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The Role of Mineral Fertilizers in Enhancing Maize Nutritional Value

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Abstract The role of mineral fertilizers in enhancing the nutritional value of maize has been extensively studied, with a focus on optimizing nutrient management practices to improve crop yield and quality. This study synthesizes findings from various studies to evaluate the impact of different fertilization strategies, including the use of mineral fertilizers alone and in combination with organic amendments such as compost, biochar, and manure. This study highlights that integrated nutrient management practices, particularly those combining mineral fertilizers with organic amendments, significantly enhance soil organic carbon content, nutrient use efficiency, and maize grain nutritional quality. For instance, long-term fertilization with manure combined with mineral fertilizers has been shown to improve soil organic carbon sequestration and maize yield. Similarly, the addition of biochar and compost with mineral fertilizers enhances nitrogen use efficiency and maize yield under water deficit conditions. The combined application of organic and mineral fertilizers also increases the concentration of essential minerals like iron and manganese in maize grains. Moreover, the use of arbuscular mycorrhizal fungi in conjunction with reduced mineral fertilizer rates can maintain high maize yields while improving soil nutrient availability. Overall, the findings suggest that integrated fertilization strategies are effective in enhancing the nutritional value of maize, promoting sustainable agricultural practices, and improving soil health.

Keywords Mineral fertilizers; Maize nutritional value; Organic amendments; Nutrient use efficiency; Soil health

1 Introduction

Maize (*Zea mays* L.) is one of the most important staple crops globally, providing a significant portion of the caloric intake for millions of people. It is a versatile crop that can be grown in diverse environmental conditions and has a wide range of uses, including human food, animal feed, and industrial raw materials (Palacios-Rojas et al., 2020; Suganya et al., 2020; Tanumihardjo et al., 2020). In many regions, particularly in Sub-Saharan Africa, maize plays a crucial role in food and nutrition security (Galani et al., 2022). The crop's adaptability and high yield potential make it a cornerstone of agricultural systems worldwide (Kumar and Ram, 2021).

The nutritional value of maize is critical for both human and animal health. Maize grains are a source of essential macronutrients such as carbohydrates, proteins, and fats, as well as micronutrients like vitamins and minerals (Suganya et al., 2020; Dragičević et al., 2022). However, the micronutrient content of maize, particularly zinc, is often low, which can lead to deficiencies in populations that rely heavily on maize as a dietary staple (Palacios-Rojas et al., 2020; Suganya et al., 2020). Enhancing the nutritional profile of maize through biofortification and improved agricultural practices is essential for addressing malnutrition and improving overall health outcomes (Palacios-Rojas et al., 2020; Kumar and Ram, 2021).

Mineral fertilizers play a pivotal role in enhancing crop yields and nutritional quality. They provide essential nutrients that are often deficient in soils, thereby improving plant growth and productivity. For instance, nitrogen fertilizers are crucial for biomass accumulation and grain yield in maize (Alves et al., 2023; Zheng et al., 2023). Similarly, zinc fertilizers can significantly increase the zinc content in maize grains, addressing micronutrient deficiencies (Suganya et al., 2020; Kumar and Ram, 2021). The use of mineral fertilizers, when managed properly, can lead to substantial improvements in both the quantity and quality of maize production (Wei et al., 2020; Dragičević et al., 2022).

This study evaluates the role of mineral fertilizers in enhancing the nutritional value of maize. This includes examining the impact of different types of mineral fertilizers on maize yield, nutrient content, and overall crop quality. By synthesizing findings from various studies, this study aims to provide insights into effective fertilization strategies that can improve the nutritional profile of maize, thereby contributing to food and nutrition security.

2 Maize Nutritional Components

2.1 Key nutrients in maize (carbohydrates, proteins, fats, vitamins, and minerals)

Maize is a vital staple crop that provides a significant portion of the world's caloric intake, alongside rice and wheat. The nutritional components of maize, including protein, oil, vitamins, minerals, etc., are of great significance for improving human nutrition and health (Li and Huang, 2024). The primary macronutrients in maize include carbohydrates, proteins, and fats. Carbohydrates are the most abundant, making up a substantial portion of maize's nutritional profile, which is crucial for energy supply. Proteins in maize are also significant, contributing to the dietary protein intake necessary for growth and repair of body tissues. Fats, although present in smaller quantities compared to carbohydrates and proteins, are essential for providing energy and supporting cell structure (Ogunyemi et al., 2018; Palacios-Rojas et al., 2020; Dragičević et al., 2022).

In addition to macronutrients, maize contains essential vitamins and minerals. Vitamins such as provitamin A carotenoids are crucial for vision and immune function, while minerals like magnesium (Mg), calcium (Ca), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) play vital roles in various biochemical processes. For instance, magnesium is important for muscle and nerve function, calcium for bone health, and iron for oxygen transport in the blood. The presence of these nutrients makes maize a valuable component of the diet, particularly in regions where it is a staple food (Ogunyemi et al., 2018; Dragičević et al., 2022; Galani et al., 2022).

2.2 Factors affecting maize nutritional content

The nutritional content of maize can be influenced by several factors, including genotype, fertilization practices, and environmental conditions. Different maize genotypes exhibit variability in nutrient composition. For example, red-kernel maize hybrids have been shown to accumulate higher levels of protein, oil, phenolics, and essential elements like calcium, iron, copper, and sulfur compared to yellow and white hybrids. Yellow-kernel maize, on the other hand, tends to have higher concentrations of yellow pigment, glutathione, phytic phosphorus, magnesium, manganese, and zinc (Figure 1) (Dragičević et al., 2022).

Dragičević et al. (2022) depicts a Principal Component Analysis (PCA) exploring the interdependence of kernel color, fertilizer treatments, and various nutritional and chemical traits in maize. The PCA reveals that the first two components explain 73.1% of the variability, with grain yield (GY), protein, and mineral content positively correlated with the first axis, while starch content is negatively correlated. The analysis indicates significant variability in traits such as starch and GSH in white-kernel maize under urea and control treatments. Yellow-kernel maize shows greater variability in GY, oil, and phenolics across all treatments. The study highlights how kernel color and fertilizer types influence maize's nutritional and chemical profile, emphasizing the complex interactions affecting crop quality.

Fertilization practices also play a crucial role in determining the nutritional quality of maize. The use of mineral fertilizers such as urea can enhance the antioxidant status and increase the bioavailability of certain minerals like zinc. Organic amendments, including biochar and compost, when combined with inorganic fertilizers, have been found to improve nitrogen use efficiency and overall nutrient uptake, especially under drought conditions. This combination can lead to higher yields and better nutritional quality of maize (Ogunyemi et al., 2018; Norhan et al., 2023).

Environmental factors, particularly water availability, significantly impact maize's nutritional content. Drought conditions can reduce the yield and nutrient uptake of maize, affecting its protein, oil, starch, and carbohydrate content. However, the addition of organic amendments can mitigate some of these adverse effects by enhancing the plant's defensive systems and nutrient use efficiency (Norhan et al., 2023).

In summary, the nutritional value of maize is determined by a complex interplay of genetic, agronomic, and environmental factors. Understanding these influences can help in developing strategies to enhance the nutritional quality of maize, thereby improving food and nutrition security.

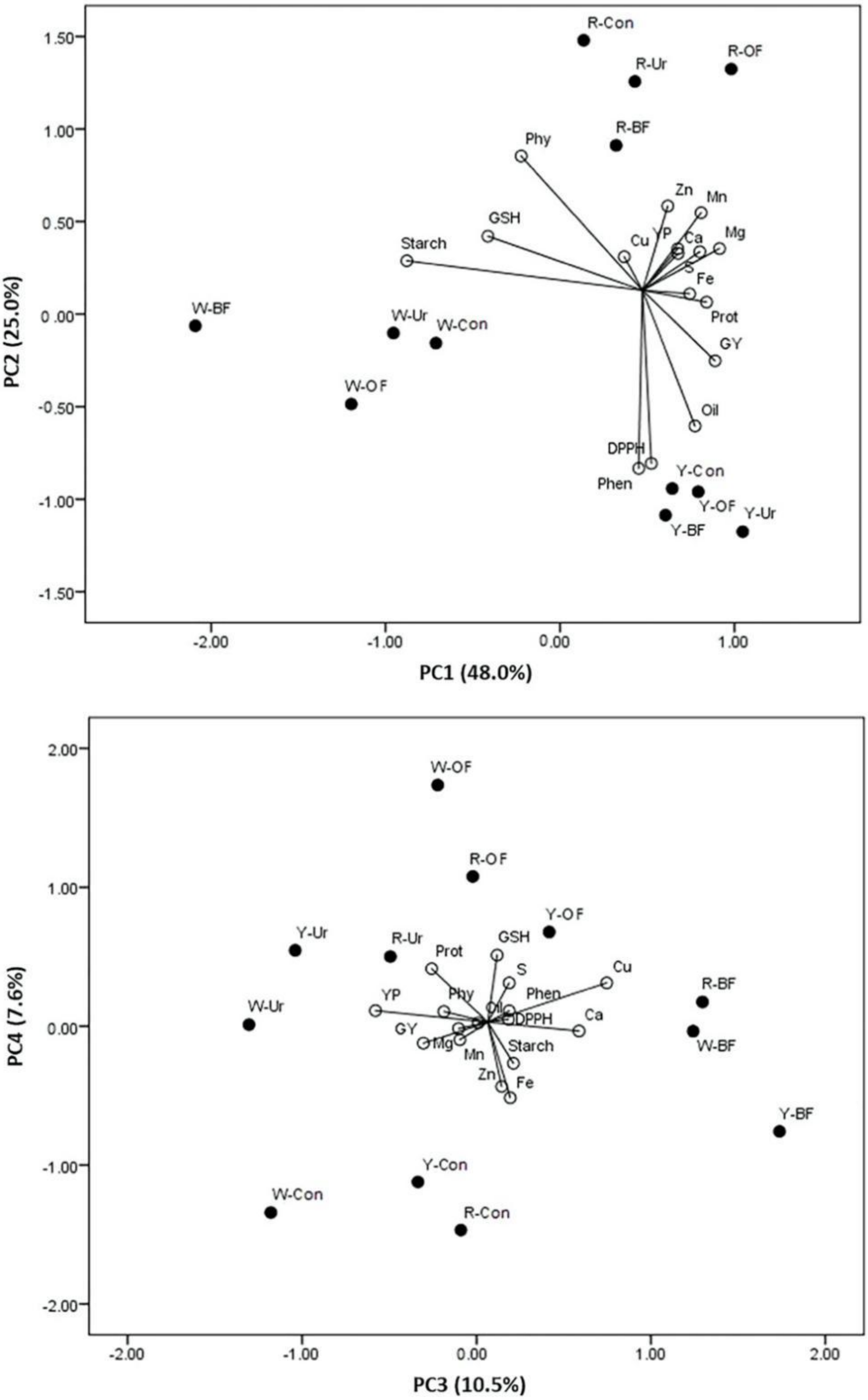

Figure 1 Principal component analysis of the grain yield (GY), protein (Prot), oil, starch, phytic phosphorus (Phy), phenolics (Phen), yellow pigment (YP), and glutathione (GSH) contents, reduction capacity of the DPPH radical (DPPH), and concentrations of Mg, Ca, Fe, Mn, Zn, Cu, and S in maize with different kernel colors (W, white; Y, yellow; R, red), under different fertilizer treatments(BF, biofertilizer; OF, organic fertilizer; Ur, urea; Con, control) (Adopted from Dragičević et al., 2022)

3 Types of Mineral Fertilizers

3.1 Nitrogen-based fertilizers

Nitrogen-based fertilizers are crucial for maize growth as they significantly enhance nitrogen uptake and utilization efficiency. Studies have shown that the application of nitrogen fertilizers, especially when combined with organic amendments like compost or biochar, can improve maize yield, oil, starch, protein, and carbohydrate content, even under varying irrigation levels (El-Syed et al., 2023). Additionally, foliar application of nitrogen-phosphorus-potassium (NPK) fertilizers at specific growth stages has been found to significantly increase nitrogen uptake and protein content in maize (Nirere et al., 2021).

3.2 Phosphorus-based fertilizers

Phosphorus is essential for energy transfer and photosynthesis in maize. The effectiveness of phosphorus fertilizers can be enhanced when used in combination with organic amendments. For instance, the application of phosphorus along with compost and organic acids in calcareous soil has been shown to significantly increase phosphorus content in maize straw and grain, thereby improving overall yield and nutritional quality (Tabbasum et al., 2020). Moreover, the combined use of phosphorus fertilizers with arbuscular mycorrhizal fungi (AMF) can enhance phosphorus availability and uptake, leading to higher maize yields (Fall et al., 2023).

3.3 Potassium-based fertilizers

Potassium plays a vital role in water regulation and enzyme activation in maize. The application of potassium fertilizers, particularly when integrated with compost and organic acids, has been demonstrated to increase potassium accumulation in maize grains and improve yield and biochemical attributes (Tabbasum et al., 2020). Additionally, foliar application of NPK fertilizers has been shown to enhance potassium uptake and soil potassium levels, contributing to better maize growth and protein content (Nirere et al., 2021).

3.4 Micronutrient fertilizers

Micronutrients such as zinc, iron, and manganese are essential for various physiological functions in maize. The combined application of mineral fertilizers and compost has been found to increase the concentration of these essential minerals in maize grains, thereby improving their nutritional quality. For example, replacing a portion of mineral nitrogen with compost significantly elevated the levels of iron and manganese in maize grains (Zerssa et al., 2023). Long-term application of balanced NPK fertilizers along with farmyard manure (FYM) and lime has also been shown to enhance the content of calcium, zinc, phosphorus, magnesium, and iron in maize (Thakur et al., 2020).

3.5 Synergistic effects of combined fertilizers

The synergistic effects of combining mineral fertilizers with organic amendments such as compost, biochar, and organic acids have been widely documented. These combinations not only improve nutrient uptake and use efficiency but also enhance soil health and mitigate environmental impacts. For instance, the integrated use of mineral NPK fertilizers with compost and organic acids significantly increased maize yield and nutrient content while improving soil properties (Tabbasum et al., 2020). Similarly, the combination of mineral fertilizers with biochar has been shown to enhance nitrogen use efficiency and yield under drought conditions (Iqbal et al., 2022). These synergistic effects highlight the importance of integrated nutrient management strategies for sustainable maize production.

4 Impact of Mineral Fertilizers on Maize Nutritional Value

4.1 Enhancement of macronutrients (e.g., protein content)

Mineral fertilizers have been shown to significantly enhance the macronutrient content of maize, particularly protein. For instance, the application of urea, a commonly used mineral fertilizer, has been found to increase the protein content in maize kernels. In a study comparing different maize genotypes and fertilizer treatments, the red-kernel hybrid maize treated with biofertilizers exhibited the highest protein accumulation, while urea treatment enhanced the antioxidant status and potential zinc bioavailability in maize kernels (Dragičević et al., 2022). Additionally, the combination of biochar with inorganic fertilizers improved the protein content and overall yield of maize, especially under drought conditions (El-Syed et al., 2023).

4.2 Improvement of micronutrient content (e.g., iron, zinc)

The application of mineral fertilizers also plays a crucial role in improving the micronutrient content of maize. Long-term nitrogen fertilization has been shown to increase the concentration of essential micronutrients such as iron (Fe) and manganese (Mn) in maize grains, although it may decrease zinc (Zn) concentration due to yield dilution (Miner et al., 2018). Soil application of zinc fertilizer has been particularly effective in increasing the zinc concentration in maize grains, enhancing both yield and nutritional quality (Liu et al., 2020). Furthermore, biofortification strategies using nitrogen fertilization have been successful in increasing the concentrations of zinc and iron in maize shoots, contributing to better-quality feed (Grujcic et al., 2021).

4.3 Influence on maize bioavailability of nutrients

The bioavailability of nutrients in maize can be significantly influenced by the type and application method of mineral fertilizers. For example, urea treatment has been shown to increase the potential bioavailability of zinc in maize kernels by 13.3% compared to biofertilizer treatment (Dragičević et al., 2022). Additionally, the use of bio-organic fertilizers, which combine biofertilizers with inorganic fertilizers, has been found to enhance the bioavailability of essential micronutrients such as iron, zinc, and manganese in maize (Hafez et al., 2021). The integration of plant growth-promoting rhizobacteria (PGPR) with mineral fertilizers also improves the bioavailability of nutrients, leading to better growth and nutritional quality of maize (Ahmad et al., 2023).

4.4 Case study in place: analyzing the effect of specific fertilizer applications on maize nutritional value

A case study conducted in the Northern region of Ghana evaluated the impact of foliar application of macro and micronutrients on maize growth and yield. The study found that the application of nitrogen in a split form, combined with foliar application of phosphorus, zinc, and iron, produced the highest grain yield. The treatment NP_2K+[P+Zn+Fe] significantly improved the leaf surface area and grain yield, demonstrating the effectiveness of balanced nutrient application in enhancing maize nutritional value (Asare, 2023). Another study in a no-till maize cropping system showed that long-term nitrogen fertilization positively impacted the concentration of iron and manganese in maize grains, although it reduced zinc concentration (Miner et al., 2018). These findings highlight the importance of region-specific fertilizer strategies to optimize maize nutritional value.

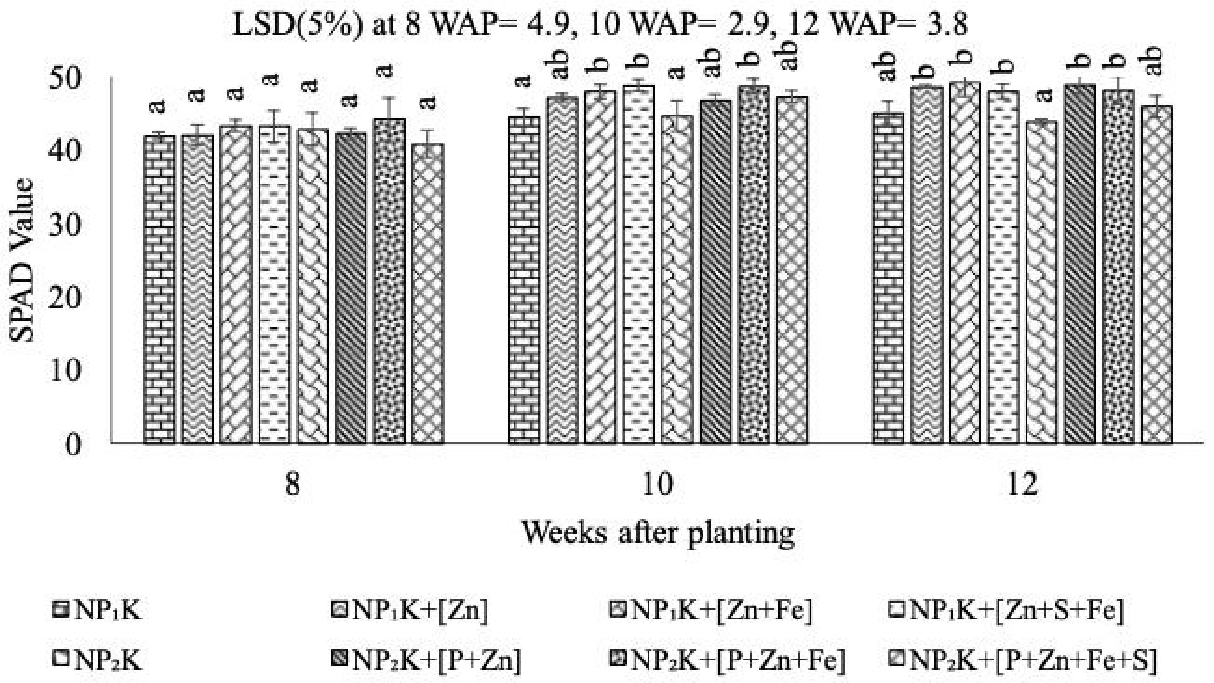

Figure 2 Effect of fertilizer treatment on SPAD values. Error bars represent Standard Error of Means (SEM). Bars of the same design and colour with similar letters on top are not significantly different (Adopted from Asare, 2023)

Asare (2023) examines the impact of different fertilizer treatments on the SPAD values of maize, which indicate chlorophyll content and plant nitrogen status. At week 8, there were no significant differences across treatments.

However, by weeks 10 and 12, variability increased, with the highest SPAD values observed in treatments combining NPK with additional sulfur, zinc, and iron. These results suggest that supplementing NPK with these micronutrients, particularly iron, significantly enhances chlorophyll content, likely due to iron's role in boosting photosynthesis. The findings underscore the importance of including micronutrients in fertilization strategies to improve maize growth and overall plant health, particularly in the later stages of development.

By integrating various mineral fertilizers and application methods, it is possible to enhance both the macronutrient and micronutrient content of maize, thereby improving its overall nutritional value and bioavailability of essential nutrients.

5 Environmental and Economic Considerations

5.1 Sustainability of mineral fertilizer use

The sustainability of mineral fertilizer use in maize production is a critical consideration, particularly in the context of long-term soil health and environmental impact. Studies have shown that substituting mineral fertilizers with organic alternatives, such as manure or compost, can significantly enhance soil organic carbon sequestration and reduce nitrogen losses. For instance, substituting mineral fertilizer with organic fertilizer increased soil organic carbon sequestration by 925 kg C ha^{-1} yr^{-1} and decreased the global warming potential by 116 kg CO_2 eq ha^{-1} (Wei et al., 2020). Additionally, the combined use of organic and mineral fertilizers has been found to improve maize yield and nutrient use efficiency over time, suggesting a more sustainable approach to fertilization (Zhang et al., 2018; Wei et al., 2020; Zerssa et al., 2023).

5.2 Economic impacts on smallholder and commercial maize production

The economic impacts of using mineral fertilizers versus organic alternatives are significant for both smallholder and commercial maize producers. Substituting mineral fertilizers with manure has been shown to increase economic profits and eco-efficiency. For example, substituting 50% of mineral-N with solid or liquid manure increased economic profits by 17.2% and 19.1%, respectively, while also reducing environmental impacts (Li et al., 2020). Similarly, replacing 75% of mineral N fertilizer with manure significantly increased net benefits by 8.47-35.51% compared to using mineral fertilizers alone (Wang et al., 2023). These findings indicate that integrating organic fertilizers can be economically beneficial, particularly for smallholders who may have limited access to mineral fertilizers (Zerssa et al., 2023).

5.3 Potential environmental risks

While mineral fertilizers are effective in boosting maize yields, their use poses several environmental risks, including soil degradation and water contamination. The application of mineral fertilizers can lead to increased greenhouse gas emissions, such as N_2O and CO_2, and contribute to soil acidification and aquatic eutrophication (Zhang et al., 2018; Zerssa et al., 2023). For instance, pure mineral fertilizer treatments resulted in higher N_2O emissions compared to treatments with compost or manure (Zerssa et al., 2021). Additionally, long-term use of mineral fertilizers without organic amendments can lead to soil nutrient depletion and reduced soil fertility (Mustafa et al., 2021). Therefore, a balanced approach that combines mineral and organic fertilizers is recommended to mitigate these environmental risks while maintaining high maize productivity (Zhang et al., 2018; Mustafa et al., 2021).

In conclusion, the integration of organic fertilizers with mineral fertilizers offers a sustainable and economically viable approach to maize production. This strategy not only enhances soil health and reduces environmental risks but also provides economic benefits to both smallholder and commercial farmers.

6 Future Directions and Innovations

6.1 Development of biofortified maize through optimized fertilizer use

The development of biofortified maize through optimized fertilizer use is a promising avenue for enhancing the nutritional value of maize. Agronomic biofortification, which involves the application of mineral micronutrient fertilizers to soil or plant leaves, has shown significant potential in increasing the micronutrient content in maize grains. For instance, the application of 50% recommended dose of fertilizers (RDF) through NPK combined with

50% RDF through farmyard manure (FYM) and foliar application of iron (Fe) and zinc (Zn) significantly improved the grain quality, including higher crude protein, starch, Fe, and Zn content (Augustine and Imayavaramban, 2021; Rajendran and Veeramani, 2022). Additionally, the use of bio-waste compost in combination with mineral fertilizers has been found to elevate the concentration of essential minerals such as iron and manganese in maize grains, thereby enhancing their nutritional quality (Zerssa et al., 2023). These findings underscore the importance of integrating organic and inorganic fertilizers to achieve biofortification and improve the nutritional profile of maize.

6.2 Precision agriculture and its role in fertilizer application

Precision agriculture offers a transformative approach to fertilizer application, ensuring that nutrients are supplied in the right amounts, at the right time, and in the right place. This method not only optimizes fertilizer use but also minimizes environmental impacts. The use of nano-fertilizers, for example, has been shown to enhance nutrient use efficiency and improve the nutritional quality of maize. A study demonstrated that applying 50% of the recommended nitrogen dose (RDN) through urea, along with dual foliar sprays of nano-urea, achieved comparable productivity to the 100% RDN through urea alone, while also enhancing protein content and reducing fiber fractions in maize (Kashyap et al., 2023). Precision agriculture techniques, such as soil testing and targeted nutrient management, can further refine fertilizer application, ensuring that maize receives the optimal nutrient mix for maximum growth and nutritional value (Bamboriya et al., 2023).

6.3 Potential for integrated nutrient management systems

Integrated nutrient management (INM) systems, which combine the use of organic and inorganic fertilizers, hold significant potential for sustainable maize production. INM practices not only improve soil health but also enhance the nutritional quality of maize. For instance, the application of 75% NPK fertilizers as per soil test response (STR) combined with enriched phosphorus compost (EPC), biofertilizers, and foliar Zn spray significantly boosted the active and passive constituents of soil organic matter, leading to improved soil health and maize productivity (Bamboriya et al., 2023). Moreover, the use of plant growth-promoting rhizobacteria (PGPR) in combination with organic and chemical fertilizers has been shown to enhance nutrient uptake and biofortification of maize grains, thereby addressing nutritional security (Ahmad et al., 2023). These integrated approaches ensure a balanced nutrient supply, promoting both crop productivity and nutritional quality.

In conclusion, the future of maize biofortification lies in the strategic use of optimized fertilizers, precision agriculture, and integrated nutrient management systems. These innovations not only enhance the nutritional value of maize but also contribute to sustainable agricultural practices, ensuring food security and improved health outcomes.

7 Concluding Remarks

The role of mineral fertilizers in enhancing the nutritional value of maize has been extensively studied, with significant findings highlighting the benefits of integrated nutrient management practices. The combination of organic amendments such as biochar and compost with inorganic fertilizers has been shown to improve maize yield, nutrient uptake, and nitrogen use efficiency, particularly under drought conditions. The use of Arbuscular Mycorrhizal Fungi (AMF) in conjunction with reduced NPK fertilization rates has also demonstrated increased maize yields and improved soil nutrient availability, suggesting a potential reduction in chemical fertilizer usage. Additionally, the foliar application of NPK fertilizers at specific growth stages has been found to significantly enhance nutrient uptake and protein content in maize. Studies have also indicated that the combined application of compost and mineral fertilizers can increase the concentration of essential minerals in maize grains and improve nutrient use efficiency. Furthermore, the strategic placement and timing of nitrogen and phosphorus fertilizers have been shown to optimize nitrogen utilization and improve maize yield.

The findings from these studies have important implications for maize production and food security. The integration of organic and inorganic fertilizers not only enhances maize yield and nutritional quality but also promotes sustainable agricultural practices by improving soil health and reducing the reliance on chemical fertilizers. This integrated approach can lead to more resilient maize production systems, particularly in regions prone to drought and soil degradation. By improving nitrogen use efficiency and reducing fertilizer application rates, these practices can also mitigate the environmental impact of maize cultivation, contributing to the sustainability of food production systems. Enhanced maize nutritional value directly supports food security by providing more nutritious food sources, which is crucial for addressing malnutrition and improving public health.

Future research should focus on optimizing the ratios and combinations of organic and inorganic fertilizers to maximize maize yield and nutritional quality under various environmental conditions. Long-term field studies are needed to assess the sustainability and environmental impact of these integrated nutrient management practices. Additionally, research should explore the genetic and metabolic mechanisms underlying nitrogen use efficiency in maize to develop more efficient fertilizer application strategies. Policymakers should promote the adoption of integrated nutrient management practices through incentives and support for farmers, including access to organic amendments and training on sustainable fertilization techniques. Policies should also encourage the use of bio-fertilizers and microbial inoculants, such as AMF, to reduce chemical fertilizer dependency and enhance soil health. By supporting research and implementing policies that promote sustainable maize production, we can improve food security and environmental sustainability.

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Conflict of Interest Disclosure
Authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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