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Insights into Environmental Factors Affecting Maize Growth

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Abstract This study systematically explores the impact of various environmental factors on maize growth, focusing on the roles of climate, soil characteristics, and biotic interactions in maize yield and health. The findings indicate that temperature fluctuations and changes in precipitation patterns due to climate change, particularly heat and drought stress, pose significant challenges to maize growth. Additionally, soil nutrient content and pH directly affect root development and water-use efficiency, impacting crop health and productivity. Biotic factors, such as pests, diseases, and beneficial microbes, also have a substantial influence on maize growth. A practical case study from Wushanxia Village, Zhejiang Province, demonstrates that integrating high-quality fresh maize varieties with advanced irrigation, fertilization, and conservation tillage practices can not only stabilize yields and improve product quality but also significantly enhance farmers' income. This research provides both a theoretical foundation and practical insights for optimizing maize management strategies to support global food security.
Keywords Maize growth; Environmental factors; Climate impact; Sustainable agriculture; Soil management

1 Introduction

Maize (*Zea mays* L.), as one of the world's major staple crops, plays a crucial role in food security and agricultural sustainability, particularly in developing regions where it serves as a primary food source and an essential component of human and animal nutrition (Tanumihardjo et al., 2020). Globally, maize also supports economic development through its applications in food, animal feed, and biofuel industries, underlining its importance beyond nutrition. Understanding the environmental factors that affect maize growth is vital to ensuring its productivity and stability, given its dependence on various climatic, soil, and biotic conditions. Maize yields are vulnerable to environmental stressors such as climate change, drought, soil nutrient depletion, and pest pressures, which threaten its productivity and thus global food security.

The significance of studying environmental impacts on maize growth lies in the potential for developing adaptive strategies that can mitigate yield losses and enhance resilience. As climate change introduces increased temperature fluctuations, altered rainfall patterns, and more frequent extreme weather events, understanding these effects on maize production is essential for sustaining crop yields and supporting agricultural policy and planning (Andrea et al., 2019). By identifying key environmental challenges and their impact on growth, researchers and farmers can adopt practices that optimize productivity and align with sustainable development goals.

This study will comprehensively analyze the environmental factors influencing maize growth, including direct environmental stresses and socioeconomic influences. In addition to reviewing global literature, it incorporates a real-world example from Wushanxia Village, Zhejiang Province, where the adoption of high-quality fresh maize varieties, coupled with precision irrigation, balanced fertilization, and conservation tillage, has not only stabilized grain production but also achieved high market value, thereby demonstrating the synergy between environmental adaptation and rural economic development.

2 Climatic Factors Influencing Maize Growth

2.1 Temperature and its impact on maize growth

Temperature is a critical climatic factor that directly affects maize growth and physiological processes. The optimal temperature range for maize growth is generally between 24 ℃-30 ℃, within which photosynthetic efficiency and dry matter accumulation are ideal (Feng, 2024). However, deviations from this range, especially extreme heat, disrupt the balance between photosynthesis and respiration, ultimately reducing yields. Studies in northern regions indicate that moderate temperature increases during planting and seedling stages can promote growth, but extreme high temperatures during the grain-filling stage can significantly reduce grain-filling rates, thus impacting yield quality (Qi et al., 2022).

Heat stress not only affects photosynthesis but also induces oxidative stress, which can damage cell structures. Under extreme heat, maize plants exhibit symptoms like leaf wilting and stunted growth, compromising overall plant development. Research from the Brazilian Cerrado shows that projected temperature increases due to climate change may drastically reduce maize dry matter accumulation, particularly during reproductive stages, thereby lowering yields (Camilo et al., 2018).

Additionally, elevated nighttime temperatures can negatively impact maize by increasing respiratory activity, leading to greater energy expenditure at night that could otherwise be stored through photosynthesis. Studies in Northeast China reveal that sustained high nighttime temperatures increase nighttime energy loss in maize, suppressing net photosynthate accumulation and ultimately affecting yields. Developing varieties that can tolerate high nighttime temperatures could be a strategy to address this challenge (Zhang et al., 2022).

2.2 Precipitation and water availability for maize

Water availability is crucial for maize, especially during sensitive stages like flowering and grain filling, when maize demands substantial water. Precipitation is the primary water source, and its distribution and seasonality significantly impact water supply. Studies in the Czech Republic have shown that summer rainfall, especially in July, is positively correlated with maize yield. Increased rainfall during this period promotes grain formation and yield, whereas water deficits lead to yield reductions, underscoring the importance of sufficient rainfall during critical growth stages (Maitah et al., 2021).

In drought-prone regions, irrigation is an effective measure to alleviate water shortages, particularly during maize's flowering and grain-filling stages. Research in Northeast China shows that drought stress during flowering can have the most severe impact on maize yield, highlighting the importance of irrigation during these critical stages. In areas with limited water resources, using drought-resistant varieties and optimizing irrigation can improve productivity (Yin et al., 2015).

However, extreme changes in rainfall patterns, such as heavy or uneven distribution, can adversely affect root development and water use in maize. Studies in Central Europe indicate that excessive soil moisture from concentrated rainfall can hinder root respiration, while prolonged drought limits water supply during flowering and grain filling, severely impacting yield. Adapting water management strategies to changing precipitation patterns is crucial to ensuring that maize receives adequate water under various climate conditions (Tang and Liu, 2020).

2.3 Solar radiation and photoperiod on maize development

Solar radiation is the primary energy source driving photosynthesis, directly influencing biomass accumulation and yield potential in maize. Research in Northeast China has shown that increased solar radiation during the grain-filling stage promotes kernel development and increases grain weight, partially offsetting the adverse effects of high temperatures on yield. This indicates that under optimal solar radiation, maize achieves better growth outcomes (Wei et al., 2023).

The length of daylight, or photoperiod, also influences maize growth patterns. Maize varieties adapted to specific regions often exhibit photoperiod sensitivity, with longer daylight hours promoting robust vegetative growth. In Central China, summer maize benefits from extended daylight and higher radiation, forming a strong plant structure. However, excessive radiation and high temperatures during the grain-filling period can hinder kernel filling, ultimately reducing yield (Ge et al., 2022).

In regions with ample sunlight but lower temperatures, such as the highlands of Southwest China, solar radiation is particularly crucial during the early and mid-stages of maize growth. High photosynthetic efficiency in these stages is essential for biomass accumulation. However, if radiation levels are too high in later stages, premature maturation may occur, shortening the grain-filling period and reducing kernel weight. Adjusting planting dates and selecting varieties adapted to specific light conditions can optimize maize yield in these regions (Tang and Liu, 2020).

3 Soil Characteristics and Their Role in Maize Growth

3.1 Soil nutrient content essential for maize

Nutrient-rich soil is vital for robust maize growth, as key nutrients such as nitrogen (N), phosphorus (P), and potassium (K) are foundational for plant development. In East Africa, studies have shown that nutrient deficiencies in phosphorus and potassium directly limit maize growth and yield, particularly in nutrient-poor soils where targeted fertilization can dramatically enhance productivity (Fischer et al., 2020). Ensuring an adequate supply of these macronutrients is essential, as they play distinct roles: nitrogen promotes leaf growth, phosphorus supports root development, and potassium enhances drought resistance and disease resilience.

Beyond macronutrients, micronutrients such as zinc (Zn) and iron (Fe) are also essential. In Himalayan maize-growing regions, a survey indicated widespread deficiencies in zinc and copper, both crucial for enzymatic activity and protein synthesis in plants (Khaliq et al., 2021). Addressing micronutrient deficiencies through soil amendments or foliar sprays can improve maize health and yield, supporting better growth outcomes in areas where soil nutrient levels are suboptimal.

Soil organic matter (SOM) enhances nutrient availability, particularly in sandy or low-fertility soils. Organic matter improves soil structure, increases water retention, and serves as a nutrient reservoir, releasing nitrogen, phosphorus, and other nutrients as it decomposes. Long-term fertilization and organic amendments, like cow manure or compost, have been shown to increase nutrient availability and yield in maize by enhancing the soil’s organic content (Saifulloh and Suntari, 2022).

3.2 Influence of soil pH on maize nutrient uptake

Soil pH significantly affects nutrient uptake by influencing nutrient solubility and microbial activity. Maize generally prefers slightly acidic to neutral pH levels, around 5.5 to 7.5. In alkaline soils, essential nutrients like phosphorus become less available, impacting maize growth and yield. Experiments using pH-lowering amendments, such as sulfur, have shown improved nutrient uptake and growth in alkaline soils by making phosphorus and other nutrients more bioavailable (Ansori and Gholami, 2015).

Acidic soils, common in high-rainfall areas, often result in aluminum toxicity, which can damage root systems and inhibit nutrient absorption. Biochar and lime amendments have proven effective in reducing soil acidity, which increases pH levels and reduces aluminum concentration, thus enhancing root growth and nutrient availability (Pandit et al., 2018). This adjustment allows maize plants to access a broader range of nutrients and promotes healthier plant growth.

Microbial inoculants, such as mycorrhizal fungi, also help maize plants in nutrient-poor or pH-imbalanced soils. Mycorrhizal associations expand root surface area, enhancing nutrient absorption even in soils with suboptimal pH levels. Studies have shown that mycorrhizae significantly increase maize uptake of phosphorus, potassium, and other key nutrients, which can mitigate the adverse effects of both low and high pH soils (Silva et al., 2016).

3.3 Soil texture and its impact on maize water retention

Soil texture, which refers to the proportion of sand, silt, and clay particles, directly influences water retention and root penetration, affecting maize’s water and nutrient availability. Sandy soils drain quickly and are prone to nutrient leaching, necessitating more frequent irrigation and fertilization. In contrast, clay soils retain water well but may restrict root growth due to compaction. Studies in hilly zones of Karnataka revealed that sandy clay loam textures support maize by balancing drainage and water retention, making nutrients more accessible during critical growth stages (Niranjana et al., 2018).

Fine-textured clay soils, while high in nutrient content, can become compacted, reducing root growth and impeding oxygen movement. Practices such as tillage or the addition of organic matter can improve aeration and structure in clay soils, making them more conducive to maize root development. Long-term studies in chernozem soils indicate that periodic tillage and residue management enhance root expansion and nutrient absorption, improving maize productivity on clay-dense soils (Wang et al., 2021).

Sandy soils can benefit from biochar additions, which improve water retention and reduce nutrient leaching. Biochar has shown promising results in enhancing water-holding capacity and nutrient retention, particularly phosphorus, making sandy soils more suitable for maize cultivation. Studies have demonstrated that biochar amendments can significantly increase maize growth and yield by improving soil texture and water availability, even in low-input environments (Rafique et al., 2019).

4 Biotic Interactions Affecting Maize Growth

4.1 Pests and pathogens impacting maize

Maize is susceptible to various pests, including root-feeding larvae and foliar herbivores, which can cause significant crop losses. For instance, Phyllophaga vetula larvae are notorious for damaging maize roots, impacting nutrient uptake and plant growth. Studies suggest that integrating entomopathogenic fungi like Beauveria bassiana with native mycorrhizal fungi can enhance maize's resilience by promoting plant growth despite root herbivory, thus helping counterbalance the effects of pests (Zitlalpopoca-Hernandez et al., 2017).

Pathogens such as fungi, bacteria, and viruses also pose threats to maize, affecting both ear and foliar health. For example, pathogens like Fusarium and Aspergillus can reduce yield and produce mycotoxins that contaminate crops. New research focuses on using atoxigenic strains of fungi to biologically control aflatoxin-producing Aspergillus flavus, which has shown success in limiting contamination in maize fields (Spadola et al., 2022).

Biological control agents, including microbial antagonists, have been developed as eco-friendly alternatives to chemical fungicides. Beneficial microbes can inhibit pathogens by competing for resources, producing antifungal compounds, or directly attacking pathogens through enzymatic activity. For example, Trichoderma species are commonly used as biocontrol agents against fungal diseases in maize (Kim et al., 2022).

4.2 Beneficial microorganisms supporting maize

Beneficial microorganisms, such as mycorrhizal fungi and plant growth-promoting bacteria (PGPB), contribute to maize growth by enhancing nutrient uptake, promoting stress tolerance, and protecting against pathogens. Mycorrhizal fungi, particularly arbuscular mycorrhizal fungi (AMF), improve phosphorus absorption in maize, supporting healthier and more robust growth. Studies have shown that AMF inoculation increases maize shoot biomass and nutrient levels even in saline soils, helping maize tolerate environmental stresses (Moreira et al., 2019).

PGPB, such as *Azospirillum brasilense* and *Pseudomonas fluorescens*, enhance maize productivity by fixing nitrogen, producing growth hormones, and synthesizing enzymes that support plant health. Field studies indicate that inoculating maize with these bacteria can increase grain yield and improve rhizosphere microbial diversity, showing their potential in sustainable agriculture (Salvo et al., 2018).

Synergistic effects occur when AMF and PGPB are used together. Co-inoculation of maize with these microorganisms has been shown to enhance root and shoot growth more effectively than either alone, as each provides unique benefits that complement the other. The combination enhances nutrient uptake, supports drought tolerance, and reduces pathogen susceptibility, creating a more resilient growth environment for maize (Prasanna et al., 2016).

4.3 Weed competition and its effects on maize growth

Weeds compete with maize for resources such as light, water, and nutrients, often leading to reduced crop yield. High weed density increases cultivation costs, lowers soil nutrient availability, and impacts maize quality. For instance, weed competition in maize fields has been found to decrease maize yield by up to 50% if left unmanaged, illustrating the necessity of effective weed control strategies (Varshitha et al., 2019).

Weeds not only compete for resources but also influence the microbial communities within the soil. Research has shown that certain weed species can alter the rhizosphere microbiota, which can indirectly support or inhibit maize growth depending on the interaction dynamics. For example, in controlled studies, the presence of Bidens pilosa or Amaranthus viridis facilitated maize growth by positively influencing soil microbial communities, showing that some weeds can have beneficial effects under certain conditions (Matos et al., 2019).

Herbicide management remains a common weed control approach; however, repeated herbicide use can reduce soil biological activity. Early post-emergent herbicide applications, when timed correctly, can control weeds effectively without substantially affecting soil microorganisms, thus supporting maize growth while preserving soil health. Integrating these practices with crop rotation and manual weeding can further minimize herbicide reliance and optimize maize productivity (Varshitha et al., 2019).

5 Case Study: Comprehensive Impact of Agricultural Practices on Maize Growth and Industrial Benefits

5.1 Case background

From early April 2022 to August 2025, Wushanxia Village in Wangzhai Town, Wuyi County, Zhejiang Province actively introduced and promoted high-quality fresh maize varieties, including Zheke Sweet No. 4, Zheke Sweet No. 6, Zhehong Sweet, Zheke Glutinous 101, Zheke Glutinous No.2, Zheke Mi 998, and Zhecainuo 474 (Figure 1). The total planting area reached 468 mu (≈31.2 hectares). The average fresh ear yield was about 1 000 kg per mu, and due to their excellent quality, the market price remained above 6 yuan/kg. The net profit per mu per season reached around 4 000 yuan. This practice not only stabilized local grain production but also created a sustainable path for increasing villagers’ income.

Figure 1 Shows the cultivation of high quality fresh corn (Photo by Keli Wang)

Fresh maize is a distinctive agricultural product that combines taste, nutrition, and economic value. Its core qualities are sweetness, stickiness, tenderness, and fragrance. It is mainly categorized into three types—sweet maize, glutinous maize, and sweet-glutinous maize-and can be marketed as fresh ears, frozen products, or vacuum-packed products to meet diverse consumer needs. Key factors for successful production include high-quality variety selection, strict isolation planting, precise water and nutrient management, timely harvesting, and efficient post-harvest handling. The Wushanxia Village case demonstrates how the integration of advanced agricultural technologies and premium variety promotion can significantly boost industrial upgrading and farmer income.

5.2 Optimization of irrigation techniques and practical outcomes

In maize cultivation, scientific irrigation is essential for improving water use efficiency and increasing yields. In fresh maize production, Wushanxia Village adopted drip irrigation combined with fertigation, delivering water and nutrients directly to the root zone to minimize resource waste. Similar studies have shown that in Northeast China, this technique increased maize yields by 41% in sandy soils and 17% in clay soils (Wu et al., 2019).

Furthermore, regulated deficit irrigation—reducing water supply during periods of low maize water demand and ensuring adequate water during flowering and grain-filling stages—has been shown to save water without reducing yields. In arid regions, combining this method with no-till farming and plastic film mulching increased soil water use efficiency and yield by 15%-22% even with a 20% reduction in irrigation volume (Guo et al., 2019). Wushanxia Village applied similar strategies in certain plots to optimize irrigation efficiency. Internationally, sensor-based technologies such as GreenSeeker have shown great potential in combining irrigation and nitrogen management. In trials conducted in India, nitrogen management guided by GreenSeeker, coupled with proper irrigation, increased maize yield to 6.9 t/ha compared with traditional practices. Such technologies offer future opportunities for Wushanxia Village to further improve water-nutrient use efficiency.

5.3 Fertilization strategies and nutrient management for yield improvement

In Wushanxia Village, fresh maize production applied a combined approach of organic and inorganic fertilizers to enhance soil fertility and maintain high yields. Studies in Ghana have shown that this approach can increase maize yields by 37.7% (Ghanney et al., 2020). Certain plots in the village also experimented with combining farmyard manure and NPK fertilizers to boost soil microbial activity and nutrient availability. Globally, conservation tillage combined with precision fertilization tools such as Nutrient Expert has been proven to increase yields by 13%-18% and improve soil biochemical properties (Pramanick et al., 2022). In Ethiopia, conservation agriculture combined with balanced fertilization improved maize yields by 54%-62% compared with traditional methods (Ayele and Petrous, 2022). These practices provide a solid basis for Wushanxia Village to implement digitalized nutrient management in the future.

5.4 Sustainable tillage and soil conservation practices

Conservation tillage practices—such as no-till farming, minimum tillage, and crop residue mulching—play a key role in improving soil structure, retaining moisture, and reducing erosion. In certain sloped plots, Wushanxia Village experimented with straw incorporation and no-till farming to reduce soil loss and increase organic matter content. Research in the Loess Plateau of China has shown that no-till farming combined with deep loosening and proper fertilization can significantly improve yield stability and reduce fertilizer loss in semi-arid areas (Zhang et al., 2018). In Nepal's rice-maize rotation systems, residue mulching with conservation tillage improved soil structure and water retention, leading to more stable yields. In northern China, no-till farming combined with straw return and optimal nitrogen application reduced N_2O emissions while maintaining high maize yields, achieving a balance between climate change mitigation and productivity (Tan et al., 2019).

6 Impacts of Climate Change on Maize Growth and Adaptation Strategies

6.1 Rising temperatures and heat stress on maize

Climate change-induced temperature increases are leading to more frequent and intense heat stress events, which significantly impact maize growth and productivity. The figure demonstrates how temperature sensitivity varies across regions, highlighting areas where rising temperatures have a pronounced effect on dry matter accumulation (Kim et al., 2022). High temperatures are particularly disruptive during critical growth stages, such as pollination and grain filling, where heat stress reduces pollen viability, silk receptivity, and overall seed set. Research has shown that in regions experiencing temperatures above 35 ℃, maize yield gains diminish substantially, as seen in studies conducted in the U.S. (Thomas, 2015).

In addition to affecting yield, elevated temperatures impair key physiological processes in maize, such as photosynthesis and respiration, resulting in reduced biomass accumulation and diminished crop quality. The figure's depiction of temperature sensitivity supports this, showing that areas with higher SEN_{Tavg} values are more susceptible to biomass losses under heat stress (Kim et al., 2022). Prolonged exposure to high temperatures accelerates plant senescence, further reducing productivity, with yield losses estimated to reach up to 30% in regions facing sustained heat stress (Himani et al., 2022).

To mitigate heat stress, adaptation strategies such as the application of biochar soil amendments have been effective. Biochar improves soil water retention, buffering maize plants against temperature fluctuations and reducing the impact of heat stress. Studies indicate that biochar helps maintain lower soil and canopy temperatures, thereby enhancing photosynthetic efficiency and overall productivity under high-temperature conditions. The figure's spatial distribution of temperature sensitivity underscores the importance of targeted adaptation strategies, especially in regions with high temperature sensitivity indices, to stabilize maize production amidst rising temperatures (Figure 2) (Wei et al., 2023).

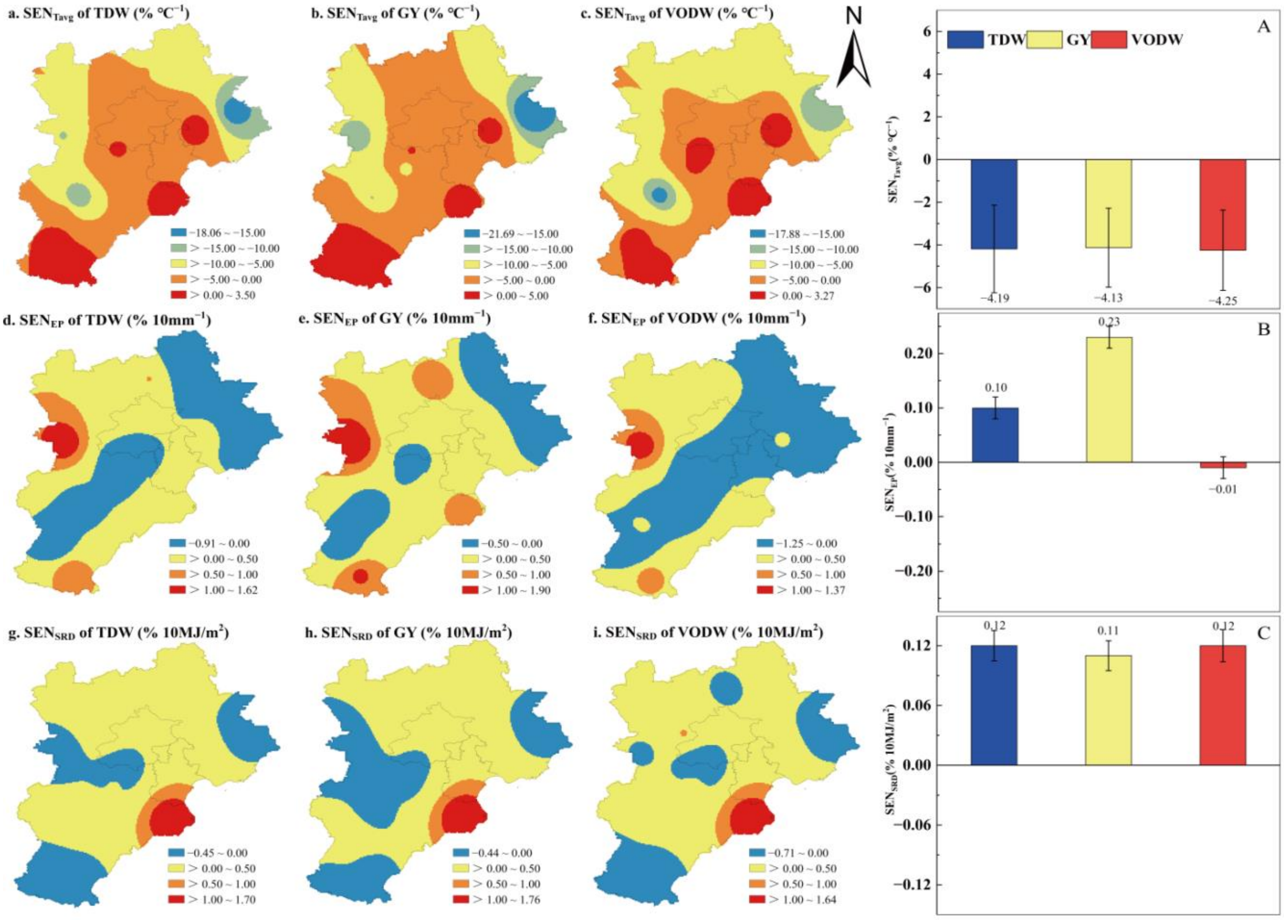

Figure 2 Spatial distribution of the sensitivity of dry matter accumulation indices to average temperature perature (SEN_{Tavg}) (Adopted from Wei et al., 2023)

6.2 Altered rainfall patterns and drought risks for maize

Climate change has altered rainfall distribution, leading to more frequent droughts and erratic precipitation patterns that threaten maize yields, particularly in rainfed agricultural systems. Drought stress during the growing season restricts water availability, hindering seedling establishment, photosynthesis, and growth. In drought-prone regions of China, for instance, maize yield reductions of up to 20% have been recorded due to prolonged water scarcity (Meng et al., 2016).

In addition to yield effects, drought conditions can increase maize sensitivity to other environmental stresses. Prolonged dry periods lower soil fertility and alter nutrient availability, compounding the impact of drought on plant health. In regions like Nigeria's savannas, climate projections show significant yield declines by mid-century if adaptation measures are not implemented, emphasizing the need for targeted drought-resistant maize varieties (Tofa et al., 2021).

Adaptation measures such as using drought-tolerant maize varieties and adopting efficient water management practices can mitigate these impacts. Drought-resistant maize varieties have been shown to sustain yields under lower rainfall conditions, providing a buffer against the challenges posed by climate change-induced water shortages (Kim and Lee, 2023).

6.3 Adaptation strategies to climate change for maize

Developing and implementing adaptation strategies is crucial to protecting maize yields in the face of climate variability. As shown in the figure, one effective approach is to use biotechnological tools to breed maize varieties that are both drought-and heat-tolerant, combining resilience traits to withstand multiple environmental stressors. Integrating drought and heat tolerance into maize varieties can nearly double yield improvements compared to varieties with only one tolerance trait (Tesfaye et al., 2017). The figure highlights advanced biotechnological methods such as transgenic research, QTL mapping, transcriptome analysis, and genome editing, which enable precise identification and modification of genes associated with drought and heat resilience (Wei et al., 2023).

In addition to genetic improvements, other adaptive practices like adjusting planting schedules and implementing soil moisture conservation techniques are effective ways to optimize resource use. The climate-adaptive planting strategies illustrated in the figure are beneficial for small-scale farmers; for instance, farmers in Kenya have successfully adapted to climate variability by changing maize varieties and modifying planting dates, resulting in increased resilience to drought and temperature fluctuations (Busolo et al., 2023). These methods help optimize resource utilization and improve crop adaptability to climate change.

Providing timely climate information and early-warning systems further enhances farmers' ability to make informed decisions and mitigate the risks associated with extreme weather events. Access to accurate climate data allows farmers to make timely adjustments to farming practices, which is especially valuable in managing the impacts of unpredictable weather patterns. As illustrated in the figure, these diversified strategies are essential to strengthening the resilience and stability of maize production, particularly under the growing pressures of climate change (Figure 3) (Wei et al., 2023).

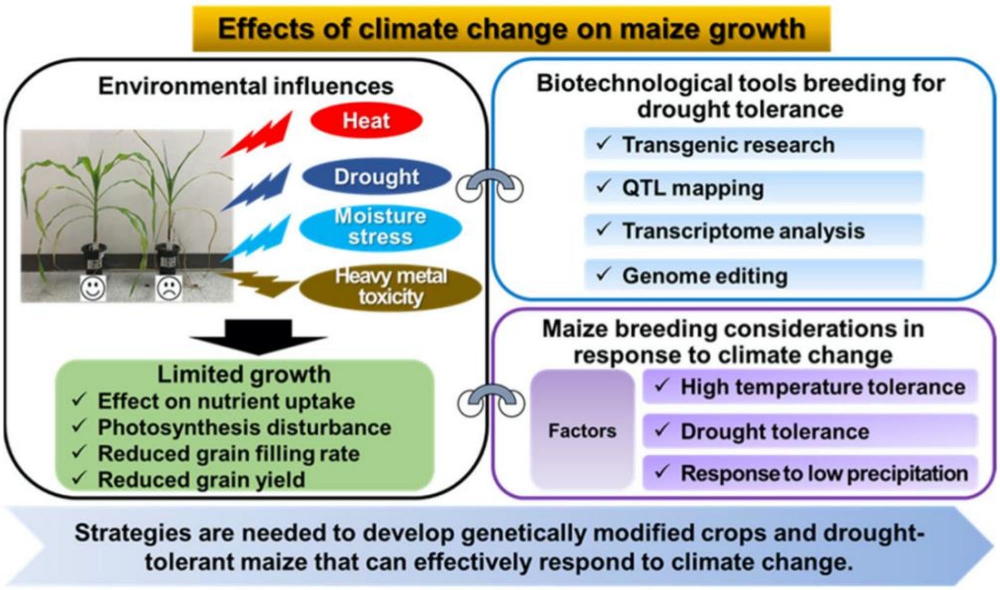

Figure 3 Maize breeding strategies to respond to climate change. (Adopted from Wei et al., 2023)

Image caption: This figure provides an overview of maize breeding strategies and biotechnological tools to address the impacts of climate change. On the left, it highlights major climate-related stressors affecting maize growth, such as heat, drought, moisture stress, and heavy metal toxicity, which lead to limited growth, disrupted nutrient uptake, impaired photosynthesis, reduced grain filling rates, and overall yield reduction. On the right, advanced biotechnological tools are presented, including transgenic research, QTL mapping, transcriptome analysis, and genome editing, allowing for precise identification and manipulation of genes associated with stress resilience. The figure also lists key breeding targets for climate adaptation, such as tolerance to high temperatures, drought resilience, and low precipitation adaptability, which are essential for developing maize varieties that can thrive under changing environmental conditions. The bottom section emphasizes the need for genetically modified and drought-tolerant maize varieties to effectively respond to climate change, ensuring sustainable production under adverse environmental conditions (Adopted from Wei et al., 2023)

7 Genetic and Breeding Approaches for Improving Maize Growth

7.1 Developing maize varieties resistant to environmental stresses

Developing maize varieties that resist environmental stresses such as drought, heat, and salinity is critical for maintaining yields amid climate change. Traditional breeding programs have emphasized selecting genotypes resilient to water scarcity and nitrogen deficiency, two major stressors in maize cultivation. These programs rely on germplasm banks to identify and select genotypes with specific traits for drought and heat tolerance. Testing in managed-stress environments allows for the accurate assessment of how well these varieties perform under simulated stress conditions, ensuring that selected genotypes are effective in real-world conditions (Loro et al., 2023).

Programs led by institutions like CIMMYT have been instrumental in developing maize varieties suited for tropical regions, where drought and extreme heat are common. These varieties are now widely used across Sub-Saharan Africa and Asia, where they play a crucial role in supporting food security for smallholder farmers. CIMMYT's approach integrates managed-stress screening and on-farm trials to ensure that selected varieties can withstand local environmental stresses (Prasanna et al., 2021).

In addition to drought and heat resistance, breeding programs also focus on secondary traits that support stress tolerance, such as root depth and the anthesis-silking interval, which is critical for synchronizing flowering and pollination during drought conditions. Secondary traits are often inherited alongside primary traits, helping breeders select for complex resilience characteristics in a single breeding cycle. By optimizing these secondary traits, researchers can produce maize varieties that are well-suited for resource-limited and variable environments (Nepolean et al., 2018).

7.2 Role of genetic engineering in maize stress tolerance

Genetic engineering has provided maize breeding with advanced tools to improve stress tolerance traits more precisely and efficiently. CRISPR/Cas9, a powerful gene-editing tool, has allowed scientists to target specific genes associated with drought and heat tolerance (Wu and Li, 2024). For instance, the BREEDIT approach combines CRISPR-based multiplex gene editing with conventional breeding to tackle complex traits like yield stability and drought resistance, significantly enhancing maize's adaptability in unpredictable climates. This multiplex approach allows the simultaneous editing of multiple genes involved in stress responses, creating a more robust stress-tolerant maize variety (Lorenzo et al., 2022).

Beyond genome editing, transgenic breeding has been effective in introducing traits from non-maize species. Genes encoding heat shock proteins (HSPs) and heat shock factors (HSFs) have been engineered into maize to provide enhanced thermal tolerance by stabilizing proteins and cellular structures during high temperatures. These transgenic varieties have shown improved productivity under extreme heat and better resilience during key growth stages like pollination and grain filling.

In addition, genetic engineering allows for the enhancement of resource-use efficiency in maize. For instance, genes that increase water-use efficiency and nitrogen uptake have been introduced into maize, allowing plants to thrive in resource-scarce environments. This approach is particularly effective in areas facing water scarcity or degraded soil conditions, providing a means to improve yields without extensive input use (Anwar and Kim, 2020). These genetic engineering advancements complement traditional breeding by offering faster, targeted solutions to enhance stress tolerance in maize.

7.3 Conservation of maize genetic diversity

Maintaining maize genetic diversity is essential for breeding programs, providing a foundation for future improvements and adaptability. Genetic diversity offers breeders a vast pool of traits that can be harnessed to enhance stress resilience, pest resistance, and yield stability. Participatory breeding programs in countries like Portugal have successfully retained genetic diversity while improving agronomic performance. By involving local farmers in the selection process, these programs ensure that diverse traits valuable for local environments are preserved.

Utilizing landraces and wild relatives is also crucial in introducing novel traits into commercial varieties. The genetic diversity of maize wild relatives provides a reservoir of tolerance to extreme conditions like drought and high salinity. With modern breeding techniques, these traits can be integrated into elite varieties without extensive backcrossing, making the process more efficient. This genetic reservoir is invaluable for developing new varieties capable of withstanding adverse environmental conditions (Kapazoglou et al., 2023).

Advances in genomic selection and high-throughput phenotyping further enhance the ability to retain diversity while improving key traits. By utilizing genome-wide selection, breeders can maximize genetic gains and accelerate the breeding cycle, ensuring that high-yielding and stress-tolerant varieties reach farmers more rapidly. This approach is essential for scaling resilience-focused varieties to regions that are vulnerable to climate change, securing food supplies in areas facing the highest climate-related risks (Prasanna et al., 2020).

8 Socioeconomic Factors Affecting Maize Production

8.1 Impact of agricultural policies on maize production

Agricultural policies have a profound influence on the productivity and profitability of maize farming. In Kenya, for instance, policies that promote access to inputs, credit, and agricultural extension services have positively influenced maize productivity. However, inconsistent policy implementation, bureaucratic hurdles, and instances of corruption limit these benefits for smallholder farmers. A study in Kenya emphasized the need for the government to streamline input distribution, reduce corruption, and improve infrastructure to enhance maize productivity. The study recommends targeted policy reforms to ensure timely distribution of inputs and the establishment of anti-corruption measures in the agricultural sector to reduce inefficiencies (Mogeni, 2019).

In Ethiopia, market reforms aimed at enhancing agricultural productivity have created mixed outcomes. While the reforms provide opportunities for private sector involvement and enhance access to inputs, they also expose farmers to market volatility and high input prices, which can strain smallholder farmers' financial resources. Studies in Ethiopia indicate that smallholders benefit from policies that directly address economic and logistical barriers, such as subsidies for fertilizers and seeds, and the establishment of farmer cooperatives to lower input costs and transportation challenges (Mohammed, 2021).

In Zambia, government programs like the Farmer Input Support Program (FISP) have sought to subsidize inputs and improve access to essential resources. However, studies show that, despite increased budgetary allocations, smallholder maize farmers often experience delays and inefficiencies in receiving inputs, impacting their planting timelines and yield potential. Policy recommendations include enhancing the transparency of these programs, reducing logistical inefficiencies, and engaging local farmer associations in the distribution process to ensure inputs reach farmers in a timely manner (Mumba and Edriss, 2018).

8.2 Access to agricultural inputs and its effect on maize growth

Access to high-quality agricultural inputs such as seeds, fertilizers, and pesticides is essential for increasing maize productivity. Studies have shown that in Ghana, limited access to quality inputs remains a key constraint for maize farmers, especially in rural and remote regions where high transportation costs and inadequate infrastructure exacerbate input costs. Research highlights that improving farmers' access to affordable credit and implementing input subsidy programs can significantly increase maize yields by enabling farmers to adopt improved seeds and fertilizers (Mohammed et al., 2019).

In Ethiopia, the lack of access to agricultural finance and capital further limits smallholder farmers' ability to purchase necessary inputs. Studies show that farmers with non-farm income sources are better able to invest in agricultural inputs and achieve higher maize yields. This finding suggests that supporting smallholders through access to financial assistance, microcredit, and income diversification programs can help them overcome financial barriers to input access (Solomon et al., 2022).

In Nigeria, the impact of input access on maize productivity is similarly constrained by high costs and inconsistent availability. Research in Nigeria finds that farmers' ability to acquire fertilizers, herbicides, and pest control products positively influences their maize output, but the lack of infrastructure and logistical support limits widespread input adoption. Policy recommendations include strengthening subsidies, improving transport and market access, and creating reliable distribution networks for essential inputs (Oyewole et al., 2022).

8.3 Farmer education and support services for maize cultivation

The education level of farmers plays a critical role in enhancing maize productivity and facilitating the adoption of new technologies. Studies show that better-educated farmers are more likely to accept and implement innovative agricultural techniques, such as improved maize seeds and conservation tillage. In Ghana, for instance, educated farmers demonstrate a higher acceptance of modern farming methods, enabling them to understand and apply advanced practices that result in higher yields and more sustainable cultivation methods (Onuwa et al., 2023).

Agricultural extension services also play an essential role in providing technical support to farmers, especially in promoting the latest maize farming techniques. Research in Nigeria has found that limited access to extension services hinders farmers' ability to adopt new technologies and improve productivity. By expanding the reach of extension services and increasing the frequency of visits, farmers can gain valuable technical guidance. Such field training and on-site support can effectively encourage farmers to adopt best practices, thereby improving productivity and resource-use efficiency (Thompson, 2018).

Farmer support services, such as cooperative memberships, offer farmers access to shared resources and collective marketing opportunities. In Zambia, cooperative models have been shown to effectively enhance farmers' productivity by providing access to inputs at lower costs and facilitating bulk purchases that reduce intermediary costs and improve market access. Additionally, training activities like farmer field schools and demonstration plots help farmers adopt soil and water conservation practices, supporting sustainable farming approaches. These educational services offer a sustainable pathway for smallholders to increase yields while achieving both environmental and economic sustainability (Mumba and Edriss, 2018).

9 Concluding Remarks

Environmental factors, including climate conditions, soil quality, and biotic interactions, profoundly impact maize growth, affecting yield, crop health, and resilience to stresses. Changes in temperature and rainfall patterns, coupled with soil nutrient challenges, have become increasingly important with the progression of climate change. These environmental pressures necessitate a comprehensive understanding of maize physiology and stress responses to develop cultivation practices that support productivity and resilience. Without addressing these factors, regions already facing environmental challenges may experience significant reductions in maize yield, further impacting food security.

To promote sustainable maize cultivation, it is crucial to adapt agricultural practices to these environmental realities. Strategies such as optimizing water and nutrient management, adopting precision irrigation techniques, and using stress-resistant maize varieties can mitigate adverse effects. The case of Wushanxia Village illustrates how integrating premium fresh maize varieties with modern agricultural practices not only enhances yield stability and crop quality but also significantly increases farmers' profitability, providing a replicable model for other rural communities. Reducing excessive fertilizer use, adjusting planting dates, and selecting early-maturing varieties help farmers better manage climatic variability, safeguarding yields against extreme weather. Collectively, these practices protect both agricultural productivity and environmental health.

Future research is essential to understand the intricate interactions between environmental factors, crop genetics, and management practices. Region-specific case studies, such as that of Wushanxia Village, highlight the value of combining scientific insights with locally adapted strategies. This approach can foster sustainable maize production systems capable of meeting global food demands while simultaneously supporting rural economic revitalization.

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Conflict of Interest Disclosure

The author affirms 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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