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Effects of Straw Incorporation and Fertilizer Interaction on Nitrogen Uptake Efficiency and Quality Improvement in Maize

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Abstract Nitrogen uptake is a critical determinant of crop yield and quality in maize production, and optimizing its efficiency remains a priority in sustainable agriculture. Straw incorporation has gained attention for its potential to improve soil health and influence nutrient dynamics, particularly when combined with appropriate fertilizer management. This study investigates the impact of straw incorporation and its interaction with different fertilizer types on nitrogen uptake efficiency and maize quality. Field experiments were conducted to analyze changes in soil microbial activity, soil structure, and nutrient availability following straw incorporation, as well as to elucidate the mechanisms underlying fertilizer and straw interactions. Our findings reveal that incorporating straw significantly enhances soil microbial biomass and enzyme activities, leading to improved soil structure and enhanced nitrogen cycling. The interaction between straw and nitrogen-based fertilizers was shown to optimize nitrogen uptake efficiency, contributing to higher grain quality in maize. A practical case study, including site-specific experimental design, provided insights into the implications of straw and fertilizer interaction for maize production. The results underscore the potential of integrating straw incorporation with fertilizer management to promote sustainable nitrogen management in maize cropping systems. Further research is recommended to explore the long-term effects of this integrated approach on soil health and crop performance under varying environmental conditions.
Keywords Nitrogen uptake efficiency; Maize quality; Straw incorporation;Fertilizer interaction; Sustainable agriculture

1 Introduction

Nitrogen (N) is a critical nutrient for maize (*Zea mays* L.) growth and development, significantly influencing its yield and quality. However, the efficiency of nitrogen uptake in maize is often suboptimal, with global nitrogen use efficiency (NUE) for cereal production averaging around 33%. This inefficiency results in substantial economic losses and environmental issues, such as nitrogen leaching and greenhouse gas emissions (Meng et al., 2021). Improving NUE in maize is essential for sustainable agricultural practices and to meet the growing food demands of the global population.

Straw incorporation into the soil is a beneficial agronomic practice that can enhance soil fertility and structure, thereby improving crop yields. Incorporating straw helps in maintaining soil organic carbon levels, enhancing soil moisture retention, and providing a slow-release source of nutrients, including nitrogen (Akhtar et al., 2023a). Studies have shown that straw incorporation can significantly increase maize grain yield and nitrogen uptake by improving soil fertility indices and nitrogen cycling (Ma et al., 2021). Additionally, straw mulching has been found to regulate soil temperature and moisture, further contributing to improved crop performance (Akhtar et al., 2023b).

The interaction between straw incorporation and nitrogen fertilization plays a crucial role in optimizing nitrogen uptake efficiency and improving maize quality. Combining straw mulch with nitrogen fertilizer has been shown to enhance soil and plant physio-chemical attributes, leading to increased photosynthetic efficiency, nitrogen use efficiency, and grain yield (Akhtar et al., 2023a). Moreover, straw incorporation can mitigate nitrogen leaching, thereby improving nitrogen recovery efficiency and reducing environmental pollution (Meng et al., 2021). Different straw management techniques, such as surface coverage and deep burial, combined with varying nitrogen application rates, have been studied to determine their effects on root distribution, nitrogen uptake, and overall maize yield (Sui et al., 2020; Zhang et al., 2020).

The study is to evaluate the effects of straw incorporation on nitrogen uptake efficiency in maize, investigate the interaction between straw incorporation and nitrogen fertilization on maize quality improvement, and determine the optimal straw and nitrogen management practices for enhancing maize yield and nitrogen use efficiency.

2 Impact of Straw Incorporation on Soil Health

2.1 Role of straw in soil microbial activity

Straw incorporation significantly enhances soil microbial activity, which is crucial for maintaining soil health. Long-term straw mulching combined with nitrogen fertilization has been shown to increase the abundance and diversity of soil microbial communities, including bacteria and fungi. This practice boosts the activities of various soil enzymes such as β-glucosidase, N-acetyl-glucosaminidase, and phosphatase, which are essential for nutrient cycling and organic matter decomposition (Chen et al., 2021; Yang et al., 2022). Additionally, straw incorporation promotes the growth of specific bacterial taxa like Proteobacteria and Acidobacteria, which play vital roles in soil nutrient transformations (Li et al., 2019).

2.2 Effects on soil structure and nutrient availability

Incorporating straw into the soil improves its physical structure and enhances nutrient availability. Studies have demonstrated that straw mulching increases soil organic carbon (SOC), total nitrogen (TN), and available phosphorus (AP) and potassium (AK) levels, which are critical for plant growth (Chen et al., 2021; Akhtar et al., 2023a). The improved soil structure resulting from straw incorporation also enhances soil moisture retention and reduces soil compaction, thereby creating a more favorable environment for root growth and nutrient uptake (Figure 1) (Sui et al., 2022). Furthermore, straw incorporation has been found to reduce nitrogen leaching, thereby increasing the retention of nitrate nitrogen (NO_3--N) in the soil profile, which is beneficial for sustained crop productivity (Meng et al., 2021).

2.3 Implications for nitrogen cycling

Straw incorporation has significant implications for nitrogen cycling in agricultural systems. It enhances nitrogen use efficiency (NUE) by promoting the mineralization of organic nitrogen and increasing the availability of nitrogen for plant uptake (Sharma et al., 2021; Akhtar et al., 2023a). The interaction between straw incorporation and nitrogen fertilization also stimulates various nitrogen cycling processes, including nitrification, denitrification, and nitrogen fixation, which are essential for maintaining soil fertility and reducing nitrogen losses (Li et al., 2019). Additionally, straw incorporation has been shown to mitigate nitrous oxide (N_2O) emissions per unit of applied nitrogen, thereby reducing the environmental impact of nitrogen fertilization (Xu et al., 2020; Liang, 2024).

3 Fertilizer Interactions with Straw Incorporation

3.1 Types of fertilizers used

In the studies reviewed, various types of nitrogen (N) fertilizers were used in combination with straw incorporation to enhance maize growth and yield. The primary fertilizers included urea, 15N-labeled urea, organic manure, and standard nitrogen fertilizers. Urea was commonly used in multiple studies, often blended with slow-release nitrogen fertilizers to improve efficiency (Guo et al., 2021). 15N-labeled urea was used to trace nitrogen uptake and utilization in maize plants, often combined with organic amendments like corn straw and woody peat (Lin et al., 2022). Organic manure, including cow manure and chicken manure, was substituted for chemical fertilizers in some studies to assess their impact on yield and nitrogen uptake (Geng et al., 2019). Standard nitrogen fertilizer was applied at varying rates (e.g., 150 kg/ha, 225 kg/ha, 300 kg/ha) to evaluate its interaction with straw incorporation (Lei et al., 2020; Meng et al., 2021).

3.2 Mechanisms of interaction

The interaction between straw incorporation and nitrogen fertilizers operates through several mechanisms. Soil fertility improvement occurs as straw incorporation enhances soil organic carbon and nutrient content, which in turn improves nitrogen availability and uptake by maize plants (Sui et al., 2020; Akhtar et al., 2023a). Reduction of nitrogen leaching is another benefit, as straw incorporation helps retain nitrogen in the soil, reducing leaching losses and making more nitrogen available for plant uptake (Meng et al., 2021; Lin et al., 2022). Enhanced root growth is achieved through different straw incorporation techniques, such as surface coverage and deep burial, which promote root growth and distribution, ultimately improving nitrogen uptake efficiency (Zhang et al., 2020). Water use efficiency is also influenced by straw mulching and incorporation, as these practices improve soil moisture retention, supporting better nitrogen utilization and overall plant growth (Guo et al., 2021; Hou et al., 2024).

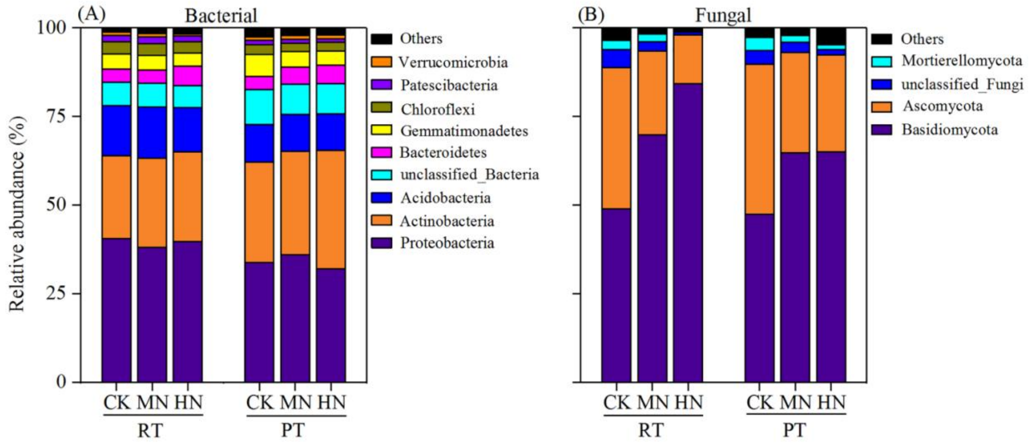

Figure 1 Changes in soil microbial (bacterial and fungal) taxonomic composition at the phylum level after tillage with straw incorporation and N fertilization levels (Adopted from Sui et al., 2022)

Image caption: Rotary tillage with straw incorporation (RTS), Plow tillage with straw incorporation (PTS), 0 (CK), 187 (MN) and 337 (HN) kg N/ha applied. The groups accounting for 1% are shown, whereas those accounting for <1% are combined as others (Adopted from Sui et al., 2022)

3.3 Impact on nitrogen uptake efficiency

The combined use of straw incorporation and nitrogen fertilizers has been shown to significantly enhance nitrogen uptake efficiency (NUE) in maize. Increased NUE has been reported in studies, showing increases of up to 31.82% when straw mulching is combined with slow-release nitrogen fertilizers (Guo et al., 2021). Similarly, full wheat straw incorporation with nitrogen application increased NUE by 9.6% (Akhtar et al., 2023a). Improved nitrogen recovery is another outcome of the incorporation of straw with nitrogen fertilizers. This practice has been shown to improve nitrogen recovery efficiency (NRE) and agronomic efficiency from nitrogen (AEN), leading to better nitrogen utilization and reduced losses (Lei et al., 2020). Sustained yield improvements have been observed in long-term studies. Consistent straw incorporation improves soil fertility and nitrogen cycling, resulting in sustained increases in maize yield and nitrogen uptake over multiple years (Ma et al., 2021).

4 Nitrogen Uptake Efficiency in Maize

4.1 Definition and importance

Nitrogen uptake efficiency (NUE) in maize refers to the plant's ability to absorb and utilize nitrogen from the soil. This efficiency is crucial for maximizing crop yield and minimizing environmental impacts. Efficient nitrogen uptake ensures that the applied nitrogen is used effectively by the plant, leading to better growth, higher yields, and reduced nitrogen losses to the environment, which can cause pollution and resource wastage (Sui et al., 2020; Meng et al., 2021; Akhtar et al., 2023a).

4.2 Factors affecting nitrogen uptake

Several factors influence nitrogen uptake efficiency (NUE) in maize, including straw incorporation, nitrogen fertilization rates, tillage practices, mulching, and nitrogen source and timing. Straw incorporation into the soil can enhance nitrogen uptake by improving soil structure and moisture retention, which facilitates better root growth and nutrient absorption (Zhang et al., 2020; Meng et al., 2021). Nitrogen fertilization rates significantly affect NUE. Optimal rates can enhance uptake, while excessive application can lead to nitrogen leaching and reduced efficiency (Akhtar et al., 2023a). Tillage practices, such as rotary tillage and plow tillage, impact root distribution and soil properties, thereby affecting nitrogen uptake (Sui et al., 2020). Mulching with straw can regulate soil temperature and moisture, improving the physiological conditions for nitrogen uptake (Guo et al., 2021; Akhtar et al., 2023a). Nitrogen source and timing, including the type of nitrogen fertilizer and the timing of its application, play a crucial role in how effectively maize plants absorb nitrogen. Split applications and the use of slow-release fertilizers have been shown to improve NUE (Abbasi et al., 2013).

4.3 Measurement techniques

Measuring nitrogen uptake efficiency involves several methods, including nitrogen recovery efficiency (NRE), nitrogen use efficiency (NUE), the ^{15}N tracer technique, and soil and plant analysis. Nitrogen Recovery Efficiency (NRE) measures the proportion of applied nitrogen that is taken up by the plant. It is calculated by comparing the nitrogen content in the plant with the amount of nitrogen applied (Zhang et al., 2020; Meng et al., 2021). Nitrogen Use Efficiency (NUE) is a broader measure that includes both the uptake and utilization of nitrogen by the plant. It is often assessed by evaluating the grain yield per unit of nitrogen applied (Guo et al., 2021; Akhtar et al., 2023a). The ^{15}N Tracer Technique involves using nitrogen isotopes to trace and quantify the uptake and distribution of nitrogen within the plant and soil system. It provides detailed insights into nitrogen dynamics and efficiency (Lin et al., 2022). Soil and Plant Analysis, through regular sampling and analysis of soil and plant tissues for nitrogen content, helps in monitoring and assessing nitrogen uptake and utilization over the growing season (Lei et al., 2020; Sui et al., 2020). By understanding and optimizing these factors and measurement techniques, farmers and researchers can improve nitrogen uptake efficiency in maize, leading to better crop performance and sustainability.

5 Quality Improvement in Maize

5.1 Indicators of maize quality

Maize quality is typically assessed through various indicators, including grain yield, nitrogen use efficiency (NUE), and the biochemical composition of the grain such as starch and soluble sugar content. For instance, the incorporation of straw and nitrogen fertilization has been shown to significantly enhance these quality indicators (Su et al., 2020). In a study conducted in the semi-arid region of China, the combination of full wheat straw mulch and nitrogen fertilization (FS+N) resulted in a 29% increase in grain yield, 9.6% improvement in NUE, and substantial increases in soluble sugar and starch content by 80% and 59%, respectively (Yu et al., 2019; Akhtar et al., 2023a; Hu et al., 2023).

5.2 Effects of nitrogen on grain quality

Nitrogen plays a crucial role in improving the grain quality of maize. Adequate nitrogen application enhances photosynthetic efficiency, which in turn boosts grain yield and quality. For example, a study found that nitrogen application at 225 kg/ha significantly improved photosynthetic traits and nitrogen accumulation in grains, leading to higher grain yield and improved nitrogen absorption efficiency (Wang et al., 2022). However, excessive nitrogen application can lead to environmental issues such as nitrate leaching, which underscores the importance of optimizing nitrogen levels (Meng et al., 2021).

5.3 Role of straw and fertilizer interaction

The interaction between straw incorporation and nitrogen fertilization has been shown to have a synergistic effect on maize quality. Straw incorporation not only improves soil fertility but also enhances nitrogen uptake and utilization. For instance, a six-year study in Northeast China demonstrated that straw incorporation at higher rates consistently improved soil fertility indices, which in turn elevated grain yield and nitrogen use efficiency over time (Ma et al., 2021). Additionally, the combination of straw incorporation with deep placement of nitrogen fertilizer significantly increased grain yield and nitrogen recovery efficiency in direct-seeded rice, suggesting similar benefits could be expected in maize (Chen et al., 2020). Another study highlighted that straw incorporation coupled with optimized nitrogen fertilization could improve maize yield and nitrogen balance, thereby enhancing overall crop quality (Lei et al., 2020; Wang et al., 2024) (Figure 2).

6 Case Study: Practical Applications of Straw Incorporation and Fertilizer Interaction

6.1 Site description and experimental design

The study was conducted in various regions of China, including the semi-arid region, the Loess Plateau, and the Hetao Irrigation District. These areas were chosen due to their distinct climatic conditions and agricultural practices, which provide a comprehensive understanding of the effects of straw incorporation and fertilizer interaction on maize. The experimental design varied across studies but generally included multiple treatments combining different rates of nitrogen (N) fertilizer and straw incorporation. For instance, treatments included control (no N or straw), various levels of N application (e.g., 150, 225, 300 kg/ha), and different straw management practices (e.g., no straw, half straw, full straw) (Zhang et al., 2020; Meng et al., 2021; Akhtar et al., 2023a). Some studies also incorporated slow-release nitrogen fertilizers and different methods of straw application, such as surface coverage and deep burial (Figure 3) (Guo et al., 2021; Hou et al., 2024).

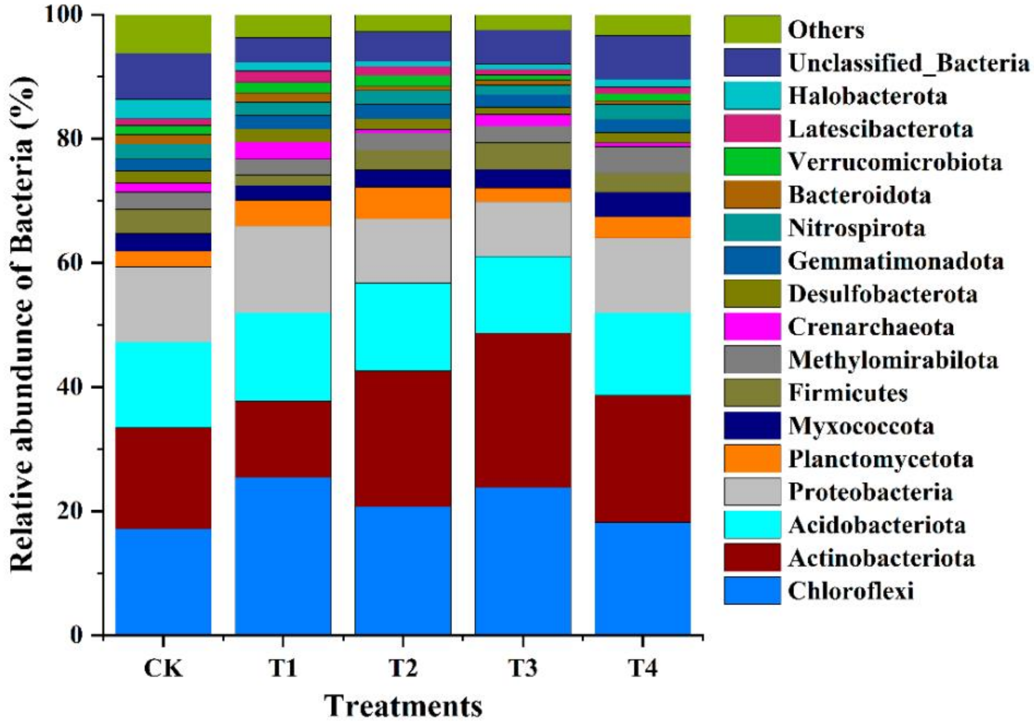

Figure 2 Impact of nitrogen fertilization on relative abundance of the bacterial phylum (Adopted from Wang et al., 2024)
Image caption: CK, (N0P0); T1, (N0P90); T2, (N60P90); T3, (N120P90); and T4, (N180P90) (Adopted from Wang et al., 2024)

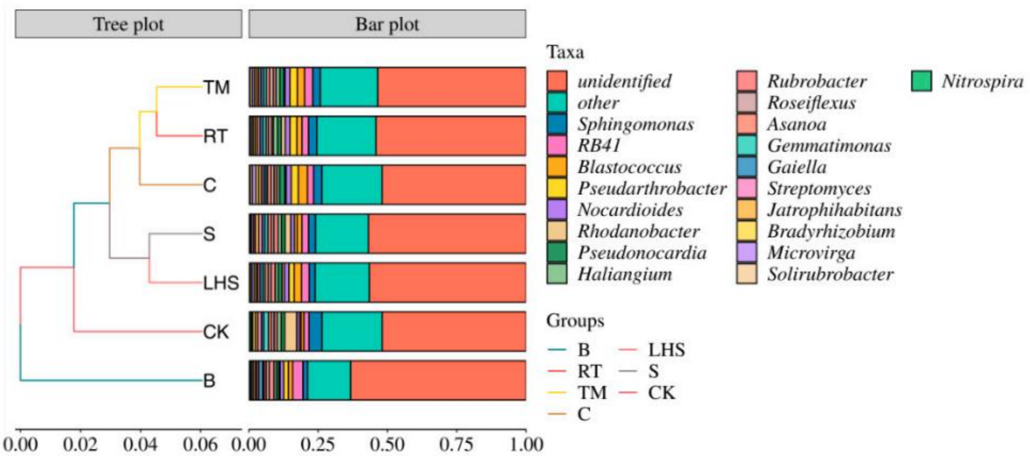

Figure 3 Clustering bar chart of soil bacterial community samples at a genus level under different returning methods (Adopted from Hou et al., 2024)

6.2 Results and findings

The results consistently demonstrated that the combination of straw incorporation and nitrogen fertilization significantly improved maize growth, yield, and nitrogen use efficiency (NUE). Yield improvement was evident as full straw incorporation combined with nitrogen fertilization increased maize grain yield by up to 29% compared to control treatments (Akhtar et al., 2023a). Similarly, straw incorporation in the Loess Plateau increased grain yield by 43.6% and 61.8% with 150 and 225 kg/ha nitrogen application, respectively (Meng et al., 2021). Nitrogen uptake and efficiency were significantly enhanced by treatments involving straw incorporation and medium to high nitrogen rates. For example, deep burial of straw combined with medium nitrogen fertilizer increased nitrogen uptake by 20.4% and maize yield by 9.3% (Zhang et al., 2020). Another study reported that straw incorporation improved nitrogen recovery efficiency by up to 188.6% (Chen et al., 2020). Soil fertility was improved through long-term straw incorporation, which enhanced soil organic carbon and increased available nitrogen and phosphorus content, supporting higher crop yields (Ma et al., 2021). Environmental benefits were also observed, as straw incorporation reduced nitrogen leaching and nitrate nitrogen infiltration into deeper soil layers, mitigating environmental pollution. Additionally, it reduced overall fertilizer-N losses and N_2O emissions per unit of applied nitrogen.

6.3 Implications for agricultural practices

The findings from these studies have significant implications for sustainable agricultural practices. Enhanced crop productivity can be achieved by integrating straw incorporation with appropriate nitrogen fertilization, which substantially increases maize yield and quality. This makes it a viable strategy for improving food security in semi-arid and rainfed regions (Guo et al., 2021; Akhtar et al., 2023a). Improved soil health is another benefit, as long-term straw incorporation enhances soil organic matter and nutrient availability, promoting sustainable soil health and fertility (Ma et al., 2021). Environmental sustainability is supported by the reduction in nitrogen leaching and greenhouse gas emissions. Straw incorporation, coupled with optimized nitrogen management, can mitigate the environmental impact of intensive farming practices (Meng et al., 2021). Economic viability is also a key advantage. The increased nitrogen use efficiency and reduced fertilizer losses translate to cost savings for farmers, making this practice economically beneficial (Lin et al., 2022).

7 Discussion

7.1 Synthesis of findings

The integration of straw incorporation and nitrogen (N) fertilization has shown significant improvements in maize growth, nitrogen uptake efficiency, and overall yield. The combination of full wheat straw mulch with nitrogen fertilization (FS+N) resulted in substantial increases in photosynthetic efficiency, nitrogen uptake, and grain yield (Akhtar et al., 2023). Similarly, straw incorporation was found to inhibit nitrogen leaching, thereby enhancing nitrogen use efficiency (NUE) and grain yield in maize (Meng et al., 2021). The long-term application of straw incorporation also consistently improved soil fertility and maize production, indicating that larger straw additions have more profound positive effects on nitrogen recovery efficiency and NUE (Wang et al., 2023). Furthermore, different tillage practices combined with straw incorporation and varying N levels significantly influenced soil physicochemical properties, root traits, and ultimately, maize grain yield (Sui et al., 2020). These findings collectively suggest that straw incorporation, particularly when combined with optimal N fertilization, can significantly enhance maize productivity and soil health.

7.2 Implications for sustainable agriculture

The results of this study have important implications for sustainable agriculture. The use of straw incorporation along with nitrogen fertilization not only improves maize yield but also enhances soil fertility and reduces environmental pollution. For instance, straw incorporation effectively prevents nitrate nitrogen infiltration, thereby reducing nitrogen leaching and promoting environmental sustainability (Meng et al., 2021). Additionally, the practice of straw return with reduced N fertilization has been shown to improve nitrogen use efficiency and reduce the optimal nitrogen rate required for maize production, which can lead to more sustainable farming practices (Sharma et al., 2021). These strategies contribute to the development of sustainable wheat-maize cropping systems that optimize crop yield while maintaining soil health and minimizing environmental impact.

7.3 Future research directions

Future research should focus on exploring the long-term impacts of different straw incorporation rates and nitrogen fertilization levels on soil health and crop productivity. Studies should investigate the optimal combinations of straw and nitrogen that maximize nitrogen use efficiency and minimize environmental pollution. Additionally, research should examine the effects of straw incorporation and nitrogen fertilization under different climatic conditions and soil types to develop region-specific recommendations. Further studies are also needed to understand the underlying mechanisms by which straw incorporation and nitrogen fertilization influence soil microbial activity, nutrient cycling, and plant physiology. Finally, the economic feasibility and practical implementation of these practices should be evaluated to ensure their adoption by farmers on a large scale. By addressing these research gaps, we can develop more effective and sustainable agricultural practices that enhance crop productivity, improve soil health, and protect the environment (Hagos et al., 2020; Sharma et al., 2021).

8 Concluding Remarks

The integration of straw incorporation and nitrogen (N) fertilization has shown significant positive effects on maize growth, nitrogen uptake efficiency, and overall crop quality. Key findings from various studies indicate that combining straw mulch with nitrogen fertilizer significantly improves soil fertility, photosynthetic efficiency, nitrogen use efficiency (NUE), and maize yield. For instance, the FS+N treatment increased photosynthetic efficiency by 56%, nitrogen uptake by 60%, and grain yield by 29% compared to the control. Straw incorporation enhances soil water retention, root distribution, and nitrogen uptake, which collectively contribute to higher grain yields and water use efficiency (WUE). Long-term straw incorporation consistently improves soil fertility indices, leading to increased grain yield and nitrogen harvest index (NHI). The optimal nitrogen rate for maize production can be reduced when combined with straw incorporation, thus promoting sustainable nitrogen management.

Based on the findings, the following recommendations are proposed for farmers and policymakers to enhance nitrogen uptake efficiency and improve maize quality sustainably. Adopt straw incorporation practices. Farmers should incorporate straw into the soil at appropriate rates (e.g., 5 000 kg/ha) along with nitrogen fertilization (e.g., 172 kg N/ha) to improve soil health and crop yield. Optimize nitrogen application. Policymakers should promote the use of optimized nitrogen rates (e.g., 187 kg N/ha) combined with straw incorporation to reduce nitrogen leaching and enhance nitrogen use efficiency. Encourage long-term practices. Long-term straw return practices should be encouraged as they significantly improve soil organic carbon, total nitrogen, and yield stability, contributing to sustainable agriculture. Support research and extension services. Continuous research and extension services should be supported to educate farmers on the benefits of integrated straw and nitrogen management practices and to develop region-specific guidelines.

Sustainable nitrogen management in maize production is crucial for achieving high yields while minimizing environmental impacts. The integration of straw incorporation with optimized nitrogen fertilization has proven to be an effective strategy to enhance nitrogen uptake efficiency, improve soil health, and increase crop quality. By adopting these practices, farmers can achieve better economic returns and contribute to environmental sustainability. Future research should focus on refining these practices under varying climatic conditions and soil types to ensure their broader applicability and effectiveness.

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Conflict of Interest Disclosure

The 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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