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Influence of Agronomic Practices on Maize Protein and Starch Contents

Xiaojing Yang, Qian Li
Modern Agricultural Research Center, Cuixi Academy of Biotechnology, Zhuji, 311800, Zhejiang, China
Corresponding author: qian.li@cuixi.org
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Abstract As a globally important food crop and feed source, the protein and starch content of maize (*Zea mays* L.) directly affects its nutritional value and industrial applications. This study delves into the impact of agronomic practices on the protein and starch content of maize. Through a comprehensive analysis of fertilization strategies, irrigation techniques, crop rotation and soil management, planting density, and spacing, the mechanisms by which these practices affect maize composition are revealed. Additionally, the study explores the influence of environmental factors such as climate and soil type on protein and starch content, as well as the interactions between agronomic practices and environmental factors. The findings indicate that proper fertilization and irrigation management can significantly increase the protein and starch content of maize, while crop rotation and soil management help maintain soil fertility, providing a favorable environment for maize growth. Moreover, optimizing planting density and spacing can enhance photosynthesis in maize plants, thereby affecting the accumulation of protein and starch. The impact of climatic conditions and soil types on maize composition is also significant. This study also introduces the application advancements of genomic methods, precision agriculture, and biotechnological interventions in improving maize quality, providing new insights for future research and practice. The aim of this study is to enhance the nutritional value and market competitiveness of maize, offering practical technical guidance for agricultural producers.
Keywords Maize (*Zea mays* L.); Protein; Starch; Agronomic practices; Environmental factors

1 Introduction

Maize (*Zea mays* L.) is one of the most significant cereal crops globally, serving as a staple food for humans and livestock. The composition of maize kernels is predominantly carbohydrates, which constitute approximately 70% of the kernel's weight. However, maize is also a crucial source of protein, especially in developing countries where it is a primary dietary component (Roodt, 2022). The protein content in maize is characterized by a high proportion of seed storage proteins, which are deficient in several essential amino acids such as lysine, methionine, and tryptophan (Roodt, 2022). This deficiency poses a challenge for nutrition, as these amino acids are vital for human and animal health. Its unique composition, particularly the protein and starch content, determines the nutritional value and industrial applications of maize.

Protein and starch are two critical components of maize that significantly influence its nutritional and industrial value. Protein in maize is essential for human and animal nutrition, but its quality is often limited by the low levels of essential amino acids (Roodt, 2022). Efforts to enhance the amino acid profile of maize through genetic and agronomic practices have been ongoing, with varying degrees of success (Roodt, 2022). Starch, on the other hand, is a major carbohydrate source and plays a crucial role in the energy supply for both humans and livestock. It also has significant industrial applications, including its use in the production of biofuels, sweeteners, and biodegradable materials (Hasan and Al-Musawi, 2023).

With population growth and economic development, the demand for maize is increasing, making the improvement of maize quality and yield a key issue in agricultural production. Agricultural practices, including cultivation methods, fertilizer use, irrigation management, and pest control, have a direct impact on the growth, development, and final yield of maize. These practices can not only increase the yield of maize but also optimize its nutritional composition (Duvick, 2005). In recent years, with continuous advancements in agricultural technology, an increasing number of studies have focused on exploring the effects of different agronomic practices on maize quality, aiming to enhance the nutritional value and economic benefits of maize through scientific management (Ciampitti and Vyn, 2013).

This study aims to evaluate the impact of various agronomic practices on the protein and starch content of maize. By synthesizing findings from multiple studies, the objective is to identify effective strategies for enhancing the nutritional quality and industrial utility of maize. This study assesses the influence of different agronomic practices on the protein content and amino acid composition of maize, explores how these practices affect the starch content and its properties, and provides recommendations for future research and practical applications to improve maize quality through agronomic interventions. By achieving these goals, this study hopes to offer practical technical guidance to agricultural producers, provide a scientific basis for improving maize quality and yield, and contribute to the optimization of maize cultivation for better nutritional outcomes and industrial applications.

2 Overview of Maize Composition

Maize (*Zea mays* L.) is a staple crop with significant nutritional and industrial value. Its composition primarily includes carbohydrates, proteins, lipids, and essential minerals. The two major components of maize that are often the focus of agronomic studies are protein and starch, both of which are crucial for its nutritional and industrial applications.

2.1 Protein content in maize

Maize contains protein, and the specific content may vary depending on the maize variety and growing conditions. Generally, maize has a protein content of about 8.5%. For example, every 100 grams of maize contains approximately 8.5 grams of protein. This protein is important for human physiological functions such as growth and tissue repair.

Protein content in maize is a critical factor for both human consumption and animal feed. The concentration of protein in maize grains can be influenced by various agronomic practices. For instance, the application of nitrogen fertilizer has been shown to increase grain yield, which can inversely affect protein concentration unless the yield increase is directly due to nitrogen application (Mason and D'croz-Mason, 2002). Additionally, irrigation practices can enhance the biological value of protein, although higher nitrogen application rates may alter the amino acid balance, potentially reducing the nutritional value of the protein (Mason and D'croz-Mason, 2002).

2.2 Starch content in maize

Maize has a high starch content, making it a primary source of carbohydrates. The starch content may vary depending on the maize variety and maturity, but generally, it is over 70%, which is significantly higher than other grains such as rice. In every 100 grams of maize, starch constitutes the majority, providing a substantial amount of energy.

Starch is the predominant carbohydrate in maize, making it a vital component for both food and industrial uses. The composition of starch, particularly the amylose-to-amylopectin ratio, can be influenced by environmental conditions and agronomic practices. For example, environmental factors such as solar radiation and temperature during the grain filling period can significantly affect the amylose/starch ratio (Martínez et al., 2019). Fertilization with nitrogen and sulfur, as well as modifications in the source/sink ratio through defoliation and plant thinning, have been studied, but these practices did not produce significant changes in starch composition (Martínez et al., 2019). However, increases in minimum temperature during early grain filling were associated with decreases in starch percentage and increases in the amylose/starch ratio (Martínez et al., 2019).

2.3 Factors affecting maize composition

Factors influencing the composition of maize include genetics, environment, and agronomic practices. Different varieties of maize exhibit differences in nutritional components, such as protein, starch, and fat content. Growing conditions, including soil, climate, irrigation, and fertilization, significantly impact the growth and development of maize, thereby affecting its nutritional content. As maize matures, its nutritional composition also changes.

While genetic improvements have historically been credited with significant yield gains, recent studies suggest that the contribution of genetic technologies to yield potential is smaller than previously thought. Instead, climate and agronomic management practices play a more substantial role in recent yield gains (Rizzo et al., 2022). For instance, a study conducted in Nebraska found that 48% of the yield gain was associated with climate trends, 39% with agronomic improvements, and only 13% with genetic yield potential improvements (Rizzo et al., 2022). This underscores the importance of focusing on agronomic practices to enhance maize composition.

In summary, the protein and starch contents of maize are significantly influenced by agronomic practices such as nitrogen fertilization, irrigation, and environmental conditions during grain filling. Understanding these influences can help optimize maize production for both nutritional and industrial purposes.

3 Agronomic Practices Affecting Maize Protein Content

3.1 Fertilization strategies

Fertilization strategies play a crucial role in determining the protein content of maize. Nitrogen (N) fertilization, in particular, has been shown to significantly impact grain protein concentration. A meta-analysis of 21 studies revealed that increasing levels of nitrogen fertilizer consistently enhanced grain protein concentration, with a protein change of +14% for low, ≤70 kg N ha^{-1}; +21% for medium, >70–150 kg N ha^{-1}; and +24% for high, >150 kg N ha^{-1} (Correndo et al., 2021). Additionally, integrated agronomic practices that include optimal fertilizer management have been found to improve nitrogen use efficiency (NUE) and grain nitrogen content, thereby promoting higher protein levels in maize (Vanlauwe et al., 2011; Liu et al., 2018; Zhou et al., 2019).

The balanced application of other nutrients, such as phosphorus (P) and potassium (K), also affects the protein content in maize. Phosphorus fertilizer can promote root growth and energy metabolism, thereby indirectly enhancing protein synthesis efficiency (Grant and Flaten, 2019). Potassium fertilizer helps improve maize's stress resistance, water use efficiency, and photosynthetic efficiency, which in turn increases grain protein content (Pettigrew, 2008).

3.2 Irrigation techniques

Irrigation techniques also influence maize protein content. Proper irrigation management can improve the biological value of protein in maize. For instance, irrigation has been shown to enhance the amino acid balance, which is crucial for the nutritional value of maize protein (Mason and D'croz-Mason, 2002). However, the timing and frequency of irrigation are critical. Studies have indicated that nighttime irrigation and low-frequency irrigation can lead to higher contamination with mycotoxins, which may indirectly affect protein quality (Herrera et al., 2023). Moreover, different irrigation levels combined with nitrogen fertilization can alter starch properties and phytic acid content, which are related to protein content in maize (Kaplan et al., 2019).

Advanced irrigation technologies such as drip irrigation and sprinkler irrigation can more precisely control water supply, reducing water wastage and preventing overly wet or dry soil conditions. Studies have found that drip irrigation can significantly improve maize's water use efficiency and protein content (Oerke, 2006). Combining water-saving irrigation techniques with scientific fertilization schemes can further enhance the protein content and overall nutritional quality of maize.

3.3 Crop rotation and soil management

Crop rotation and soil management practices are essential for maintaining soil fertility and enhancing maize protein content. Integrated Soil Fertility Management (ISFM), which includes the combined application of organic inputs and fertilizers, has been shown to maximize the agronomic efficiency of applied nutrients, thereby improving grain protein content (Vanlauwe et al., 2011). Additionally, practices such as subsoiling tillage and optimal planting density have been found to increase soil mineral nitrogen content and root length, which are crucial for nitrogen uptake and protein synthesis in maize (Liu et al., 2017; Zhou et al., 2019).

Crop rotation can improve soil structure, increase soil nutrients, and reduce the frequency of pest and disease occurrences. For example, rotating with leguminous crops can enhance the nitrogen content in the soil, thereby indirectly increasing the protein content in maize. Appropriate soil management practices, such as the application of organic fertilizers and the use of crop residue mulching, can improve soil fertility and microbial activity, further promoting the accumulation of protein in maize.

3.4 Planting density and spacing

Planting density and spacing significantly affect maize protein content by influencing nutrient uptake and plant growth. Higher planting densities, when combined with appropriate fertilization and soil management practices, can lead to increased nitrogen accumulation and higher grain protein content (Liu et al., 2018; Zhou et al., 2019). Optimized planting density ensures better light interception and nutrient utilization, which are essential for protein synthesis in maize. Studies have shown that integrated agronomic practices, including optimal planting density, can enhance root growth and development, thereby improving nitrogen uptake and protein content in maize (Vanlauwe et al., 2011; Liu et al., 2017).

Reasonable planting density can optimize the utilization of light, water, and nutrients, promoting the healthy growth of maize. Studies have shown that appropriately reducing planting density can increase nutrient supply per plant, thereby enhancing the protein content in grains (Andrade and Abbate, 2005). However, excessively low planting density may lead to decreased land use efficiency. Therefore, it is essential to find a balance to ensure both high yield and high protein content.

4 Agronomic Practices Affecting Maize Starch Content

4.1 Fertilization and nutrient management

Fertilization and nutrient management play a crucial role in determining the starch content in maize. Studies have shown that nitrogen fertilization can influence starch properties, although its impact is less pronounced compared to its effect on protein content. For instance, nitrogen levels have been found to affect the amylose-amylopectin ratio, with higher nitrogen levels generally leading to increased amylopectin content and decreased amylose content (Kaplan et al., 2019). Additionally, the use of slow-release fertilizers versus conventional fertilizers can result in different starch characteristics, such as granule size and crystallinity, which are essential for the functional properties of maize starch (Figure 1) (Wang and Lu, 2022). Integrated agronomic practices, including optimal fertilization strategies, have also been shown to enhance maize yield and nitrogen use efficiency, indirectly affecting starch accumulation (Liu et al., 2018; Zhou et al., 2019).

Wang and Lu (2020) studied the volume percentage, average granule size, and relative crystallinity of starch granules in maize varieties JY877 and SY30 under no fertilization (0F), conventional fertilization (CF), and slow-release fertilization (SF) conditions. The results showed that fertilization significantly increased the average size of starch granules, with no significant difference between CF and SF treatments. Conventional fertilization (CF) significantly increased the relative crystallinity of starch, while the slow-release fertilization (SF) treatment did not show a significant difference compared to no fertilization (0F). In summary, different fertilization modes significantly affect the size and crystallinity of maize starch granules, with conventional fertilization having the most significant effect.

4.2 Irrigation practices

Irrigation practices significantly impact maize starch content. Different irrigation levels can alter the total starch accumulation in maize. For example, a study found that the highest starch values were obtained from a combination of moderate irrigation and high nitrogen levels, while the lowest starch levels were recorded under full irrigation with lower nitrogen levels (Kaplan et al., 2019). Moreover, the timing and frequency of irrigation can influence starch properties. Nighttime irrigation and low-frequency irrigation have been associated with higher mycotoxin levels, which can indirectly affect starch quality (Herrera et al., 2023). Therefore, optimizing irrigation practices is essential for maintaining high starch content and quality in maize.

4.3 Timing of planting and harvesting

The timing of planting and harvesting is another critical factor affecting maize starch content. Early planting can lead to better starch accumulation due to longer growing periods and optimal use of available resources.

Conversely, delayed planting may result in reduced starch content due to shorter growing periods and increased susceptibility to adverse weather conditions. Harvesting time also plays a role; harvesting at the right maturity stage ensures maximum starch accumulation and optimal starch properties (Zhou et al., 2019). Integrated agronomic practices that include precise timing of planting and harvesting can significantly enhance starch content and overall grain quality (Liu et al., 2018).

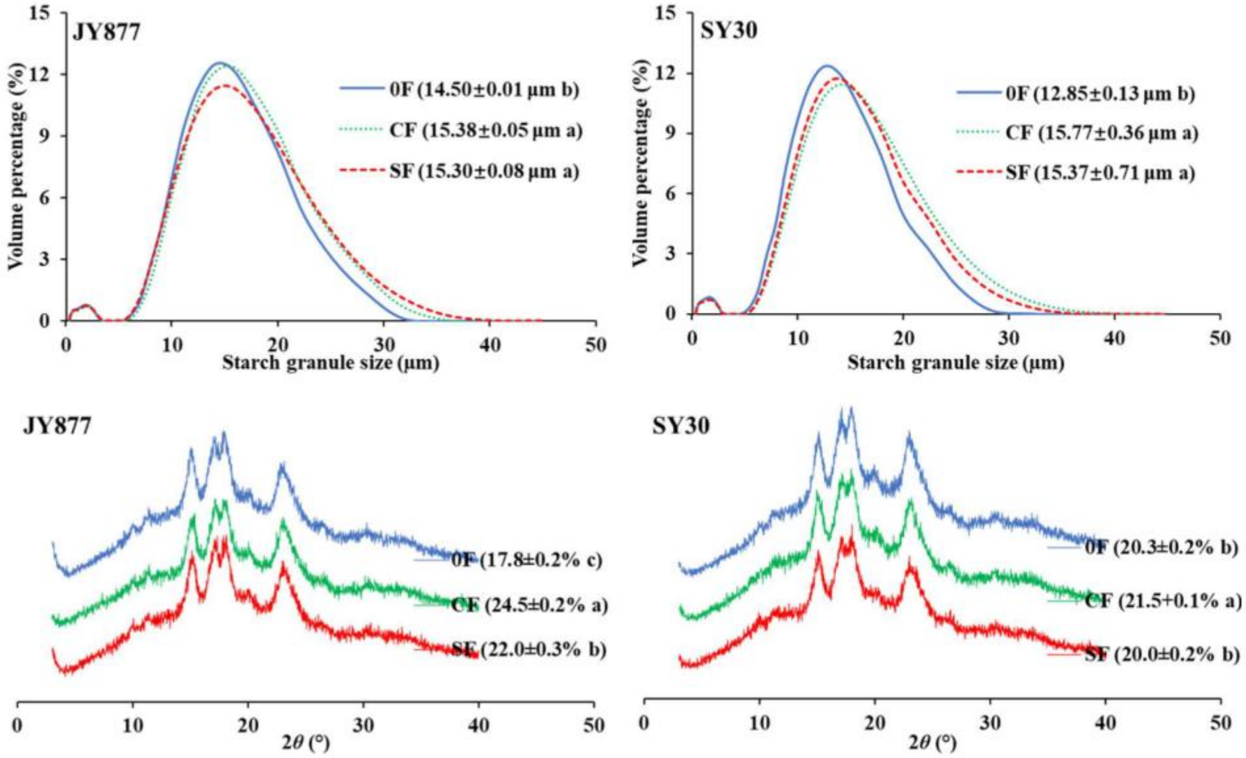

Figure 1 Effects of different fertilization modes on the starch granule size distribution and X-ray diffraction patterns of common maize (Adapted from Wang and Lu, 2022)

Image caption: Different letters indicate significant differences, $p<0.05$; JY877: Jiangyu 877; SY30: Suyu 30; 0F: no fertilization; CF: conventional fertilization; SF: slow-release fertilization (Adapted from Wang and Lu, 2022)

4.4 Pest and disease control

Effective pest and disease control is vital for maintaining high starch content in maize. Pests and diseases can cause significant damage to maize crops, leading to reduced starch accumulation and altered starch properties. For instance, mycotoxin contamination, which can be influenced by irrigation and tillage practices, can adversely affect starch quality (Herrera et al., 2023). Implementing integrated pest management strategies and adopting resistant maize varieties can help mitigate these effects and ensure high starch content. Additionally, maintaining healthy crops through proper pest and disease control measures can enhance overall grain quality, including starch content (Mason and D'croz-Mason, 2002).

In conclusion, various agronomic practices, including fertilization and nutrient management, irrigation practices, timing of planting and harvesting, and pest and disease control, play a significant role in influencing maize starch content. Optimizing these practices can lead to improved starch accumulation and quality, thereby enhancing the overall value of maize as a food and industrial crop.

5 Interaction Between Agronomic Practices and Environmental Factors

5.1 Climate conditions

Climate conditions significantly influence the effectiveness of agronomic practices on maize protein and starch contents. For instance, climate trends have been shown to account for a substantial portion of maize yield gains, with 48% of yield increases attributed to favorable climate conditions over a decade (Rizzo et al., 2022).

Additionally, extreme weather events, such as excessively wet or dry seasons, can drastically affect maize yield and grain composition. During extremely wet years, excessive irrigation can reduce grain yield due to water stress, while in dry years, appropriate irrigation can significantly boost yield (Marković et al., 2021). Moreover, climate change impacts, such as increased minimum temperatures and decreased solar radiation, have been found to affect maize yield differently across various agro-ecological zones, necessitating adaptive agronomic strategies (Zhang et al.. 2020).

5.2 Soil types and characteristics

Soil fertility and characteristics play a crucial role in determining the effectiveness of agronomic practices on maize protein and starch contents. Integrated agronomic practices (IAP), which include optimal planting density, split fertilizer application, and subsoiling tillage, have been shown to increase maize grain yield and nitrogen use efficiency (NUE) more effectively in high soil fertility (HSF) fields compared to low soil fertility (LSF) fields (Zhou et al., 2019). The type of fertilization also impacts starch properties, with conventional fertilization methods leading to larger starch granules and higher relative crystallinity compared to slow-release fertilizers (Wang and Lu, 2022). Additionally, soil mineral nitrogen content and root length are critical factors that enhance post-silking dry matter and nitrogen accumulation, thereby improving grain yield and NUE, especially in HSF fields (Zhou et al., 2019).

5.3 Interaction effects on protein and starch contents

The interaction between agronomic practices and environmental factors significantly affects maize protein and starch contents. Nitrogen fertilization consistently increases grain protein concentration, with higher fertilizer levels resulting in greater protein content (Correndo et al., 2021). However, the impact of irrigation on grain quality components such as protein, starch, and oil concentrations can vary depending on the duration, timing, and intensity of water stress treatments (Correndo et al., 2021). For instance, irrigation combined with high nitrogen levels can lead to increased protein yield, but excessive irrigation during wet years can reduce grain yield due to water stress (Figure 2) (Marković et al., 2021). Furthermore, the combination of appropriate agronomic practices and favorable climate conditions can enhance maize yield and stability, particularly in low-yielding zones (Zhang et al.. 2020). The optimization of genotype-environment-management interactions is essential for developing sustainable intensification options that improve yield and grain quality with minimal environmental impact (Zhang et al., 2020).

Marković et al. (2021) found that proper irrigation and fertilization strategies are crucial for optimizing maize quality and yield. Irrigation and nitrogen fertilization significantly affect maize yield and nutritional components, especially under extreme weather conditions. Their study examined the effects of different irrigation regimes (rainfed, 60%~100% field capacity, 80%~100% field capacity) on various variables under extremely wet, extremely dry, and average years (Figure 2a-d). The results showed that in extremely dry conditions, increasing irrigation significantly improved yield and starch content ($P<0.01$), but had little effect on protein and oil content. Figure 2(e-h) illustrates the impact of different nitrogen fertilization rates (b1: 0 kg N ha^{-1}, b2: 100 kg N ha^{-1}, b3: 200 kg N ha^{-1}) on various variables under different weather conditions. The results indicated that increasing nitrogen fertilization significantly enhanced yield and protein content ($P<0.01$), while the effects on starch and oil content were less pronounced.

In summary, the interplay between agronomic practices and environmental factors such as climate conditions and soil characteristics is critical in determining maize protein and starch contents. Effective management strategies that consider these interactions can lead to significant improvements in maize yield and grain quality.

6 Advances in Research and Technology

6.1 Genomic approaches and breeding

Recent studies have highlighted the limited contribution of genetic technologies to maize yield potential in favorable environments. A comprehensive analysis of maize production in Nebraska from 2005 to 2018 revealed that only 13% of yield gains were attributable to genetic improvements, with the majority of gains resulting from climate trends and agronomic practices (Rizzo et al., 2022). This finding underscores the need to reevaluate the role of genetic progress in yield potential across different environments and crops. Despite this, advancements in genomic approaches, such as CRISPR technology, hold promise for future crop improvement by enabling precise genetic modifications that can enhance traits like protein and starch content (Nemade et al., 2023).

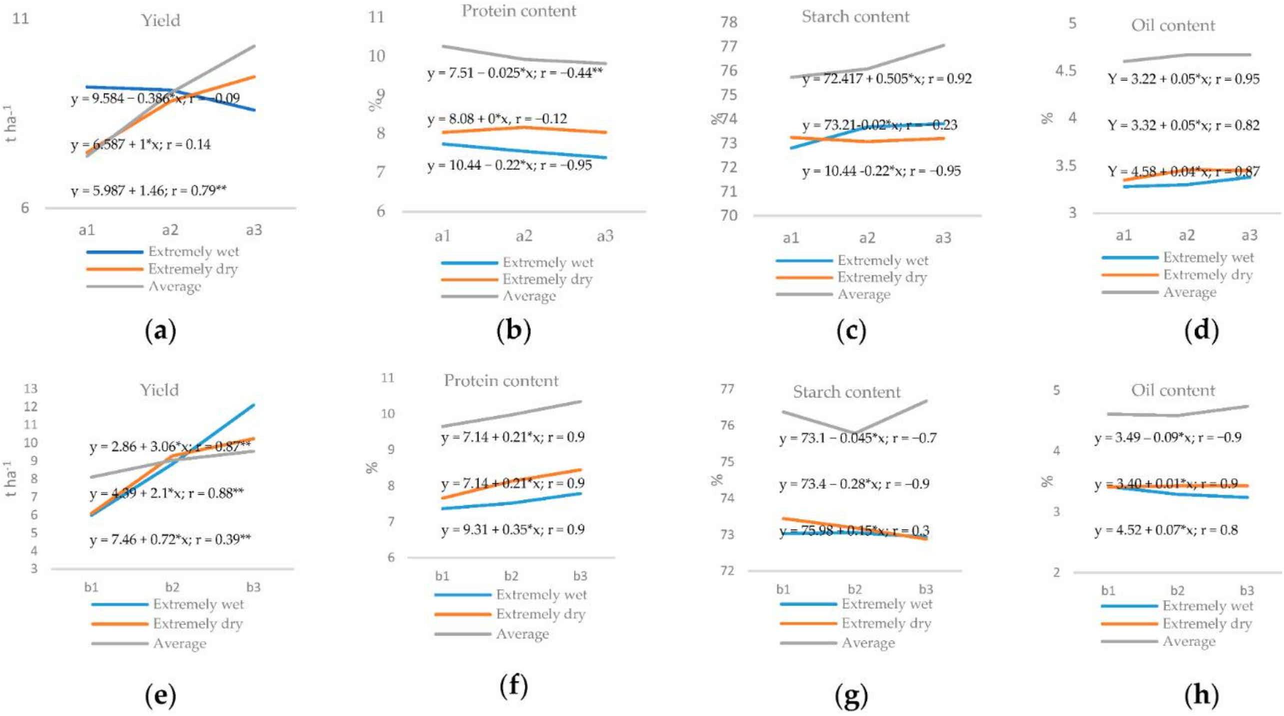

Figure 2 Effects of irrigation and nitrogen fertilization on maize yield, protein, starch, and oil content under different climate conditions (Adapted fromMarković et al., 2021)

Image caption: a1: Rainfed; a2: 60%~100% Field Capacity (FC); a3: 80%~100% Field Capacity (FC); (a): Yield; (b): Protein; (c): Starch; (d): Oil content; Nitrogen fertilization rates (b1: 0 kg N ha^{-1}, b2: 100 kg N ha^{-1}, b3: 200 kg N ha^{-1}); (e): Yield; (f): Protein; (g): Starch; (h): Oil content; $p < 0.05$ (*); $p < 0.01$ (**) (Adapted fromMarković et al., 2021)

6.2 Precision agriculture

Precision agriculture has revolutionized modern farming by integrating advanced technologies such as satellite and drone imagery, sensor-based monitoring systems, and artificial intelligence. These tools facilitate precise resource management and data-driven decision-making, which are crucial for optimizing maize protein and starch contents. For instance, precision agriculture allows for the targeted application of nitrogen fertilizers, which has been shown to increase grain yield and protein concentration (Mason and D'croz-Mason, 2002; Nemade et al., 2023). Additionally, irrigation practices, a key component of precision agriculture, have been found to improve the biological value of maize protein and reduce kernel breakage susceptibility (Mason and D'croz-Mason, 2002).

6.3 Biotechnological interventions

Biotechnological interventions, including the use of genetically modified organisms (GMOs) and advanced breeding techniques, play a significant role in enhancing maize quality. The application of biotechnological tools can lead to the development of maize varieties with improved nutritional profiles, such as higher protein and starch contents. For example, the use of nitrogen fertilizers, a common biotechnological intervention, has been shown to alter the amino acid balance in maize, thereby affecting its nutritional value (Mason and D'croz-Mason, 2002). Furthermore, the integration of biotechnological innovations with sustainable agronomic practices can help mitigate the ecological impacts of traditional farming methods, promoting a more balanced and environmentally friendly approach to maize production (Nemade et al., 2023).

In summary, while genetic technologies have contributed to maize yield improvements, their impact is relatively modest compared to agronomic practices and climate trends. Precision agriculture and biotechnological interventions offer promising avenues for enhancing maize protein and starch contents, thereby supporting sustainable crop production and food security.

7 Case Studies

7.1 Case study on fertilization practices

Fertilization practices play a crucial role in determining the protein and starch contents of maize. Research has shown that nitrogen fertilizer application significantly influences maize grain quality. Higher nitrogen application rates can alter the amino acid balance, thereby reducing the nutritional value of the protein, while also increasing kernel breakage susceptibility and kernel density. However, excessive nitrogen fertilization can deteriorate grain-filling characteristics and reduce yield (Mason and D'croz-Mason, 2002; Yu et al., 2021). Optimal nitrogen rates promote endogenous hormone balance, improving grain-filling characteristics and ultimately increasing grain yield (Yu et al., 2021). Additionally, integrated agronomic practices that include optimized fertilizer treatments have been shown to enhance nitrogen use efficiency and grain yield, particularly in fields with high soil fertility (Zhou et al., 2019).

7.2 Case study on irrigation management

Irrigation management is another critical factor influencing maize protein and starch contents. Proper irrigation practices have been found to improve the biological value of maize protein. Irrigation reduces kernel breakage susceptibility and kernel density, which are otherwise increased by higher nitrogen fertilizer application rates (Mason and D'croz-Mason, 2002). Moreover, irrigation can enhance the overall grain quality by maintaining an optimal moisture level, which is essential for the proper development of maize kernels. The balance between irrigation and fertilization practices is vital for achieving high-quality maize grain with desirable protein and starch contents.

7.3 Case study on integrated agronomic practices

Integrated agronomic practices (IAP) have been shown to significantly improve maize grain yield and quality. IAP strategies, which include optimal planting density, split fertilizer application, and subsoiling tillage, have been demonstrated to increase maize grain yield and nitrogen use efficiency under various soil fertility conditions (Zhou et al., 2019). These practices promote greater dry matter and nitrogen accumulation, leading to higher grain yields. Additionally, IAP can enhance root growth and development, which is crucial for nutrient uptake and overall plant health (Liu et al., 2017). By improving tillage models, optimizing fertilizer rates and periods, increasing planting density, and delaying harvest, IAP promotes hormone balance, improves grain-filling rates, and lengthens the active grain-filling period, ultimately increasing grain yield and quality (Figure 3) (Liu et al., 2017; Yu et al., 2021).

Yu et al. (2021) studied the effects of Integrated Agronomic Practices Management (IAPM) and different Nitrogen Application Rates (NAT) on the endogenous hormone content in summer maize grains. The results showed that the contents of IAA (indole-3-acetic acid) and ZR (zeatin riboside) significantly increased 10-30 days after pollination and then decreased. Both IAPM and NAT treatments significantly affected the levels of these hormones ($p < 0.05$). The GA3 (gibberellin) content peaked 20-30 days after pollination, while the ABA (abscisic acid) content peaked at 40 days after pollination. The effects of IAPM and NAT treatments on GA3 and ABA were not significant. In summary, integrated management practices and nitrogen application rates significantly influence the dynamic changes in endogenous hormones in summer maize, and appropriate management measures can optimize maize growth and development.

In summary, the integration of fertilization, irrigation, and other agronomic practices is essential for optimizing maize protein and starch contents. Each practice contributes uniquely to the overall quality and yield of maize, and their combined application can lead to significant improvements in grain quality and productivity.

8 Implications for Maize Production and Quality

8.1 Yield and nutritional quality

Agronomic practices have a significant impact on both the yield and nutritional quality of maize. Integrated agronomic practices (IAP), which include optimal planting density, split fertilizer application, and subsoiling tillage, have been shown to increase maize grain yield and nitrogen use efficiency (NUE) significantly. For instance, IAP increased maize grain yield by 25%~28% in low soil fertility fields and by 36%~37% in high soil fertility fields over two growing seasons (Zhou et al., 2019). Additionally, the application of nitrogen fertilizers has been found to increase protein concentration in maize, although it may alter the amino acid balance, potentially reducing the nutritional value (Mason and D'croz-Mason, 2002). Other agronomic measures, such as the use of N, P, K, and S fertilizers, can enhance the nutritional quality of maize by increasing protein and essential amino acid concentrations (Wang and Malhi, 2008).

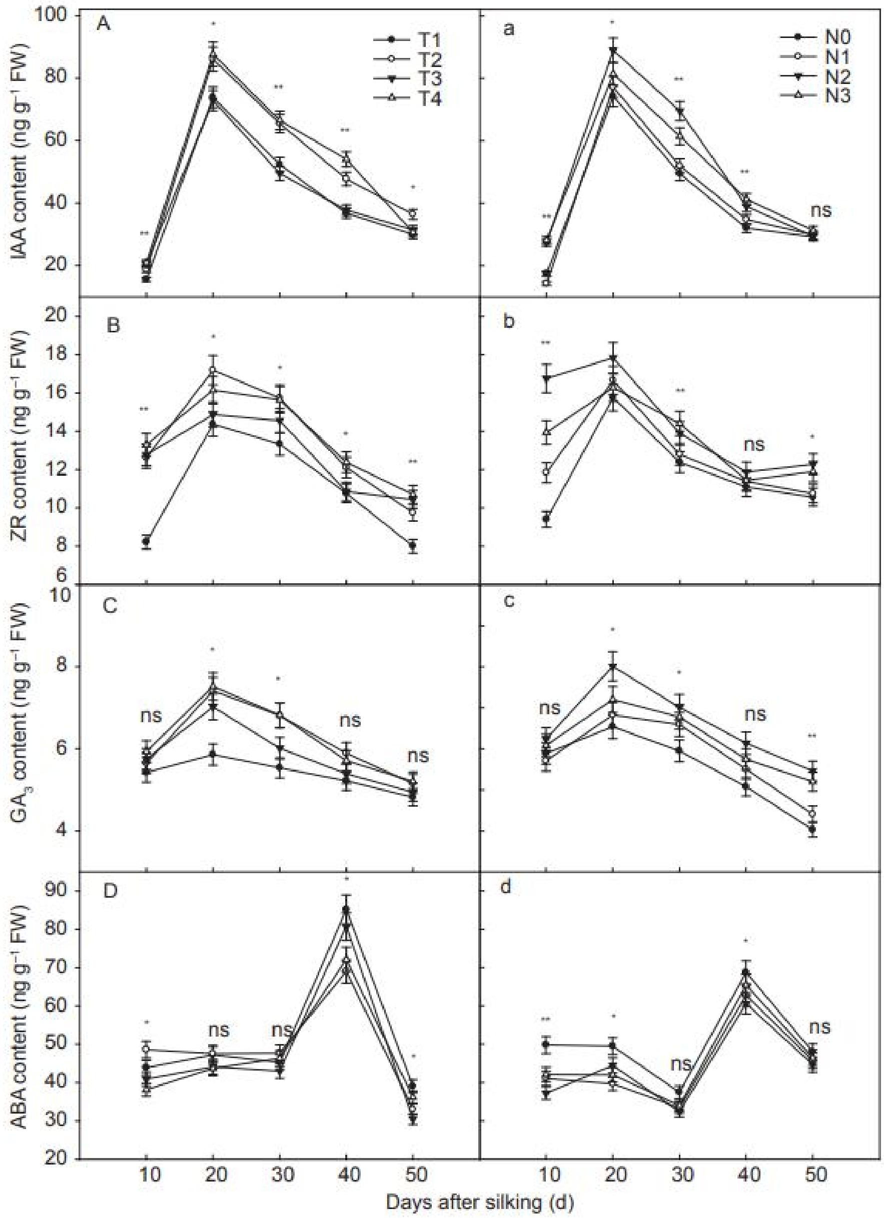

Figure 3 Effects of Integrated Agronomic Practices Management (IAPM) and Nitrogen Rate Testing (NAT) on endogenous hormone content in summer maize grains (Adapted from Yu et al., 2021)

Image caption: A-D: IAPM treatments, a-d: NAT treatments; IAPM (four treatments); T1: conventional cultivation; T2: based on T1, increase planting density, reduce nitrogen rate, increase phosphorus and potassium rates, adjust fertilization time and delay harvesting; T3: based on T2, further increase density and fertilizer for high yield; T4: based on T3, reduce density and fertilizer; NAT (four nitrogen levels): N0, 1 kg N ha^{-1}; N1: 129.0 kg N ha^{-1}; N2: 184.5 kg N ha^{-1}; N3: 300.0 kg N ha^{-1}, Standard Error (n=3); ns: no significant difference; ** and * indicate significant differences at the 0.01 and 0.05 probability levels, respectively (Adapted from Yu et al., 2021)

8.2 Economic impact

The economic implications of adopting improved agronomic practices are substantial. Enhanced yield and nutritional quality can lead to higher market value and better economic returns for farmers. For example, the use of agronomic biofortification, which involves the application of fertilizers containing essential mineral micronutrients, can increase the concentration of target minerals in maize, thereby improving its marketability and economic value (Augustine and Kalyanasundaram, 2021). Moreover, the reliance on improved agronomic practices rather than genetic modifications for yield gains suggests that investments in agronomic research and development could be more cost-effective and sustainable in the long run (Rizzo et al., 2022).

8.3 Recommendations for farmers

To maximize both yield and nutritional quality, farmers should consider adopting integrated agronomic practices tailored to their specific soil fertility conditions. Recommendations include:

1) Optimal Planting Density and Split Fertilizer Application: Implementing these practices can significantly increase grain yield and NUE, particularly in high soil fertility fields (Zhou et al., 2019).

2) Balanced Fertilization: Applying a balanced mix of N, P, K, and S fertilizers can enhance protein and essential amino acid concentrations in maize, improving its nutritional quality (Wang and Malhi, 2008).

3) Agronomic Biofortification: Utilizing fertilizers that contain essential mineral micronutrients such as iron and zinc can address micronutrient deficiencies in human diets and improve the economic value of maize (Augustine and Kalyanasundaram, 2021).

4) Irrigation Management: Proper irrigation can improve the biological value of protein and reduce kernel breakage susceptibility, thereby enhancing both yield and quality (Mason and D'croz-Mason, 2002).

By following these recommendations, farmers can achieve higher yields, better nutritional quality, and improved economic returns, contributing to sustainable maize production and food security.

9 Future Directions

9.1 Areas for further research

Future research should focus on understanding the intricate interactions between agronomic practices and maize protein and starch contents. While significant progress has been made, there are still gaps in our knowledge, particularly regarding the physiological and molecular mechanisms underlying these interactions. For instance, the role of integrated agronomic practices in enhancing nitrogen use efficiency and its subsequent impact on protein yield needs further exploration (Szulc et al., 2020; Zhou et al., 2019). Additionally, the effects of different fertilization modes on starch quality and its physicochemical properties warrant more detailed studies (Wang and Lu, 2022). Investigating the genetic diversity within maize starch pathways and how it can be leveraged to improve starch content and quality is another promising area (Whitt et al., 2002).

9.2 Potential innovations in agronomic practices

Innovations in agronomic practices hold great potential for improving maize protein and starch contents. Integrated agronomic practices, which include optimal planting density, split fertilizer application, and subsoiling tillage, have already shown promise in increasing maize yield and nitrogen use efficiency (Liu et al., 2017; Zhou et al., 2019). Further optimization of these practices, such as fine-tuning the timing and type of fertilizer application, could lead to even greater improvements. Additionally, the development and use of slow-release fertilizers could enhance starch quality by providing a more consistent nutrient supply (Wang and Lu, 2022). Exploring the use of advanced technologies, such as precision agriculture and remote sensing, to monitor and manage crop growth and nutrient status in real-time could also lead to significant advancements (Yu et al., 2020; Rizzo et al., 2022).

9.3 Policy and support for sustainable practices

To ensure the widespread adoption of sustainable agronomic practices, supportive policies and frameworks are essential. Governments and agricultural organizations should promote practices that enhance nitrogen use efficiency and reduce environmental impacts, such as integrated agronomic practices and the use of slow-release fertilizers (Liu et al., 2018; Zhou et al., 2019). Providing incentives for farmers to adopt these practices, such as subsidies or tax breaks, could accelerate their implementation. Additionally, investing in research and development to further refine these practices and develop new innovations is crucial. Policies should also focus on education and training programs to equip farmers with the knowledge and skills needed to implement sustainable practices effectively (Arodudu et al., 2017). Finally, fostering collaboration between researchers, policymakers, and farmers can help ensure that research findings are translated into practical, on-the-ground solutions (Szulc et al., 2020;Yu et al., 2020; Rizzo et al., 2022).

By addressing these areas, future research and policy efforts can significantly enhance the protein and starch contents of maize, contributing to improved food security and sustainability.

10 Concluding Remarks

The systematic review on the influence of agronomic practices on maize protein and starch contents has revealed several critical insights. Integrated agronomic practices management (IAPM) significantly enhances grain yield and quality by optimizing hormone balance and improving grain-filling characteristics. The application of nitrogen fertilizer, while beneficial to yield, must be carefully managed to avoid negative impacts on protein concentration and amino acid balance. Additionally, IAPM has been shown to increase nitrogen use efficiency (NUE) and dry matter accumulation, particularly in high soil fertility conditions. Root growth and development are also positively influenced by IAPM, contributing to higher grain yields.

Agronomic practices play a crucial role in determining the quality of maize grain. The choice of practices such as optimal planting density, split fertilizer application, and subsoiling tillage can significantly impact the protein and starch contents of maize. For instance, higher nitrogen application rates can improve kernel density and reduce breakage susceptibility, but excessive nitrogen can lower the nutritional value of the protein. Integrated practices that balance hormone levels and enhance root development are essential for achieving high-quality maize with optimal protein and starch contents.

In conclusion, the adoption of integrated agronomic practices is vital for improving both the yield and quality of maize. Future research should focus on fine-tuning these practices to maximize their benefits while minimizing any adverse effects. It is recommended that farmers adopt a holistic approach to agronomic management, considering factors such as soil fertility, nitrogen application rates, and root development. By doing so, they can achieve sustainable increases in maize yield and quality, ultimately contributing to food security and agricultural 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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