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Maize in Global Food Security: Role and Challenges

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Abstract Maize plays a critical role in global food security due to its significance as a staple crop and its various applications in agriculture. This study examines the historical and modern advancements in maize production, the challenges faced, and the environmental impacts associated with its cultivation. It discusses traditional classifications and uses of maize, significant changes in production and consumption, and the introduction of modern agricultural technologies. It also addresses genetic improvement, precision agriculture, and digital management techniques. The challenges section highlights agronomic, economic, market, social, and political issues affecting maize production and consumption. Furthermore, this study analyzes sustainable agricultural practices and the impact of maize production on biodiversity and climate change. Innovations and solutions, including policy support and community-based approaches, are proposed to overcome these challenges. Case studies of successful maize production systems and lessons learned from various regions are presented. This study concludes with future research directions, policy recommendations, and the application of cutting-edge technologies in maize production and aims to provide a framework for enhancing maize's role in global food security.
Keywords Maize; Food security; Agricultural technology; Sustainable farming; Environmental impact

1 Introduction

Maize (*Zea mays*), commonly known as corn, is one of the most significant staple crops globally. It is characterized by its erect green stalk and kernels, which are storage organs containing essential components for plant growth and reproduction. These components, including starch, protein, and micronutrients, are crucial for human health, making maize a vital part of global agriculture and human diets (Nuss and Tanumihardjo, 2010). Historically, maize has been integrated into various cultural traditions and agricultural practices worldwide, particularly in regions such as sub-Saharan Africa, Southeast Asia, and Latin America, where it serves as a primary food source.

Maize plays a critical role in global food security due to its widespread cultivation and consumption. It is a cornerstone crop not only for human nutrition but also for animal feed and biofuel production, aligning with the Sustainable Development Goals (SDGs) to support nutritious food production for healthy populations (Tanumihardjo et al., 2020). The crop's significance is further underscored by its contribution to the stability and availability dimensions of food security, particularly in Africa and Asia, where it is a major component of the cereal value chains. However, challenges such as land degradation, water scarcity, and climate change threaten maize production, necessitating innovations to maintain and increase productivity (Grote et al., 2021). Additionally, efforts to improve the nutritional quality of maize through biofortification and other agronomic approaches are ongoing to address malnutrition in regions heavily dependent on maize.

The study is to explore the role of maize in global food security and identify the challenges associated with its production and utilization. By examining various aspects of maize agro-food systems, this study provides a comprehensive understanding of how maize can contribute to achieving food and nutrition security in alignment with the SDGs, highlights the ecological and socio-economic drivers affecting maize value chains and propose strategies to overcome these challenges. Ultimately, this study seeks to inform future research and policy recommendations to enhance the sustainability and nutritional value of maize, thereby supporting global efforts to ensure food security for all.

2 Historical Perspective on Maize in Food Security

2.1 Traditional classification and uses of maize

Maize (*Zea mays*) has been a cornerstone of human nutrition and agriculture for centuries (de Souza Camacho et al., 2019). Traditionally, maize has been classified based on kernel type, such as dent, flint, sweet, and popcorn, each serving different culinary and agricultural purposes. In many regions, maize is a staple food, providing essential macronutrients and micronutrients necessary for human health. The cultural significance of maize is profound, particularly in areas like sub-Saharan Africa, Southeast Asia, and Latin America, where it forms a critical part of the diet and culinary traditions. Additionally, maize has been utilized in various forms, including whole kernels, flour, and processed products, to meet diverse dietary needs (Karnatam et al., 2023).

2.2 Major changes in maize production and consumption

Over the years, maize production and consumption have undergone significant transformations driven by technological advancements and changing global demands. The Green Revolution introduced high-yielding maize varieties, which significantly boosted production. However, ecological challenges such as land degradation, water scarcity, and climate change continue to impact maize production (Grote et al., 2021). Innovations in maize breeding, such as biofortification, have improved the nutritional profiles of maize, increasing its protein, provitamin A carotenoid, and zinc contents (Palacios-Rojas et al., 2020). Additionally, the demand for maize has expanded beyond human consumption to include its use in animal feed and biofuel production, aligning with the Sustainable Development Goals (SDGs) to support global food and nutrition security (Tanumihardjo et al., 2020).

2.3 Challenges faced in traditional agriculture

Traditional maize agriculture faces numerous challenges that hinder its potential to ensure food security (Chinthiya et al., 2019). In Sub-Saharan Africa, malnutrition persists despite high maize consumption, partly due to nutrient loss during processing and consumer preferences that do not always align with nutritional needs (Ekpa et al., 2019). Furthermore, the adoption of innovative agricultural practices is often constrained by limited access to seeds, finance, and education/training (Grote et al., 2021). The environmental impacts of traditional maize farming, such as nutrient mining and water resource depletion, also pose significant challenges (Karnatam et al., 2023). Addressing these issues requires a multifaceted approach, including the development of maize varieties tailored for specific uses, improved processing techniques, and enhanced farmer education and support systems. By understanding the historical context and evolving dynamics of maize production and consumption, researchers can better address the challenges and leverage opportunities to enhance maize's role in global food security (Ruanjaichon et al., 2021).

3 Modern Advancements in Maize Production

3.1 Introduction to modern agricultural technologies

Modern agricultural technologies have revolutionized maize production, significantly contributing to global food security. These advancements encompass a range of innovations, from improved farming practices to cutting-edge genetic techniques. The integration of these technologies aims to enhance productivity, sustainability, and resilience of maize crops, addressing the challenges posed by climate change, land degradation, and resource scarcity (Grote et al., 2021).

3.2 Genetic improvement and breeding techniques

Genetic improvement and breeding techniques have been pivotal in advancing maize production. Traditional breeding methods have been complemented by modern biotechnological approaches, such as Marker-Assisted Selection (MAS), Genomic Selection (GS), and CRISPR-Cas9. These techniques enable precise manipulation of maize genetics to enhance yield, disease resistance, and nutritional quality (Abideen et al., 2023). For instance, biofortification through traditional plant breeding has successfully increased the protein, provitamin A carotenoid, and zinc contents of maize, thereby improving its nutritional profile and contributing to better health outcomes for consumers (Palacios-Rojas et al., 2020).

3.3 Precision agriculture and digital management

Precision agriculture and digital management tools are transforming maize farming by optimizing resource use and improving crop management (Hua et al., 2019). These technologies include the use of GPS, remote sensing, and data analytics to monitor and manage field variability, ensuring efficient use of inputs such as water, fertilizers, and pesticides. By providing real-time data and predictive insights, precision agriculture helps farmers make informed decisions, ultimately enhancing productivity and sustainability (Grote et al., 2021). The adoption of these innovations, however, faces constraints such as access to seeds, finance, and education/training, which need to be addressed to fully realize their potential. In summary, modern advancements in maize production, encompassing agricultural technologies, genetic improvement, and precision agriculture, are crucial for enhancing global food security. These innovations not only improve the productivity and nutritional quality of maize but also ensure its sustainability and resilience in the face of environmental challenges (Ulrike et al., 2021).

4 Challenges in Maize Production and Consumption

4.1 Agronomic challenges

Maize production faces several agronomic challenges that impact its yield and sustainability. One significant issue is the adverse effects of climate change, which threaten agricultural productivity through unpredictable weather patterns and increased incidences of pests and diseases (Ekpa et al., 2019). Additionally, land degradation and water scarcity are critical ecological drivers that impair maize production. Soil fertility decline and the presence of the striga weed further exacerbate these challenges, particularly in regions like Sub-Saharan Africa. Innovations in maize breeding, such as biofortification and the development of drought-resistant varieties, are essential to address these agronomic issues and improve overall productivity (Palacios-Rojas et al., 2020).

4.2 Economic and market challenges

Economic and market challenges also play a significant role in maize production and consumption. Smallholder farmers, who are the primary producers of maize in many regions, often face financial constraints that limit their access to quality seeds, fertilizers, and other essential inputs (Grote et al., 2021). This economic barrier is compounded by the lack of access to education and training, which hinders the adoption of innovative farming practices. Furthermore, the market dynamics for maize are influenced by its dual role as a staple food and a key component in animal feed and biofuel production, leading to fluctuating demand and prices (Tanumihardjo et al., 2020). The negative perception of yellow maize as a "poor man's crop" and its association with food aid also affect its marketability and consumption, despite its superior nutritional value compared to white maize.

4.3 Social and political challenges

Social and political factors significantly impact maize production and consumption. In many regions, maize is deeply embedded in cultural practices and dietary preferences, which can influence its acceptance and utilization4. For instance, the preference for white maize over yellow maize in some African countries is driven by cultural norms and misconceptions about its nutritional value (Aguk et al., 2021). Political instability and inadequate policy support further exacerbate these challenges by disrupting supply chains and limiting investment in agricultural research and infrastructure. Addressing these social and political challenges requires comprehensive educational campaigns to change perceptions about maize varieties and robust policy frameworks to support sustainable maize production and consumption (Aguk et al., 2021). By understanding and addressing these agronomic, economic, market, social, and political challenges, stakeholders can work towards enhancing maize production and consumption, thereby contributing to global food security (Li et al., 2017).

5 Environmental Impacts of Maize Production

5.1 Sustainable agricultural practices

Sustainable agricultural practices are essential to mitigate the environmental impacts of maize production (Uffelmann et al., 2021). Aligning maize agro-food systems with the Sustainable Development Goals (SDGs) can support the production of nutritious maize while minimizing environmental degradation. Practices such as optimizing sowing windows and selecting appropriate cultivars can significantly enhance maize yields under varying climate conditions, thereby promoting sustainability (Figure 1) (Huang et al., 2020). Additionally, innovations in agricultural techniques, such as improved irrigation and nutrient management, are crucial for maintaining productivity and sustainability in maize farming (Farooq et al., 2023).

Huang et al. (2020) found that under both 1.5 °C and 2 °C warming scenarios, the potential sowing window for maize in China's Maize Belt shows variability across different regions. The optimal sowing dates, indicated by blue dots, aim to achieve the highest yields and demonstrate significant regional differences. The study highlights that the actual sowing dates recorded at agro-meteorological sites (green gaps) and the potential sowing windows (gray gaps) have some overlap, but there is a notable shift in the optimal sowing periods under the warming scenarios. Early-maturing maize cultivars (yellow gaps) and late-maturing cultivars (red gaps) present different optimal sowing windows, with the optimal dates for highest yield moving earlier as temperatures rise. This suggests a need for adjustments in sowing strategies to maintain maize productivity under future climate conditions.

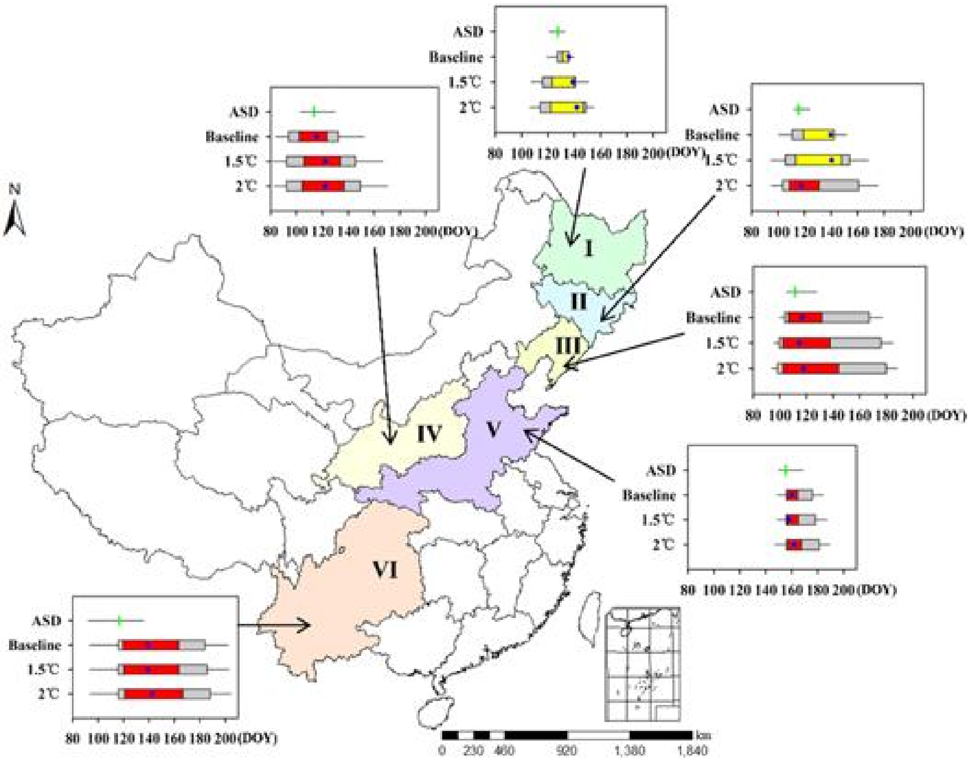

Figure 1 The actual sowing window (ASD) and the potential sowing window, the optimal sowing window and the optimal maize cultivar maturity across china's maize belt under the baseline scenario and the 1.5 °c and 2 °c warming scenarios (Adopted from Huang et al., 2020)

Image caption: DOY in the x-axes of the timeline plots represents day of year. The green gaps show the actual sowing window recorded at the agro-meteorological sites, and the whiskers around the green gaps represent the standard deviation of the actual sowing date. The gray gaps show the potential sowing window, and the whiskers around the gray gaps represent the standard deviation of the earliest and latest potential sowing dates. The red or yellow gaps show the optimal sowing window, and the yellow and red shadings represent the early- and late-maturing maize cultivars, respectively. The blue dots show the optimal sowing date with the highest yield (Adopted from Huang et al., 2020)

5.2 Impact on biodiversity and ecosystems

Maize production can have profound effects on biodiversity and ecosystems. The intensive use of land for maize cultivation often leads to habitat loss and a decline in biodiversity. Moreover, the monoculture nature of maize farming can reduce ecosystem resilience and increase vulnerability to pests and diseases. Sustainable practices, such as crop rotation and the integration of agroforestry, can help mitigate these impacts by enhancing biodiversity and ecosystem services (Tanumihardjo et al., 2020). It is also important to consider the ecological drivers, such as land degradation and water scarcity, which can further exacerbate the negative impacts on biodiversity (Grote et al., 2021).

5.3 Effects of climate change

Climate change poses significant challenges to maize production, with potential impacts on crop yields and food security. Increased temperatures and altered precipitation patterns can negatively affect maize yields, particularly in regions near the equator. However, in cooler regions, climate change may lead to increased yields due to higher carbon dioxide concentrations and extended growing seasons (Khanna, 2018). Adaptation strategies, such as adjusting sowing dates and developing climate-resilient maize varieties, are essential to mitigate the adverse effects of climate change on maize production. These strategies can help ensure the stability and availability of maize, thereby contributing to global food security (Grote et al., 2021). By implementing sustainable agricultural practices, protecting biodiversity, and adapting to climate change, the maize production system can be optimized to support global food security while minimizing its environmental footprint (Guo et al., 2023).

6 Innovations and Solutions

6.1 Innovations in agricultural technologies

Innovations in agricultural technologies are crucial for enhancing maize productivity and ensuring global food security. One significant advancement is the development of improved maize varieties, which have been shown to positively impact household food security. For instance, in South Africa, the adoption of improved maize varieties has led to increased food expenditure per capita, particularly benefiting female farmers who are more likely to adopt these varieties (Sinyolo, 2020). Additionally, biofortification through traditional plant breeding has increased the nutritional content of maize, enhancing its protein, provitamin A carotenoid, and zinc levels, which are essential for improving human nutrition and overall health (Palacios-Rojas et al., 2020). These innovations not only boost productivity but also contribute to better nutritional outcomes, thereby supporting food security (Cortes et al., 2021).

6.2 Sustainable farming methods

Sustainable farming methods are essential for maintaining the long-term productivity of maize while minimizing environmental impacts (Figure 2) (Gong et al., 2015). In the Eastern Himalayas, the integration of short-duration crops such as French beans into the maize-fallow system has proven to be highly effective. This system has demonstrated the highest productivity, energy efficiency, and economic profitability, while also reducing the carbon footprint compared to traditional maize-fallow systems (Babu et al., 2020). Such sustainable practices are vital for achieving a circular economy in agriculture and ensuring the environmental sustainability of maize production.

Gong et al. (2015) found that an ideal maize plant, or ideotype, should exhibit specific shoot and root traits to maximize productivity and resilience under changing climatic conditions. The shoot traits include optimal leaf angles to maximize light capture and uniform, moderate plant and ear height to facilitate mechanized harvesting and provide lodging resistance. Root traits are described as "steep, cheap, and deep," which suggests a root system designed to enhance water and nutrient uptake efficiently. This ideotype aims to improve the plant's overall stress resistance, ensuring that maize can maintain high productivity even as environmental conditions fluctuate. By adopting these traits, maize plants can better adapt to future agricultural challenges, contributing to sustainable crop production.

6.3 Policy and institutional support

Policy and institutional support play a critical role in facilitating the adoption of innovative agricultural technologies and sustainable farming methods. Policies that promote the dissemination of improved maize varieties, particularly targeting female farmers, can significantly enhance household food security. In South Africa, policy recommendations include facilitating access to less costly improved seed varieties and improving information dissemination to support the adoption of technological innovations among smallholder farmers (Sinyolo, 2020). Additionally, aligning maize agro-food systems with the Sustainable Development Goals (SDGs) can provide a comprehensive framework for ensuring food and nutrition security while addressing economic, environmental, and social dimensions (Tanumihardjo et al., 2020).

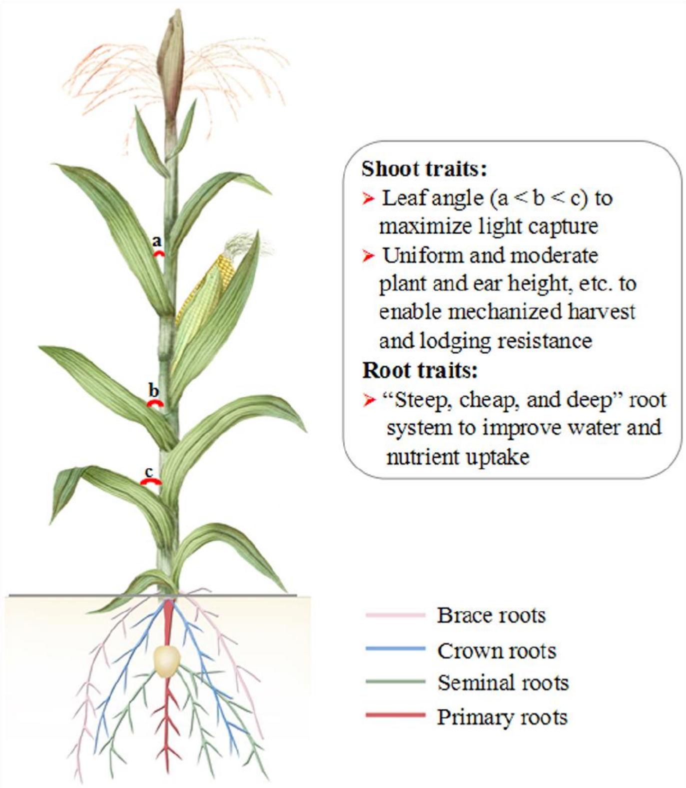

Figure 2 A diagram of proposed maize ideotype (Adopted from Gong et al., 2015)

Image caption: Maize ideotype plants will have improved shoot and roots traits and phenotype, enhanced stress resistance and maintain a high productivity in a changing climate (Adopted from Gong et al., 2015)

6.4 Community-based approaches

Community-based approaches are essential for fostering local engagement and ensuring the successful implementation of innovations and sustainable practices. Educational outreach to improve consumer knowledge about the nutritional benefits of maize can drive demand for biofortified varieties, thereby supporting market opportunities for producers. Moreover, addressing the constraints in adopting innovations, such as access to seeds, finance, and education/training, is crucial for empowering communities to enhance their food security (Grote et al., 2021). By involving local communities in the decision-making process and providing them with the necessary resources and knowledge, sustainable and resilient maize agro-food systems can be developed. In conclusion, a multifaceted approach involving technological innovations, sustainable farming methods, supportive policies, and community-based strategies is essential for enhancing the role of maize in global food security and addressing the associated challenges.

7 Case Studies

7.1 Successful maize production systems

Successful maize production systems have been identified in various regions, demonstrating the potential for high yields and sustainable practices (Liu et al., 2016). For instance, in China, optimizing the sowing window and selecting appropriate cultivars have shown significant yield improvements under climate change scenarios. By adjusting the sowing date and choosing late-maturing cultivars, maize yields increased by 11.1% to 53.9% under 1.5 °C and 2 °C warming scenarios, respectively. This adaptation strategy highlights the importance of tailored agricultural practices to enhance productivity in the face of global warming (Huang et al., 2020).

7.2 Case analysis of overcoming challenges

Overcoming challenges in maize production often involves addressing ecological and socio-economic constraints. In Africa and Asia, maize production is increasingly impaired by land degradation, water scarcity, and climate change (Figure 3) (Zheng et al., 2018). However, innovations such as improved seed varieties, better access to finance, and enhanced education and training have shown promise in maintaining and increasing productivity. These innovations are crucial for ensuring the availability and stability of maize, which in turn affects economic and physical access to this staple crop.

Zheng et al. (2018) found that significant spatial variations exist in maize production, yield, and water productivity across different regions globally. The meta-analysis of 360 locations shows that high maize production areas are concentrated in North America, China, and Brazil. However, yield per hectare varies considerably, with the highest yields observed in countries like the United States and France, while many regions in Africa and Asia show lower yields. Water productivity, which measures the efficiency of water use in maize production, also displays notable disparities. Some regions, particularly in South America and Europe, achieve high water productivity, whereas other areas, especially in Africa and parts of Asia, have much lower values. These findings highlight the potential for closing water productivity gaps to enhance food and water security, emphasizing the need for region-specific strategies to improve maize production efficiency globally.

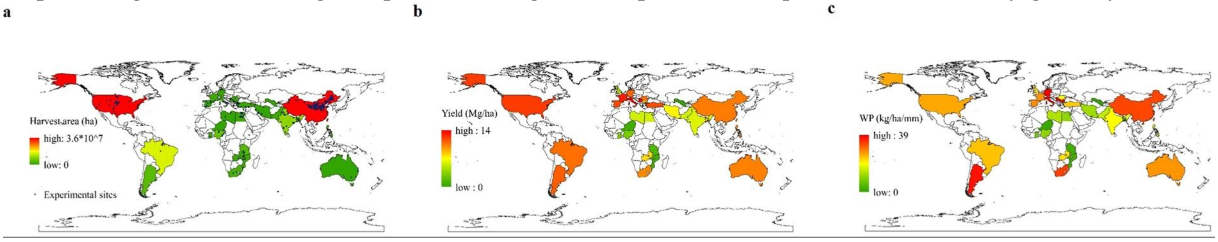

Figure 3 Closing water productivity gaps to achieve food and water security for a global maize supply (Adopted from Zheng et al., 2018)

Image caption: (a) Location of study sites in the meta-analysis (n = 360 locations) and spatial variation in maize production areas, (b) Spatial variation in maize yield based on averages per country (n = 31), (c) Spatial variation in water productivity based on averages per country (n = 31) (Adopted from Zheng et al., 2018)

7.3 Experiences and lessons from typical regions

Experiences from different regions provide valuable lessons for improving maize production systems globally (Hao et al., 2018). In the context of the Sustainable Development Goals (SDGs), the maize agro-food system plays a critical role in ensuring food and nutrition security. Aligning maize production with the SDGs involves not only increasing yields but also promoting sustainable practices that support human health and environmental sustainability. This holistic approach underscores the importance of integrating multiple disciplines to address the complex challenges of global food security (Tanumihardjo et al., 2020). By examining these case studies, it becomes evident that successful maize production systems require a combination of innovative agricultural practices, overcoming ecological and socio-economic challenges, and aligning with broader sustainability goals. These insights can guide policymakers and stakeholders in developing strategies to enhance maize production and contribute to global food security (Sahito et al., 2024).

8 Future Directions

8.1 New directions in research and development

The future of maize research and development must address the multifaceted challenges posed by climate change, land degradation, and the need for sustainable agricultural practices. Innovations in crop breeding, such as the development of new integrative omics tools, advanced genome editing, and synthetic biology, are essential for designing future crops that can withstand environmental stresses and improve productivity (Tian et al., 2020). Additionally, there is a need to focus on the nutritional enhancement of maize through biofortification, which has shown promise in increasing the protein, provitamin A carotenoid, and zinc contents of maize (Palacios-Rojas et al., 2020). Research should also explore the optimization of sowing windows and cultivar choices to adapt to varying climatic conditions, as demonstrated by studies in China's Maize Belt (Huang et al., 2020).

8.2 Policy recommendations and international cooperation

To ensure global food security, it is crucial to develop policies that support sustainable maize production and address the socio-economic barriers to innovation adoption. Policies should facilitate access to quality seeds, finance, and education/training for farmers. International cooperation is vital to share knowledge, technologies, and best practices across borders. Collaborative efforts can help mitigate the impacts of climate change on maize production and promote the equitable transformation of food systems (Grote et al., 2021). Aligning maize agro-food systems with the Sustainable Development Goals (SDGs) can further enhance food and nutrition security globally (Guo et al., 2019).

8.3 Application of cutting-edge technologies in maize production

The application of cutting-edge technologies in maize production is pivotal for achieving sustainable agriculture. The use of advanced genome editing tools and synthetic biology approaches can accelerate the development of maize varieties that are resilient to biotic and abiotic stresses. Additionally, the integration of molecular and genetic mechanisms into agricultural practices can improve crop yields and ensure food security (Tyczewska et al., 2018). Optimizing agricultural strategies, such as adjusting sowing dates and selecting appropriate cultivars, can significantly boost maize yields under different climate scenarios (Shiferaw et al., 2011). These technological advancements must be supported by robust research and development frameworks to maximize their potential benefits.

9 Concluding Remarks

Maize plays a critical role in global food security, serving as a staple crop for billions of people worldwide. However, its production faces numerous challenges, including pest infestations, climate change, and socio-economic factors. Postharvest losses due to insect pests like the maize weevil and large grain borer can reach up to 40% in developing countries, highlighting the need for insect-resistant varieties and improved storage solutions. Additionally, the maize agro-food system's alignment with the Sustainable Development Goals (SDGs) underscores its importance in ensuring food and nutrition security. In regions like Central Malawi, maize production is hindered by factors such as climate change, land degradation, and high input costs, necessitating policy reviews and sustainable practices to enhance productivity. Conservation agriculture has shown potential in increasing maize yields and nutrient content, although it may exacerbate certain nutrient deficiencies. Climate change poses a significant threat to maize yields, with projections indicating substantial yield reductions under increased global temperatures. Furthermore, emerging diseases like Maize Lethal Necrosis (MLN) present additional risks to maize-based food security in Sub-Saharan Africa.

Continued research is essential to address the multifaceted challenges facing maize production and its role in global food security. Developing insect-resistant maize varieties and improving storage techniques can significantly reduce postharvest losses. Research into the impacts of climate change on maize yields and the efficacy of adaptation methods is crucial for mitigating future risks. Additionally, exploring the genetic diversity of maize and enhancing its nutritional profile through biofortification can improve food and nutrition security. Understanding the effects of conservation agriculture on nutrient yields and addressing potential nutrient deficiencies will be vital for sustainable agricultural practices. Collaborative efforts to manage emerging diseases like MLN and improve disease-resistant germplasm are also critical. Overall, a coordinated approach to research and knowledge sharing can enhance the resilience and productivity of maize, ensuring its continued contribution to global food security.

Maize remains a cornerstone of global food security, providing essential calories and nutrients to billions of people. However, its production is increasingly threatened by biotic and abiotic stresses, socio-economic challenges, and climate change. Addressing these issues requires a multifaceted approach, including the development of resilient maize varieties, sustainable agricultural practices, and effective policy interventions. Continued research and innovation are paramount to overcoming these challenges and ensuring that maize can meet the growing food demands of the future. By leveraging scientific advancements and fostering international collaboration, we can enhance the sustainability and resilience of maize production, securing its role in global food security for generations to come.

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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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