regarding the number of flowers per plant in chilies under different electroculture treatments are present in (Figure 4) and analysis of variance in (Table 3). Among the treatments, Magnetic treatment produced the highest flower count (12.00 flowers per plant), followed by copper (10.50), iron (9.50), and silver (8.75).

other treatments ($P = 0.0052$, $P < 0.05$). In contrast, copper, silver, and iron had higher flower counts than control, but their differences were not statistically significant when compared to using the LSD value (5.07).

3.3.2. Fresh biomass of root (g):

The findings related to the fresh weight of root biomass (g) of chili plants subjected to various electroculture treatments are presented in (Figure 4) and analysis of variance in (Table 3). Among the treatments, magnetic treatment produced the highest mean fresh weight of root biomass (1.64 g). Iron treatment also resulted in a notable increase in fresh weight of root biomass (1.43 g). The control had a mean biomass of 1.20 g, copper treatment had (1.58 g), and silver treatment showed the lowest mean (1.52 g). Differences among treatments were statistically non-significant ($P = 0.2218$, $P >$

Table 3. Analysis of variance for number of flowers per plant, fresh biomass of root (g) and fresh biomass of shoot (g)

Level of Significance	Number of flowers per plant	Fresh biomass of root (g)	Fresh biomass of shoot (g)
SE	2.3805	0.2731	1.8322
LSD @ 5%	5.0739	0.5821	3.9921
P value	0.0052	0.2218	0.0647

The control, which received no electroculture treatment, had the lowest flowers count (5.75 per plant). The magnetic treatment showed a statistically significant increase in the number of flowers per plant compared with the control and

0.05). Overall, the data suggests that electroculture treatments, including magnetic exposure, did not have a significant effect on fresh root biomass of chili.

3.3.3. Fresh biomass of shoot (g):

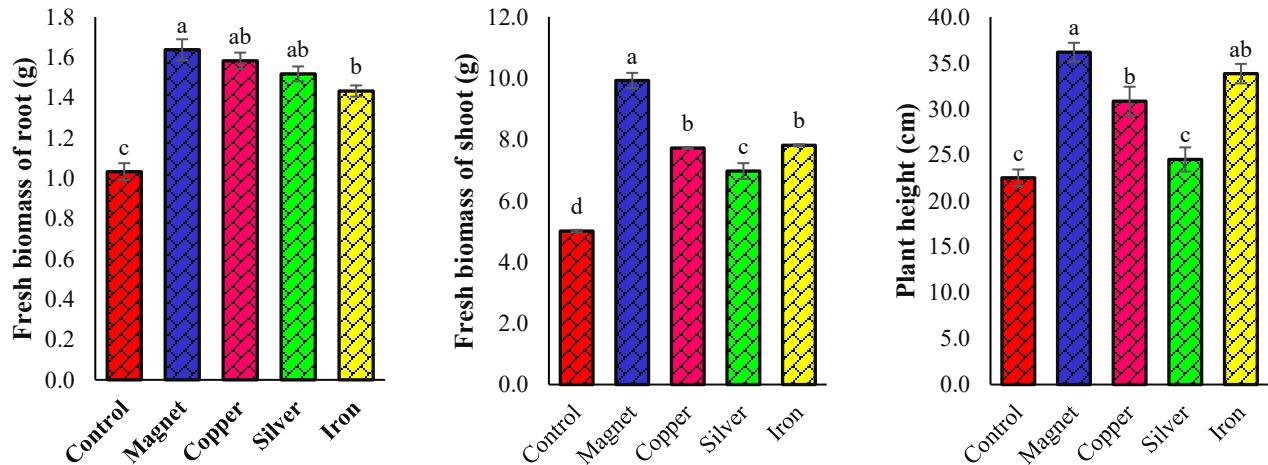


Figure 3. Effect of different electroculture treatments on fresh root biomass (g), fresh shoot biomass (g), and plant height (cm) in chili (*Capsicum annuum* L.). Bars show mean $\pm$ SE. Bars sharing the same letter(s) are statistically similar at the 5% level of probability under Tukey’s HSD test.

The findings related to the fresh weight of root biomass (g) of chili plants subjected to various electroculture treatments are presented in (Figure 4) and analysis of variance in (Table 3). Among the treatments, magnetic treatment produced the highest shoot biomass (9.93 g), followed by iron (7.81 g), copper (7.72 g), and silver (6.97 g). The control recorded the lowest biomass (5.01 g). The overall effect of electroculture treatments on shoot biomass was marginally non-significant ($P = 0.0647$, $P > 0.05$). Among treatments, magnetic treatment produced significantly higher biomass compared with control and silver treatment, as the differences exceeded the LSD value. In contrast, copper, iron, and silver did not differ significantly from the control or among each other. Although the overall treatment effect was not statistically significant at the 5% level, magnetic treatment showed a notable positive impact on shoot fresh biomass.

3.4. Pearson Correlation Analysis

The correlation matrix (Figure 6) revealed strong and significant associations among germination, vegetative, and reproductive traits of chili under different electroculture treatments. Seed germination (SG) showed positive correlations with most vegetative and yield-related parameters, including number of leaves per plant (NLPP; $r = 0.30$), number of branches per plant (NBPP; $r = 0.36$), days to flower initiation (DTFI; $r = 0.63$), number of flowers per plant (NFPP; $r = 0.37$), fresh root biomass (FBR; $r = 0.58$), fresh shoot biomass (FBS; $r = 0.35$), and plant height (PH; $r = 0.18$). In contrast, days to germination (DSG) exhibited negative correlations with nearly all growth attributes, particularly NLPP ($r = -0.35$), NBPP ($r = -0.36$), DTFI ($r = -0.32$), FBS ($r = -0.41$), and PH ($r = -0.30$), indicating that delayed germination was associated with reduced vegetative vigor and biomass accumulation. Strong positive relationships were observed among vegetative and reproductive traits. NLPP was highly correlated with NBPP ($r = 0.64$), DTFI ($r = 0.76$), NFPP ($r = 0.87$), FBR ($r = 0.73$), FBS ($r = 0.90$), and PH ($r = 0.80$). Similarly, NBPP demonstrated significant positive associations with DTFI ($r = 0.75$), NFPP ($r = 0.65$), FBR ($r = 0.70$), and FBS ($r = 0.68$). Reproductive traits also exhibited strong interrelationships. DTFI was positively correlated with NFPP ($r = 0.70$), FBR ($r = 0.82$), FBS ($r = 0.70$), and PH ($r = 0.55$). The number of flowers per plant showed particularly strong correlations with FBS ($r = 0.88$), FBR ($r = 0.77$), and PH ($r = 0.80$), highlighting the close linkage between floral development and biomass production. Among biomass-related traits, FBR and FBS were strongly correlated ($r = 0.79$), and both exhibited positive associations with plant height (FBR: $r = 0.61$; FBS: $r = 0.83$). Overall, fresh shoot biomass demonstrated one of the strongest relationships with other growth parameters, particularly NLPP and NFPP. These results indicate that improved early establishment and

vegetative growth under electroculture treatments were closely linked with enhanced flowering and biomass accumulation. The strong positive correlations among leaves, flowers, shoot biomass, and plant height suggest that vegetative vigor plays a central role in determining reproductive performance in chili under electroculture conditions. Conversely, delayed germination negatively affected subsequent growth and productivity traits. Pearson's correlation coefficients among growth and yield parameters were calculated, and the correlation matrix was visualized using OriginPro software (OriginLab Corporation, Northampton, MA, USA).

4. Discussion

Electroculture and related metallic interventions produced treatment-dependent effects on chili germination and early growth, highlighting that physical and chemical modifications of seeds and the environment can trigger distinct physiological pathways. The overall pattern observed in this study—improved germination under certain metallic treatments and markedly enhanced vegetative growth under magnetic exposure—aligns with prior evidence showing that electromagnetic and metal-based stimuli modulate membrane permeability, enzyme activities, and hormonal signals (Alattar et al., 2021; Martínez et al., 2019; Shine et al., 2022). Interpreting these patterns in mechanistic terms clarifies why magnetic and metallic treatments can produce divergent short-term and longer-term outcomes.

Magnetic exposure consistently promoted seedling vigor and biomass accumulation, likely due to enhanced ion fluxes, improved water uptake, and activation of hydrolytic enzymes that mobilize seed reserves for radicle protrusion (Martínez et al., 2019). Weak magnetic fields can also alter the kinetics of membrane transport proteins and modulate growth regulators such as gibberellins and auxins, accelerating germination and early elongation (Alattar et al., 2021; Shine et al., 2022). The observed delay in flowering under magnetic treatment likely reflects an extended vegetative phase driven by enhanced assimilate production and altered hormonal balance, as reported for magnetically treated crops (De Souza et al., 2020). Increased chlorophyll content and photosynthetic efficiency may underpin the higher shoot (9.93 g) and root biomass (1.64 g) recorded here (Aladjadjiyan, 2019; Flórez et al., 2019).

Metallic treatments produced more nuanced effects. Silver and iron treatments improved seed germination percentages, which is consistent with silver's antimicrobial properties that reduce seed surface pathogens, thereby improving emergence (Veen, 2021). Silver's antimicrobial action, coupled with potential modulation of ethylene signaling, can favor rapid germination (Rai & Ingle, 2020). However, silver frequently exhibits dose-dependent trade-offs: strong early germination

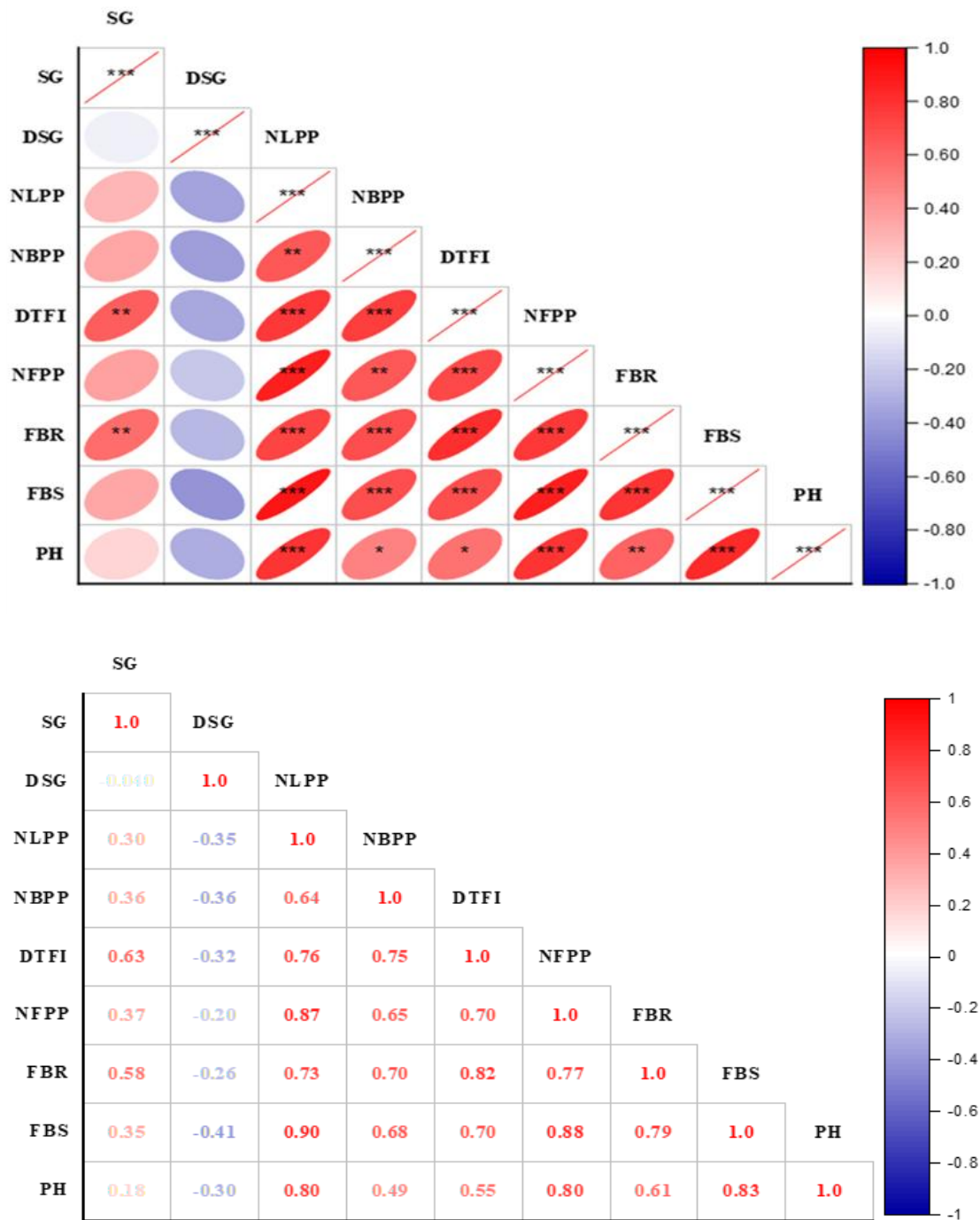


Figure 6. Correlation matrix of growth and yield traits in chili (*Capsicum annuum* L.) under electroculture treatments. Color intensity and ellipse shape indicate correlation strength; significance: *P ≤ 0.05, **P ≤ 0.01, ***P ≤ 0.001. Traits: SG = seed germination, DSG = days to germination, NLPP = number of leaves, NBPP = number of branches, DTFI = days to flower initiation, NFPP = number of flowers, FBR = fresh root biomass, FBS = fresh shoot biomass, PH = plant height.

gains may be followed by suppressed vegetative growth due to metabolic disturbance or interference with mitochondrial function (Pereira et al., 2023). In this study, higher germination under silver corresponded with lower vegetative performance, consistent with previously reported antagonistic effects (Mawale et al., 2024).

Iron improved germination and modestly affected vegetative traits. Iron's central role in chlorophyll biosynthesis and electron transport likely underlies improved early establishment (Marschner, 2020). Nevertheless, when iron is present in forms or microenvironments that limit bioavailability, the expected enzymatic and photosynthetic benefits may not fully materialize, explaining why iron treatments sometimes support germination but not maximal vegetative growth (Akdemir, 2021; Carbonell et al., 2022). Additionally, ferromagnetic properties can locally modify field gradients around the seed zone, and the interaction of iron's micronutrient role with its physical properties likely produced the intermediate response observed.

Copper treatment displayed moderate germination but the lowest vegetative growth among metallic treatments. This aligns with copper's status as an essential micronutrient that becomes phytotoxic at supra-optimal concentrations: excess copper promotes reactive oxygen species (ROS) generation, inhibits key enzymes, and damages membranes, reducing growth (Maksymiec, 2019; Yruela, 2020). Copper-induced oxidative stress and lipid peroxidation have been reported as proximate causes of stunted growth under metallic exposure (Rascio & Navari-Izzo, 2022). The relative underperformance of copper in this study likely reflects localized oxidative stress or disrupted nutrient homeostasis rather than a lack of micronutrient function (Mansoori, 2017).

The divergence between “what improves germination” and “what sustains later biomass” highlights an important conceptual point: germination is sensitive to surface and initial physiological cues (e.g., microbial load, membrane permeability), whereas sustained vegetative growth depends on ongoing metabolic balance, nutrient transport, and oxidative stress control. Silver and iron can enhance initial emergence, but only treatments that support ongoing photosynthesis, enzyme function, and redox balance, as observed under magnetic and selected copper treatments, produced the largest biomass gains (Díaz-Parra et al., 2025).

Strong positive correlations among germination, vegetative, reproductive, and biomass traits reinforce these interpretations. Early seedling vigor, reflected in higher leaf (Magnetic: 33.75; Iron: 30.50) and branch numbers (Magnetic: 10.25; Iron: 8.25), was closely linked with greater flower production (Magnetic: 12.00; Copper: 10.75) and shoot biomass (Magnetic: 9.93 g; Iron: 7.81 g), indicating that improvements in initial establishment directly translated

into enhanced reproductive and yield potential. Conversely, delayed germination negatively affected subsequent growth and biomass accumulation, emphasizing that interventions targeting early germination can have cascading effects on overall plant performance. Pearson correlation analysis also confirmed these interrelationships, demonstrating integrated growth responses rather than isolated trait improvements.

Comparative work with nanoparticle priming in *Capsicum* supports these interpretations. ZnO, TiO₂, Cu, and Ag nanoparticles have been reported to increase antioxidant compounds and germination indices at optimized doses, but higher concentrations provoke inhibitory effects, indicating a narrow beneficial window (Riya Mary, 2020; Gupta et al., 2022). Mawale et al. (2024) and Díaz-Parra et al. (2025) further emphasize that metal type, speciation, and exposure method (wire, priming, foliar) substantially alter physiological outcomes, consistent with the variability observed in our trial.

The control plants' earlier flowering with low biomass suggests a stress-escape response, where plants under suboptimal establishment accelerate reproduction at the expense of vegetative growth, a strategy well-documented in annual plants (Simpson & Dean, 2018). This explains why control plants flowered sooner (40.75 days) but produced fewer flowers (2.50 per plant) and smaller biomass overall (Shoot: 5.01 g; Root: 1.03 g). Overall, the mechanistic reading of our data indicates three practical takeaways: (1) magnetic exposure appears to improve sustained physiological performance (water and ion fluxes, photosynthetic efficiency) and is thus promising for biomass and flower production (Vashisth & Nagarajan, 2017; Martínez et al., 2019); (2) metallic interventions can boost germination via antimicrobial or micronutrient effects but carry risks of oxidative toxicity and growth inhibition when improperly dosed (Pittman, 2020; Rascio & Navari-Izzo, 2022); and (3) optimal outcomes will depend on material form, concentration, exposure duration and crop-specific responses, underscoring the need for dose-response and mechanistic assays (De Souza et al., 2020). Finally, while the present study did not measure biochemical markers directly (a limitation discussed below), the pattern of results strongly motivates follow-up work to quantify antioxidant enzyme activities, proline and MDA, nutrient uptake, and gene expression. Such measurements will be essential to confirm the enzymatic, hormonal and oxidative mechanisms inferred here (Akdemir, 2021; Pereira et al., 2023).

5. Conclusion

This study revealed that electroculture, particularly magnetic treatment, substantially improved germination, vegetative growth, and flower production in chili (*Capsicum annuum* L.), outperforming metallic interventions such as copper,

silver, and iron. The novelty of this research lies in a simple, eco-friendly approach that can enhance chili productivity while minimizing dependence on chemical inputs. These results highlight the practical potential of electroculture as a sustainable horticultural tool, with implications for both smallholder and commercial chili cultivation. However, the study was limited to morphological traits, and future work should incorporate physiological, biochemical, and molecular parameters to elucidate underlying mechanisms and optimize treatment protocols. Long-term, multi-environment trials will be essential to validate electroculture as a scalable, climate-smart technology.

6. Funding

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7. Acknowledgment

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8. Conflict of Interest

The authors declare no conflict of interest.

9. Authors' Contribution

Aijaz Jabbar, Saba Ambreen Memon, and Muzafaruddin Chachar conceptualized the research framework, designed the methodology, and led the primary investigation. Hina Panhwar and Sana Shazia Jiskani performed data acquisition, formal analysis, and curated experimental datasets. Mian Muhammad Ahmed and Isha Aftab contributed to the software validation, literature visualization, and assisted in drafting the manuscript. Waseem Abbas provided supervision, resources, and conducted the final critical review and editing of the paper. All authors have reviewed and approved the final version of the manuscript.

10. SDGs Addressed

This research contributes to the United Nations Sustainable Development Goals by promoting sustainable agricultural practices. The study aligns with SDG 2: Zero Hunger through improved chili production and yield, supporting food security and nutrition. It also addresses SDG 12: Responsible Consumption and Production by exploring non-chemical, eco-friendly electroculture methods that reduce reliance on synthetic inputs, and SDG 13: Climate Action by promoting low-input, resource-efficient crop management strategies.

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