Greenhouse Plant Production Journal

Enhancing maize (*Zea mays* L.) growth and yield through seed priming and micronutrient coating: effects on agronomic traits and soil nutrient deficiencies

Mohammad Reza Ahmadi[a*], Maryam Salehi[b]

[a] *Department of medicine plants, Arak University, Arak, Iran*
[b] *Department of Agronomy Science, Azad Arak University, Arak, Iran*

Original Article

Use your device to scan and read the article online

Citation: Ahmadi, M.R. and Salehi, M. 2024. Enhancing maize (*Zea mays* L.) growth and yield through seed priming and micronutrient coating: effects on agronomic traits and soil nutrient deficiencies. Greenhouse Plant Production Journal, 1(3): 13-27.

https://doi.org/10.61186/gppj.1.3.13

KEYWORDS

Maize growth
Micronutrient coating
Nutrient deficiency
Seed priming
Yield enhancement

ABSTRACT

This study investigates the effects of seed priming and micronutrient treatments on the growth and yield of maize (*Zea mays*. L.), focusing on the single cross 704 cultivar in nutrient-deficient soils. A factorial arrangement within a randomized complete block design (RCBD) was employed, with treatments including hydroprimed and non-hydroprimed seeds coated with various combinations of micronutrients (Fe, Zn, Cu, FeZn, FeCu, ZnCu, and FeZnCu). Hydropriming involved soaking seeds in distilled water for 6 h, followed by air-drying, while seed coating used kaolinite clay and sugar beet molasses to apply micronutrients. Results revealed that hydroprimed seeds generally performed better across most measured traits, including fresh and dry weights of stem and leaves, number of leaves, and plant height, particularly when treated P-Zn. The combination of P-FeZnCu yielded the highest dry weights for stem and leaves, indicating a synergistic effect of these micronutrients. Non-primed seeds also showed positive responses, especially with NP-Fe, but overall performance was lower compared with primed seeds. Regression analysis highlighted the complex interactions between different micronutrient treatments. While some combinations, like Fe and Zn, exhibited significant positive effects, others, such as ZnCu and FeZnCu, demonstrated significant negative impacts, suggesting potential antagonistic interactions. These findings underscore the potential of seed priming and targeted micronutrient treatments to enhance maize growth and yield, particularly in soils with nutrient deficiencies. The study provides insights for optimizing agronomic practices and suggests that future research should focus on refining micronutrient combinations and concentrations to improve maize productivity in similar soil conditions. Long-term studies are recommended to evaluate the sustainability and economic viability of these practices in large-scale maize cultivation.

ARTICLE HISTORTY

Received: 4 august 2024
Revised: 7 September 2024
Accepted: 8 September 2024

* Corresponding author: M. R. Ahmadi
E-mail address: reza522003@yahoo.com

Publisher: Arak University

1. Introduction

Maize (*Zea mays* L.) is a crucial cereal crop, playing a significant role in global food security, animal feed, and industrial applications (Erenstein et al., 2022). In Iran, maize is particularly important for its contributions to the agricultural sector and its role in food and feed production (Tashayo et al., 2020). However, maize production in Iran faces several challenges, primarily due to the nutrient deficiencies prevalent in Iranian soils. These soils often lack essential nutrients such as nitrogen (N), phosphorus (P), and critical micronutrients like iron (Fe), zinc (Zn), and copper (Cu). As a result, farmers heavily rely on chemical fertilizers to achieve satisfactory crop yields. The extensive use of chemical fertilizers, especially nitrogen, poses significant environmental and economic concerns. Over-application of nitrogen fertilizers can lead to soil acidification, groundwater contamination through nitrate leaching (Sharafi et al., 2023), and the emission of nitrous oxide (N_2O), a potent greenhouse gas (Sharafi et al., 2023). These environmental issues highlight the need for more sustainable agricultural practices that can enhance crop productivity while minimizing negative environmental impacts (Ataei et al., 2021; Feilinezhad et al., 2022; Majidian et al., 2024).

Seed priming is a pre-sowing treatment that aims to improve seed performance and crop yield. Hydropriming, a specific type of seed priming involving soaking seeds in water, has garnered attention for its ability to enhance seed germination, seedling vigor, and overall plant growth. The process activates early metabolic activities in the seed, leading to faster and more uniform germination. Hydropriming has been shown to be particularly beneficial under stress conditions such as drought and salinity, which are common in many parts of Iran (Farooq et al., 2020; Kashif et al., 2021; Zulfiqar, 2021). Another promising strategy to address soil nutrient deficiencies is the application of micronutrients directly to seeds, a method known as seed coating or seed plating. Seed coating involves applying a thin layer of nutrients to the seed surface, ensuring that essential elements are readily available to the young seedling. This method can enhance nutrient use efficiency and reduce the need for soil-applied fertilizers. Micronutrients such as Fe, Zn, and Cu are vital for numerous plant physiological and biochemical processes, including photosynthesis, enzyme activation, and stress resistance (Alloway, 2008; Zaim et al., 2023).

The critical roles of micronutrients in crop production cannot be overstated. Fe is essential for chlorophyll synthesis and is a component of many enzymes involved in respiration and photosynthesis (Shah et al., 2022). Zn plays a vital role in protein synthesis, hormone regulation, and membrane integrity (Umair et al., 2020), while copper is involved in lignin synthesis, photosynthesis, and acts as a cofactor for several oxidative enzymes (Pradeep and Aishwarya, 2023). Deficiencies in these micronutrients can lead to stunted growth, reduced yield, and lower nutritional quality of the harvested crop (Zewide and Sherefu, 2021; Ali et al., 2023). Recent research has focused on combining seed priming with micronutrient seed coating to maximize the benefits of both techniques (Tondey et al., 2021). This integrated approach aims to improve seedling establishment, enhance nutrient uptake, and ultimately increase crop yield. For instance, a study by Bordolui and Mukherjee (2021) demonstrated that maize seeds primed with water and coated with a combination of Fe, Zn, and Cu showed significant improvements in germination rate, seedling growth, and grain yield compared with untreated seeds. These findings suggest that combining hydropriming with micronutrient seed coating could be a viable strategy for improving maize production in nutrient-deficient soils.

The present study investigates the effects of hydropriming and seed plating with various combinations of Fe, Zn, Cu, and their mixtures (FeZn, FeCu, ZnCu, FeZnCu) on maize yield. The objectives are to evaluate the impact of hydropriming on maize seed germination and early growth, assess the effectiveness of seed plating with different micronutrient combinations on maize yield, and compare the performance of treated seeds with a control treatment under field conditions. The significance of this study lies in its potential to provide a sustainable solution to the nutrient deficiencies in unfertile soils. By improving seed germination and early growth through hydropriming and enhancing nutrient availability with micronutrient seed coating, this approach could reduce the dependency on chemical fertilizers. This, in turn, would mitigate the environmental impacts associated with excessive fertilizer use, such as soil degradation and water pollution. Moreover, this study could contribute to the broader understanding of integrated nutrient management practices. The findings could be applicable to other regions facing similar soil fertility challenges, promoting sustainable agricultural practices globally. The integration of hydropriming and micronutrient seed coating represents an innovative approach that aligns with the goals of sustainable agriculture—enhancing crop productivity while preserving environmental health.

2. Materials and Methods

2.1. Soil analysis

Some physical properties and the nutrient status of the soil test are given in Table 1.

Table 1. The physical and chemical attributes of experimental farm

Soil								
pH	EC ($ds\ cm^{-3}$)	Bulk density ($g\ cm^{-3}$)	O.C	O.M	Clay (%)	Sand	Silt	Soil texture
7.14	2.2	1.56	1.12	0.65	34.11	31.2	34.69	Clay loam
Nutrition								
T.N (%)	P	K	S	Ca	Mg ($mg\ kg^{-1}$)	Fe	Zn	Cu
0.12	22	314	0.1	524	253	6.91	1.17	1.45

2.2. Experiment design

In order to investigate the effects of hydropriming and non hydropriming and the various levels of seed plating (Fe, Zn, Cu, FeZn, FeCu, ZnCu, and FeZnCu)) on quantitative and qualitative traits of the maize grain of the single cross 704 cultivar, an experiment was conducted by using the factorial arrangement of randomized complete block design (RCBD) with three replications (2022).

2.3. Seed hydropriming

In this experiment, maize seeds were subjected to hydropriming to enhance germination and early growth. The hydropriming process involved soaking the seeds in distilled water for 6 hours. After soaking, the seeds were air-dried in the shade for 48 hours to return them to their original moisture content. This hydropriming treatment was applied to half of the seed batch (Sharafi et al., 2009; Eiraji et al., 2023).

2.4. Seed coating

To improve nutrient availability and seedling growth, both hydroprimed and non-hydroprimed seeds were coated with micronutrients using kaolinite clay and sugar beet molasses as adhesives. A slurry was prepared using kaolinite clay and sugar beet molasses as binding agents. Micronutrients (Fe, Zn, Cu) were added to the slurry at a rate of 3 gr per micronutrient per treatment, including individual micronutrients and their combinations. The prepared slurry was uniformly applied to the surface of the seeds. After coating, the seeds were air-dried in the shade to ensure proper adhesion of the coating and return to their original moisture content.

2.5. Experimental design

The experiment was designed to evaluate the effects of hydropriming and micronutrient seed coating on maize growth and yield. Seeds were sown in a randomized complete block design (RCBD) under field conditions, with each treatment replicated to ensure statistical reliability. Standard agronomic practices were followed throughout the growing season to manage the crop and ensure uniform growth conditions across all treatments. To assess the impact of the treatments, several parameters were measured, including plant growth parameters (fresh weight of stem and leaves, fresh weight of stem, fresh weight of leaves, number of leaves, plant height, dry weight of stem and leaves, dry weight of stem, and dry weight of leaves), and yield components (fresh weight of ear, dry weight of ear). Data were subjected to statistical analysis to compare the performance of the different treatments and to draw conclusions about the effects of hydropriming and micronutrient seed coating on maize yield and growth.

2.6. Statistical analysis

Statistical analysis was performed as a combination using SAS 9.3 statistical software (SAS Institute Inc 2013. SAS/ACCESS 9.4 Interface to ADABAS: Reference. Cary, NC: SAS Institute Inc.); analysis of variance was performed and the mean was compared using Duncan's multiple range test at the level of 5 percent probability, with correlation analysis and standardized regression.

3. Results

In this experiment the traits including fresh weight of ear (FEW), dry weight of ear (DWE), fresh weight of stem and leaves (FWSL), fresh weight of stem (FWS), fresh weight of leaves (FWL), number of leaves (NL), plant height (PH), dry weight of stem and leaves (DWSL), dry weight of stem (DWS), and dry weight of leaves (DWL) were evaluated. The Table 2 presents quantitative data on various maize traits, revealing significant differences between primed (P) and non-primed (NP) seeds under different micronutrient treatments. For fresh weight of ear (FEW) and dry weight of ear (DWE), non-primed seeds treated with iron (NP-Fe) exhibited the highest values, whereas non-primed seeds treated with a combination of iron, zinc, and copper (NP-FeZnCu) showed the lowest. In terms of fresh weight of stem and leaves (FWSL), the primed seeds treated with zinc (P-Zn) demonstrated the highest value, and the non-primed control group (NP-Control) had the lowest. The fresh weight of stem (FWS) and leaves (FWL) was also highest in primed seeds treated with zinc (P-Zn), with the lowest weights recorded in primed seeds treated with iron and zinc (P-FeZn) and iron and copper (P-FeCu), respectively. For the number of leaves (NL), primed seeds treated with zinc (P-Zn) had the highest count, while non-primed seeds treated with zinc and copper (NP-ZnCu) had the lowest. Plant height (PH) was greatest in primed seeds treated with iron (P-Fe), whereas the shortest plants were found in non-primed seeds treated with iron and zinc (NP-FeZn).

Regarding dry weights, the combined dry weight of stem and leaves (DWSL), stem alone (DWS), and leaves alone (DWL) were highest in primed seeds treated with iron, zinc, and copper (P-FeZnCu), while the lowest values for these dry weights were observed in primed seeds treated with iron and zinc (P-FeZn). Overall, primed seeds generally showed superior growth performance across the measured traits compared with non-primed seeds, especially when treated with specific combinations of micronutrients. This suggests that seed priming, particularly with appropriate micronutrient treatments, can significantly enhance maize growth and yield, addressing the nutrient deficiencies often found in Iranian soils.

The findings of this study highlight the significant impact of seed priming and micronutrient coating on the growth and yield of maize, particularly in nutrient-deficient soils such as those commonly found in Iran. The data indicate that priming seeds with water (hydropriming) followed by coating with specific micronutrient combinations substantially enhances both the vegetative and reproductive parameters of maize. One of the most notable results was the superior performance of primed seeds, especially those treated with zinc (P-Zn). These seeds exhibited the highest fresh weight of stem and leaves (FWSL), fresh weight of stem (FWS), fresh weight of leaves (FWL), and number of leaves (NL). Zinc plays a crucial role in numerous plant physiological processes, including enzyme activation, protein synthesis, and hormone regulation, which are vital for plant growth and development (Mousavi et al., 2013; Bhantana et al., 2021). The primed seeds treated with zinc not only showed improved vegetative growth but also had the highest plant height (PH), suggesting that zinc significantly contributes to robust plant architecture.

Moreover, the combination treatments (FeZnCu) in primed seeds demonstrated the highest dry weights for stem and leaves combined (DWSL), stem alone (DWS), and leaves alone (DWL). This indicates a synergistic effect of these micronutrients when applied together, enhancing the overall biomass accumulation. The higher dry weights observed in these treatments can be attributed to the essential roles of iron, zinc, and copper in photosynthesis, respiration, and nutrient uptake (Liu et al., 2021). The improved growth parameters and biomass accumulation suggest that these micronutrient combinations can effectively mitigate nutrient deficiencies and promote optimal maize growth in deficient soils. Interestingly, non-primed seeds also responded well to micronutrient treatments, particularly with iron (NP-Fe), which recorded the highest fresh and dry weights of the ear (FEW and DWE). This underscores the importance of iron in reproductive development and grain filling, which are critical for achieving higher yields (Miner et al., 2022). However, the overall performance of non-primed seeds was generally lower compared with primed seeds, highlighting the added benefits of hydropriming in enhancing seedling vigor and early establishment, which are crucial for maximizing yield potential. In conclusion, the study demonstrates that seed priming combined with appropriate micronutrient treatments can significantly enhance maize growth and yield, particularly in nutrient-deficient soils. These findings provide valuable insights for agronomic practices aimed at improving maize productivity in regions with similar soil conditions. Future research should focus on optimizing the concentrations and combinations of micronutrients for different soil types and environmental conditions to further enhance the effectiveness of these treatments. Additionally, long-term field studies are needed to evaluate the sustainability and economic viability of these practices in large-scale maize production.

Table 2. Summary statistics (Quantitative data) of Maize

Traits	Min.	Max.	Mean	St. D
Fresh weight of ear (FEW)	150 (NP-FeZnCu)	627.36 (NP-Fe)	363.09	14.7
Dry weight of ear (DWE)	53.53 (NP-FeZnCu)	223.88 (NP-Fe)	129.57	8.07
Fresh weight of stem and leaves (FWSL)	395 (NP-Control)	1125 (P-Zn)	701.77	66.5
Fresh weight of stem (FWS)	290 (P-FeZn)	760 (P-Zn)	525.48	20.7
Fresh weight of leaves (FWL)	85 (P-FeCu)	365 (P-Zn)	176.35	14.5
Number of leaves (NL)	14 (NP-ZnCu)	21 (P-Zn)	17.06	1.4
Plant height (PH)	1.54 (NP-FeZn)	2.8 (P-Fe)	1.98	0.025
Dry weight of stem and leaves (DWSL)	0.06 (P-FeZn)	0.42 (P-FeZnCu)	0.2	0.0008
Dry weight of stem (DWS)	0.035 (P-FeZn)	0.31 (P-FeZnCu)	0.14	0.007
Dry weight of leaves (DWL)	0.025 (P-FeZn)	0.65 (P-FeZnCu)	0.074	0.009

*P; is seed primed, NP; is seed non-primed.

Fig. 1a-b, presents the regression analysis results for different treatments on the fresh weight of ear (FEW). The intercept has a significant value of 281.4 ($p<0.0001$), indicating a notable baseline effect. The Control treatment shows a positive and significant impact with a value of 52.3 ($p=0.023$). The Fe and FeZn treatments also exhibit significant positive effects, with values of 148.04 ($p=0.002$) and 163.3 ($p=0.001$), respectively. In contrast, Zn, Cu, and FeCu treatments do not show significant effects. The ZnCu and FeZnCu treatments have significant negative effects, with values of -188.9 ($p=0.0$) and -91.888 ($p=0.04$), respectively. These results indicate that certain micronutrient treatments significantly impact FEW, either positively or negatively. The positive effects of Fe and FeZn suggest their importance in enhancing maize growth and yield. The significant negative effects of ZnCu and FeZnCu highlight potential antagonistic interactions when these micronutrients are applied together, reducing performance. These findings emphasize the need to consider micronutrient combinations carefully to optimize maize growth, particularly in nutrient-deficient soils (Gondwe, 2018; Guardiola-Márquez ET AL., 2022). Further research is required to explore the mechanisms behind these interactions to refine fertilization strategies for improved agricultural productivity.

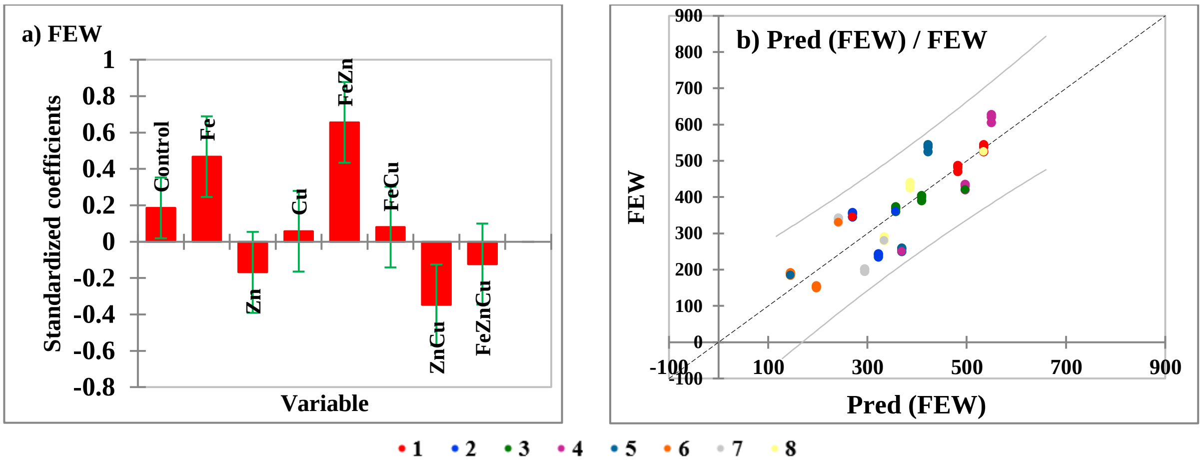

Fig. 1. a) Standardized coefficients (95% conf. interval), b) observed and predicted of FEW

Fig. 2 a-b, presents the standardized coefficients from a regression analysis focusing on the dry weight of ear (DEW). The Control treatment shows a positive and significant effect with a value of 0.19 ($p=0.02$). The Fe treatment also has a positive and significant effect, with a value of 0.36 ($p=0.002$). Zn has a negative coefficient (-0.15) but is not statistically significant ($p=0.15$). Cu has a small, non-significant positive effect (0.057, $p=0.6$). The combination treatment of FeZn has the highest positive and significant effect (0.405, $p=0.001$). The combination of FeCu shows a non-significant positive effect (0.089, $p=0.424$). The ZnCu combination shows a significant negative effect (-0.47, $p=0.0$). Lastly, the FeZnCu combination has a significant negative effect (-0.23, $p=0.04$). The standardized coefficients reveal the varying impacts of different micronutrient treatments on FEW. The positive and significant effects of the Control, Fe, and FeZn treatments suggest these are beneficial for enhancing FEW. Fe, alone and with Zn, demonstrates substantial positive effects, aligning with its critical role in plant physiological processes. The significant positive impact of the FeZn combination suggests a synergistic effect, possibly due to the complementary roles of Fe and Zn in plant metabolism. Conversely, the ZnCu and FeZnCu treatments exhibit significant negative effects, indicating these combinations may interfere with maize growth or nutrient uptake, possibly due to antagonistic interactions between the micronutrients. The non-significant results for Zn and Cu alone, as well as FeCu, suggest these treatments do not substantially affect DEW, potentially due to suboptimal concentrations or specific experimental conditions. These findings highlight the complexity of nutrient interactions in maize cultivation and emphasize the need for tailored fertilization strategies considering both individual and combined micronutrient effects (Qin et al., 2022).

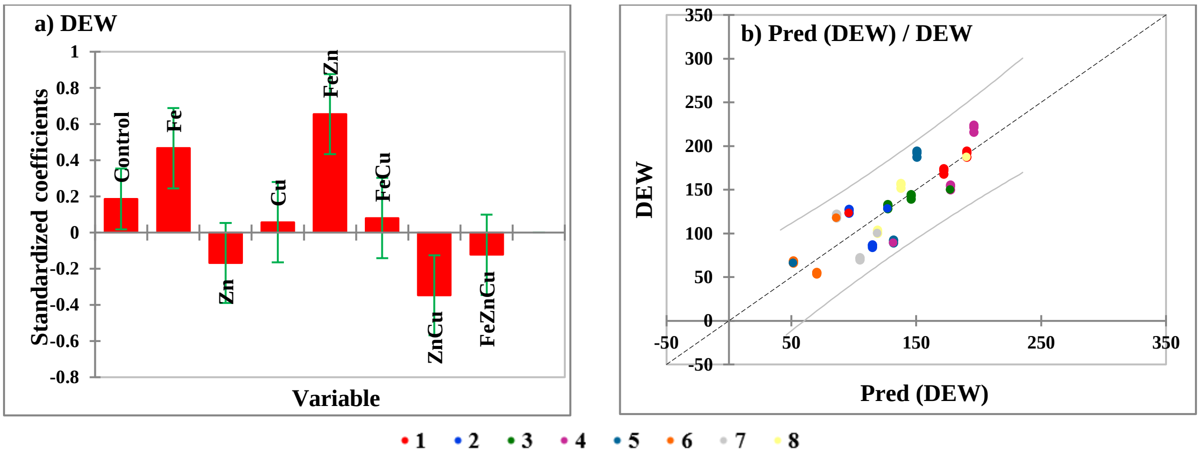

Fig. 2. a) Standardized coefficients (95% conf. interval), b) observed and predicted of DEW

The standardized coefficients for the fresh weight of stem and leaves (FWSL) reveal a variety of effects from different micronutrient treatments. The Control treatment shows a positive but non-significant effect on FWSL with a value of 0.13 (p=0.35), indicating that the baseline conditions provide a slight, though not statistically significant, improvement. Conversely, Fe and Zn both exhibit negative, non-significant effects with values of -0.16 (p=0.4) and -0.16 (p=0.4), respectively. Cu also shows a negative, non-significant effect (-0.13, p=0.5). The FeZn combination presents a more pronounced negative effect, though still non-significant, with a value of -0.3 (p=0.13). FeCu stands out with a significant negative effect (-0.43, p=0.03), suggesting that this combination may adversely impact FWSL. ZnCu shows a negative effect nearing significance (-0.35, p=0.07), while FeZnCu exhibits a negative, non-significant effect (-0.3, p=0.1) (Fig. 3a-b). These findings suggest that most micronutrient treatments tend to reduce the fresh weight of the stem and leaves, with FeCu having a notably significant negative impact, possibly due to antagonistic interactions between iron and copper. The Control treatment, while positive, does not significantly enhance FWSL, indicating that baseline conditions are not substantially beneficial. The non-significant results for Fe, Zn, Cu, FeZn, and FeZnCu imply that these treatments may require optimization in concentration or application methods to be effective. The near-significant negative effect of ZnCu highlights potential issues when these elements are combined. These results emphasize the complexity of nutrient interactions in maize cultivation and the necessity for further research to optimize fertilization strategies, particularly in nutrient-deficient soils. Understanding these interactions is essential for improving agricultural productivity and developing effective fertilization regimes tailored to specific crop and soil needs (Melash et al., 2019; Faisal et al., 2020; Ramezanpour et al., 2022).

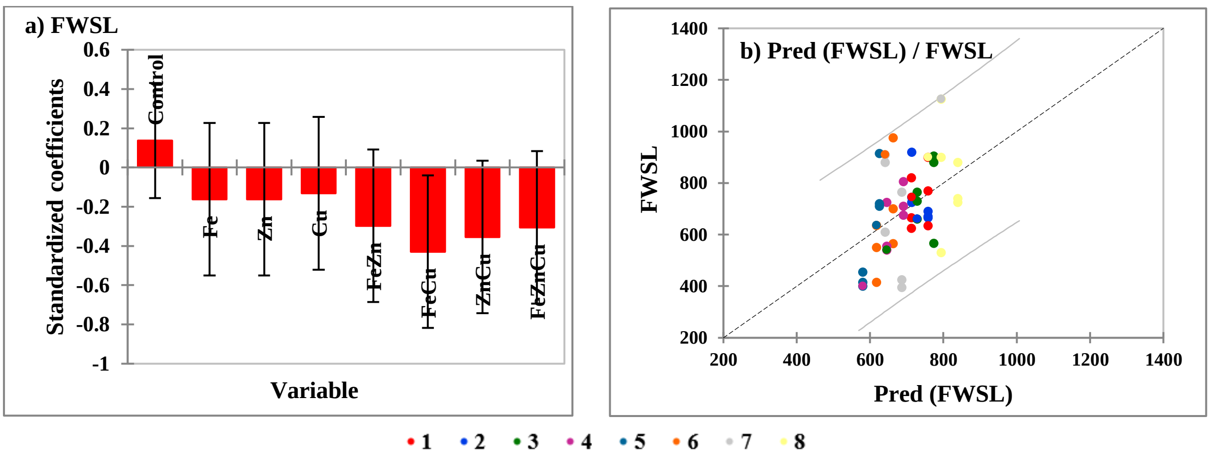

Fig. 3. a) Standardized coefficients (95% conf. interval), b) observed and predicted of FWSL

The standardized coefficients for the fresh weight of stem (FWS) show varied effects from different micronutrient treatments. The Control treatment has a positive but non-significant effect on FWS with a value of -0.129 (p=0.39), suggesting that the baseline conditions provide a slight improvement that is not statistically significant. Treatments involving Fe, Zn, and Cu all show negative, non-significant effects with values of -0.081 (p=0.69), -0.131 (p=0.51), and -0.055 (p=0.78), respectively. The FeZn combination also presents a negative, non-significant effect with a value of -0.138 (p=0.49). The FeCu treatment, while still not significant, shows a more substantial negative effect (-0.323, p=0.114), indicating potential adverse interactions between these elements. ZnCu also shows a negative effect (-0.25, p=0.2), as does FeZnCu (-0.2, p=0.3), though neither is statistically significant (Fig. 4a-b).

These findings indicate that most micronutrient treatments have a tendency to reduce the fresh weight of the stem. The negative coefficients for Fe, Zn, and Cu, whether alone or in combination, suggest that these micronutrients, in the given concentrations, do not enhance FWS and may even inhibit it. The Control treatment's positive effect, although not significant, implies that baseline conditions might be somewhat beneficial compared with the treatments. The FeCu combination, showing a relatively higher negative effect, points to possible antagonistic interactions, which could hinder stem growth. These results underscore the complexity of nutrient interactions in maize cultivation and highlight the necessity for further optimization of fertilization strategies. Adjusting the concentrations or application methods of these micronutrients might be crucial for achieving better outcomes in terms of stem growth (Dhaliwal et al., 2022; Saquee et al., 2023).

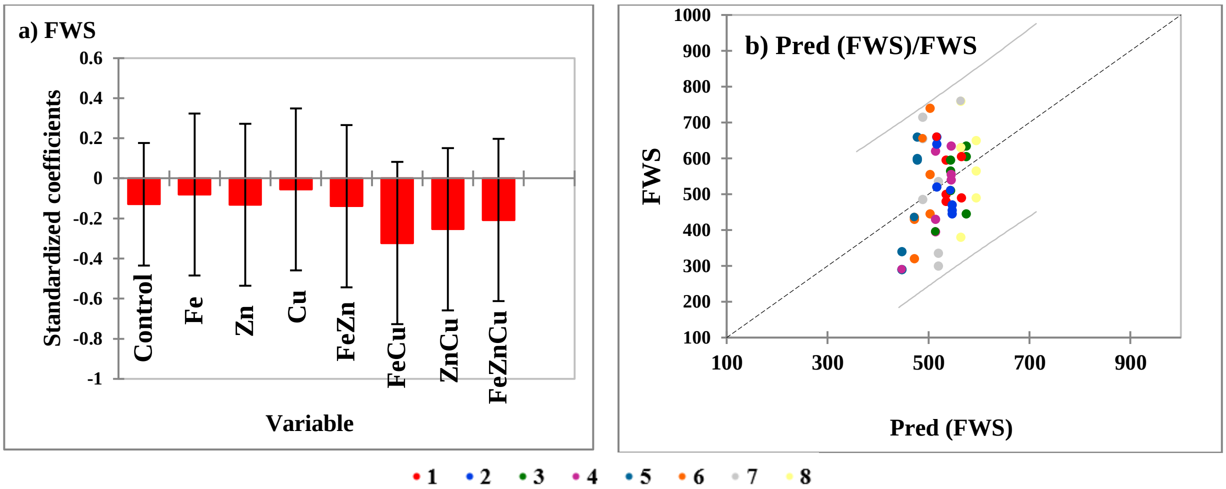

Fig. 4. a) Standardized coefficients (95% conf. interval), b) observed and predicted of FWS

Fig. 5a-b presents standardized coefficients from a model examining the effects of various sources and their interactions on a dependent variable of Fresh weight of leaves (FWL). The interactions between FeZn, FeCu, ZnCu, and FeZnCu show statistically significant negative impacts, with p-values less than 0.05. Specifically, the coefficients for FeZn (-0.51), FeCu (-0.5), and ZnCu (-0.44) are significant, indicating that these interactions likely reduce the dependent variable. The confidence intervals for these coefficients do not include zero, reinforcing the notion that these interactions contribute to a decrease in the outcome. In contrast, the Control, Fe, Zn, and Cu variables do not exhibit statistically significant effects on their own, as their p-values exceed the 0.05 threshold. In discussing these results, it is evident that the combined presence of Fe, Zn, and Cu, especially in interactions, plays a more substantial role in affecting the dependent variable than the individual elements. The significant negative coefficients for FeZn, FeCu, and ZnCu interactions suggest that these combinations amplify the detrimental impact on the outcome variable, potentially due to synergistic effects. The lack of significance for individual variables highlights the importance of considering interactions rather than focusing solely on individual factors.

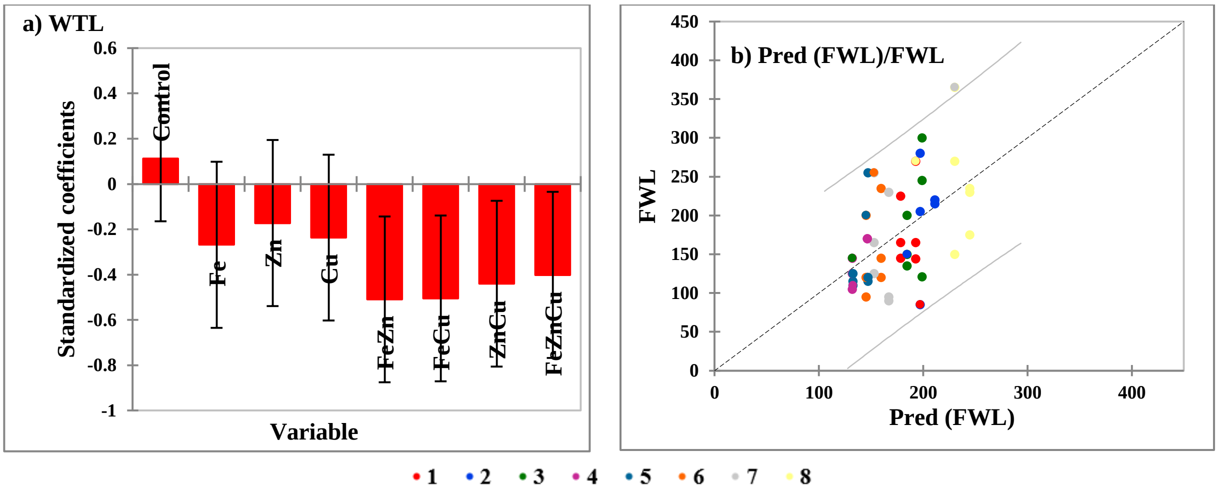

Fig. 5. a) Standardized coefficients (95% conf. interval), b) observed and predicted of FWL

Fig. 6a-b displays standardized coefficients from a model analyzing the effects of different sources and their interactions on a dependent variable for number of leaf (NL). The coefficients for Control, Fe, Zn, Cu, FeZn, FeCu, ZnCu, and FeZnCu are not statistically significant, with p-values all exceeding the 0.05 threshold. This indicates that these individual sources and their interactions do not have a discernible effect on the dependent variable. Specifically, the coefficients for Fe (-0.238), Cu (-0.079), and their interactions, including FeZn (-0.159), FeCu (-0.198), and FeZnCu (0.159), do not show significant deviations from zero, suggesting their influence is negligible. Similarly, the coefficients for Zn (0.079) and ZnCu (0.238) also lack statistical significance. These results suggest that neither individual sources nor their interactions have a meaningful impact on the outcome variable in this context. The lack of significant findings across all variables and interactions implies that these factors do not contribute to changes in the dependent variable for NL (Bassu et al., 2014; Burke et al., 2017). This could indicate that other variables or factors not included in the model might be influencing the outcome or that the effects of these sources and their combinations are not pronounced enough to be detected with the current data. Further research may be needed to explore additional variables or refine the model to uncover potential influences.

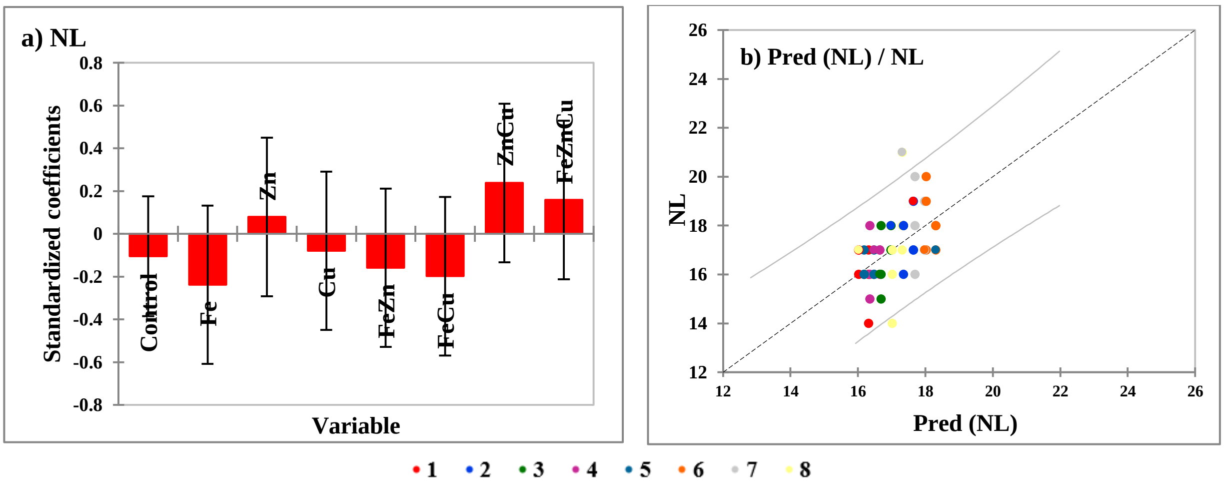

Fig. 6. a) Standardized coefficients (95% conf. interval), b) observed and predicted of NL

Fig. 7a-b provides standardized coefficients for the effects of various sources and their interactions on a dependent variable for plant height (PH). None of the coefficients are statistically significant, with p-values for all variables and interactions exceeding the 0.05 threshold. This indicates that the effects of Control (-0.081), Fe (-0.12), Zn (-0.12), Cu (0.118), and their interactions (FeZn, FeCu, ZnCu, and FeZnCu) on the dependent variable are not distinct from zero. Specifically, the coefficients for FeZn (0.27) and FeZnCu (-0.18) are not significant, suggesting that these interactions do not have a substantial impact on the outcome variable. In discussing these results, it appears that neither individual sources nor their combinations have a meaningful influence on the dependent variable in this context. The lack of significant findings implies that the variables considered may not be contributing to changes in the outcome, or that their effects are too small to be detected with the current data. This suggests that additional factors or different variables may need to be explored to better understand what influences the dependent variable. Further investigation could help identify other potential drivers or refine the model to capture more nuanced effects (Daryanto et al., 2012; Daryanto et al., 2016).

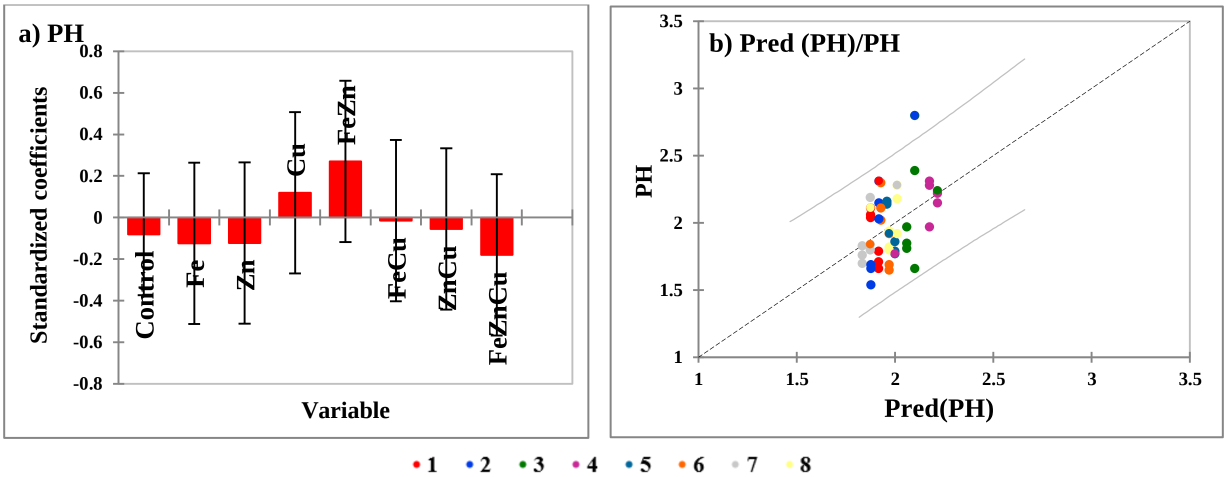

Fig. 7. a) Standardized coefficients (95% conf. interval), b) observed and predicted of PH

Fig. 8a-b presents standardized coefficients for the effects of different sources and their interactions on a dependent variable for dry weight of stem and leaves (DWSL). None of the coefficients are statistically significant, with p-values all exceeding 0.05. This lack of significance suggests that the effects of Control (0.05), Fe (0.032), Zn (-0.1), Cu (0.018), and their interactions (FeZn, FeCu, ZnCu, and FeZnCu) on the dependent variable are not distinguishable from zero. The coefficients for individual sources and their combinations, including FeCu (-0.31) and ZnCu (-0.24), show no significant impact on the outcome. In discussing these results, it is evident that neither the individual elements nor their interactions have a notable effect on the dependent variable in this context. The absence of significant findings indicates that these factors do not contribute meaningfully to variations in the outcome variable. This suggests that either the influence of these variables is minimal or that other, unmeasured factors might be at play. Future research may need to explore additional variables or refine the model to identify potential influences more effectively.

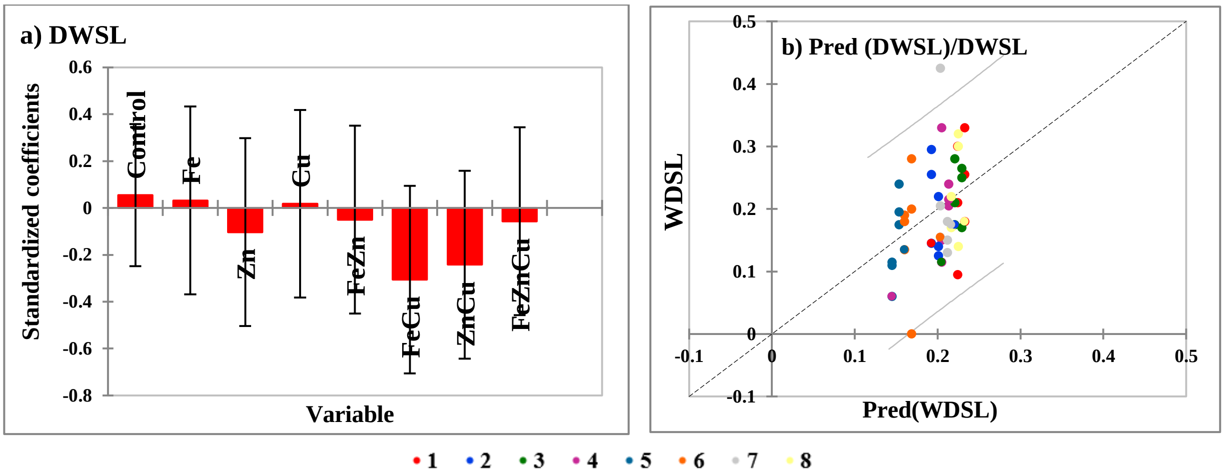

Fig. 8. a) Standardized coefficients (95% conf. interval), b) observed and predicted of DWSL

Fig. 9a-b presents standardized coefficients for the effects of various sources and their interactions on the dry weight of stem (DWS). None of the coefficients are statistically significant, with p-values all exceeding 0.05. This indicates that the effects of Control (0.030), Fe (0.067), Zn (-0.113), Cu (0.004), and their interactions (FeZn, FeCu, ZnCu, and FeZnCu) on DWS are not distinguishable from zero. Specifically, coefficients for individual sources and their interactions, including FeCu (-0.265) and ZnCu (-0.193), do not show significant impacts. These results, it is clear that neither individual elements nor their interactions have a meaningful effect on the dry weight of stem in this context. The absence of significant findings suggests that these factors do not significantly influence DWS, indicating either their effects are too minor to detect with the current data or that other factors not included in the model might be influencing the outcome. Further research may be necessary to explore additional variables or refine the model to better understand what influences DWS.

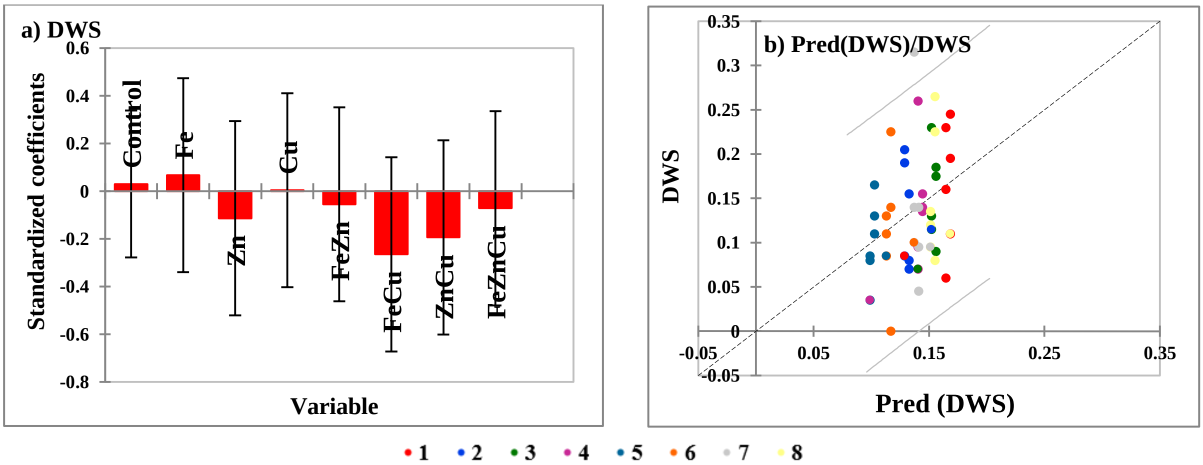

Fig. 9. a) Standardized coefficients (95% conf. interval), b) observed and predicted of DWS

Fig. 10a-b shows standardized coefficients for the effects of various sources and their interactions on the dry weight of leaves (DWL). None of the coefficients for individual sources—Control (-0.129), Fe (-0.022), Zn (0.013), and Cu (0.013)—are statistically significant, as indicated by their p-values exceeding 0.05. The same lack of significance applies to the interactions between these sources, including FeZn (-0.003), FeCu (-0.074), and ZnCu (-0.070). The only interaction that approaches significance is FeZnCu (0.358), with a p-value of 0.071, suggesting a potential but not conclusive effect on DWL. In discussing these results, it appears that individual elements and most of their interactions do not significantly impact the dry weight of leaves. The near-significant result for the FeZnCu interaction suggests that while there might be a possible effect, it is not statistically strong enough to confirm a significant influence at the 0.05 level. This could indicate that other variables or factors might be influencing DWL, or that the effects of these sources and interactions are too subtle to be detected with the current data. Further research might be needed to explore additional variables or to refine the analysis to better understand the factors affecting DWL (Sharafi et al., 2021).

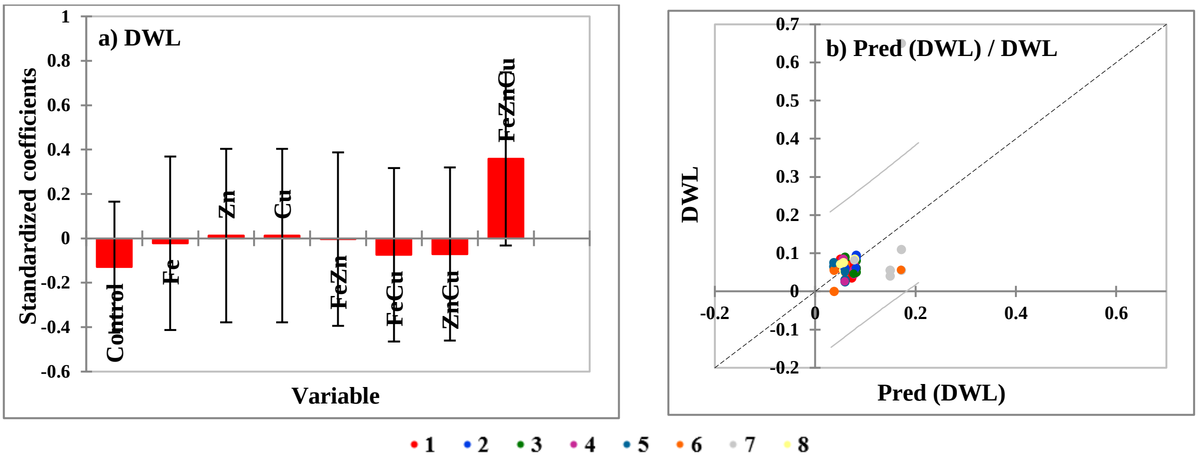

Fig. 10. a) Standardized coefficients (95% conf. interval), b) observed and predicted of DWL

4. Conclusion

The results of this study underscore the significant impact of seed priming and micronutrient treatments on maize growth and yield, particularly in nutrient-deficient soils such as those commonly found in Iran. The comprehensive analysis of various traits, including fresh weight and dry weight of different maize plant parts, number of leaves, and plant height, revealed that seed priming combined with specific micronutrient treatments can substantially enhance maize growth.

Primed seeds, especially those treated with Zn (P-Zn), consistently exhibited superior performance across most traits, including fresh weight of stem and leaves (FWSL), fresh weight of stem (FWS), fresh weight of leaves (FWL), and number of leaves (NL). This indicates that zinc plays a crucial role in enhancing maize growth by supporting key physiological processes. The combined treatment of P-FeZnCu showed the highest dry weights for stem and leaves combined (DWSL), stem alone (DWS), and leaves alone (DWL), suggesting a synergistic effect of these micronutrients in promoting biomass accumulation. Interestingly, non-primed seeds also responded well to certain micronutrient treatments, particularly Fe (NP-Fe), which resulted in the highest fresh and dry weights of the ear (FEW and DWE). However, non-primed seeds generally demonstrated lower overall performance compared with primed seeds, highlighting the additional benefits of seed priming in improving seedling vigor and early establishment.

The regression analysis provided insights into the complex interactions between different micronutrient treatments. While some treatments showed significant positive effects, others exhibited negative effects, particularly when multiple micronutrients were combined. For instance, the combinations of ZnCu and FeZnCu showed significant negative impacts on various traits, suggesting potential antagonistic interactions. These findings emphasize the need for careful consideration of micronutrient combinations to optimize maize growth. Overall, this study illustrates the potential of seed priming and tailored micronutrient treatments to enhance maize productivity, especially in soils with nutrient deficiencies. Future research should focus on refining the concentrations and combinations of micronutrients for different soil types and environmental conditions. Long-term field studies are also needed to assess the sustainability and economic viability of these practices in large-scale maize production. By addressing nutrient deficiencies and optimizing fertilization strategies, it is possible to improve maize yield and support agricultural productivity in regions with similar soil conditions.

Author Contributions: All Authors; Conceptualization: Methodology: Software: Validation: Technical Investigation: Writing (Original draft preparation): Writing (review and editing): Supervision; they have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Agricultural Experiment Station of Arak University.

Acknowledgments: We thank the Agricultural Experiment Station of Arak University.

Conflicts of Interest: The authors declare no conflict of interest.

References

Ali, S., Riaz, A., Mamtaz, S., & Haider, H. 2023. Nutrients and Crop Production. Current Research in Agriculture and Farming, 4(2): 1-15.

Ataei, P., Sadighi, H., Aenis, T., Chizari, M., & Abbasi, E. 2021. Challenges of applying conservation agriculture in Iran: an overview on experts and farmers' perspectives. Air, Soil and Water Research, 14: 1178622120980022.

Bassu, S., Brisson, N., Durand, J. L., Boote, K., Lizaso, J., Jones, J. W., ... & Waha, K. 2014. How do various maize crop models vary in their responses to climate change factors?. Global change biology, 20(7): 2301-2320.

Bhantana, P., Rana, M. S., Sun, X. C., Moussa, M. G., Saleem, M. H., Syaifudin, M., ... & Hu, C. X. 2021. *Arbuscular mycorrhizal* fungi and its major role in plant growth, zinc nutrition, phosphorous regulation and phytoremediation. Symbiosis, 84: 19-37.

Bordolui, S. K., & Mukherjee, A. 2022. Eminent Roles of Micro-nutrients in Quality Seed Production. International Journal of Plant & Soil Science, 34(23): 324-342.

Burke, W. J., Jayne, T. S., & Black, J. R. 2017. Factors explaining the low and variable profitability of fertilizer application to maize in Zambia. Agricultural economics, 48(1): 115-126.

Ciampitti, I. A., & Vyn, T. J. 2012. Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review. Field Crops Research, 133: 48-67.

Daryanto, S., Wang, L., & Jacinthe, P. A. 2016. Global synthesis of drought effects on maize and wheat production. PloS one, 11(5): e0156362.

Dhaliwal, S. S., Sharma, V., Shukla, A. K., Verma, V., Kaur, M., Shivay, Y. S., ... & Hossain, A. 2022. Biofortification—A frontier novel approach to enrich micronutrients in field crops to encounter the nutritional security. Molecules, 27(4): 1340.

Eiraji, R., Rezaduost, S., Jalili, F., Roshdi, M., & Mahalleh, J. K. 2023. Effect of irrigation cut off and antitranspirants on yield and some physiological characteristics of Pinto beans.

Erenstein, O., Jaleta, M., Sonder, K., Mottaleb, K., & Prasanna, B. M. 2022. Global maize production, consumption and trade: trends and R&D implications. Food security, 14(5): 1295-1319.

Faisal, M., Iqbal, M. A., Aydemir, S. K., Hamid, A., Rahim, N., El Sabagh, A., ... & Siddiqui, M. H. 2020. Exogenously foliage applied micronutrients efficacious impact on achene yield of sunflower under temperate conditions. Pak. J. Bot, 52(4): 1215-1221.

Farooq, M., Ullah, A., Usman, M., & Siddique, K. H. 2020. Application of zinc and biochar help to mitigate cadmium stress in bread wheat raised from seeds with high intrinsic

zinc. Chemosphere, 260: 127652.
Feilinezhad, A., Mirzaeiheydari, M., Babaei, F., Maleki, A., & Rostaminya, M. 2022. The effect of tillage, organic matter and mycorrhizal fungi on efficiency and productivity use of nutrients in maize. Communications in Soil Science and Plant Analysis, 53(20): 2719-2733.
Gondwe, C. 2018. Improving Yields and Enhancing Dietary Zinc and Selenium Intake in the Zambian Population Through Agronomic Biofortification of Maize and Wheat (Doctoral dissertation).
Guardiola-Márquez, C. E., Santos-Ramírez, M. T., Segura-Jiménez, M. E., Figueroa-Montes, M. L., & Jacobo-Velázquez, D. A. 2022. Fighting obesity-related micronutrient deficiencies through biofortification of agri-food crops with sustainable fertilization practices. Plants, 11(24): 3477.
Kashif, M. S., Nawaz, M., Wahla, A. J., Shahbaz, M., Ali, L., & Chaudhary, M. T. 2021. Effect of different seed priming techniques on germination and yield of wheat at different sowing dates. Egyptian Journal of Agricultural Research, 99(1): 118-127.
Liu, Z., Bai, Y., Luo, L., Wan, J., Wang, W., & Zhao, G. 2021. Effects of high dose copper on plant growth and mineral nutrient (Zn, Fe, Mg, K, Ca) uptake in spinach. Environmental Science and Pollution Research, 28(28): 37471-37481.
Majidian, P., Ghorbani, H. R., & Farajpour, M. 2024. Achieving agricultural sustainability through soybean production in Iran: Potential and challenges. Heliyon, 10(4).
Melash, A. A., Mengistu, D. K., Aberra, D. A., & Tsegay, A. 2019. The influence of seeding rate and micronutrients foliar application on grain yield and quality traits and micronutrients of durum wheat. Journal of Cereal Science, 85: 221-227.
Miner, G. L., Delgado, J. A., Ippolito, J. A., Johnson, J. J., Kluth, D. L., & Stewart, C. E. 2022. Wheat grain micronutrients and relationships with yield and protein in the US Central Great Plains. Field Crops Research, 279: 108453.
Mousavi, S. R., Galavi, M., & Rezaei, M. 2013. Zinc (Zn) importance for crop production-a review.
Pradeep, S. D., & Aishwarya, K. R. 2023. The Role of Copper in Plants and Its Uptake and Assimilation by Plants. Just Agriculture, 3(5): 403-407.
Qin, X., Wang, Z., Guo, C., Guo, R., Lv, Y., & Li, M. 2022. Fulvic acid degradation in Fenton-like system with bimetallic magnetic carbon aerogel Cu-Fe@ CS as catalyst: Response surface optimization, kinetic and mechanism. Journal of Environmental Management, 306: 114500.
Ramezanpour, M. R., Farajpour, M., & Yousefian, M. 2022. Enhancing the quality and quantity of date palm (Phoenix Dactylifera) by micronutrients under calcareous soils with a high pH level. Journal of Natural Fibers, 19(15): 11749-11762.
Saquee, F. S., Diakite, S., Kavhiza, N. J., Pakina, E., & Zargar, M. 2023. The efficacy of micronutrient fertilizers on the yield formulation and quality of wheat grains. Agronomy, 13(2): 566.
Shah, A. A., Yasin, N. A., Mudassir, M., Ramzan, M., Hussain, I., Siddiqui, M. H., ... & Kumar, R. 2022. Iron oxide nanoparticles and selenium supplementation improve growth and photosynthesis by modulating antioxidant system and gene expression of chlorophyll synthase (CHLG) and protochlorophyllide oxidoreductase (POR) in arsenic-stressed Cucumis melo. Environmental Pollution, 307: 119413.
Sharafi, S., Gholami, A., Ghasemi, S., & Sharafi, A. 2009. Pinto bean seed reserve utilization and seedling growth as affected by seed size, salinity and drought stress. J Food Agric Environ, 7(2): 411-414.
Sharafi, S., Kazemi, A., & Amiri, Z. 2023a. Estimating energy consumption and GHG emissions in crop production: A machine learning approach. Journal of Cleaner Production, 408: 137242.

Sharafi, S., Mohammadi Ghaleni, M., & Dragovich, D. 2023b. Simulated Runoff and Erosion on Soils from Wheat Agroecosystems with Different Water Management Systems, Iran. Land, 12(9): 1790.

Sharafi, S., Sharifdost, F., & Mohajeri, F. 2021. Effect of Fe, Zn and Cu on quantity and quality characteristics and nutrient accumulation in wheat. Journal of Crop Science and Biotechnology, 1-8.

Tashayo, B., Honarbakhsh, A., Akbari, M., & Eftekhari, M. 2020. Land suitability assessment for maize farming using a GIS-AHP method for a semi-arid region, Iran. Journal of the Saudi Society of Agricultural Sciences, 19(5): 332-338.

Tondey, M., Kalia, A., Singh, A., Dheri, G. S., Taggar, M. S., Nepovimova, E., ... & Kuca, K. 2021. Seed priming and coating by nano-scale zinc oxide particles improved vegetative growth, yield and quality of fodder maize (Zea mays). Agronomy, 11(4): 729.

Umair Hassan, M., Aamer, M., Umer Chattha, M., Haiying, T., Shahzad, B., Barbanti, L., ... & Guoqin, H. 2020. The critical role of zinc in plants facing the drought stress. Agriculture, 10(9): 396.

Zaim, N. S. H. B. H., Tan, H. L., Rahman, S. M. A., Abu Bakar, N. F., Osman, M. S., Thakur, V. K., & Radacsi, N. 2023. Recent advances in seed coating treatment using nanoparticles and nanofibers for enhanced seed germination and protection. Journal of Plant Growth Regulation, 42(12): 7374-7402.

Zewide, I., & Sherefu, A. 2021. Review paper on effect of micronutrients for crop production. J. Nutr. Food Process, 4(7): 1-8.

Zulfiqar, F. 2021. Effect of seed priming on horticultural crops. Scientia horticulturae, 286: 110197.