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ARTICLE

Analyzing the Impact of Climate Change on Maize Production to Develop Innovative Strategies for Ensuring Global Food Security

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ABSTRACT

This study examines the role of maize in food security and economic stability, focusing on its response to climate change and strategies to enhance resilience. Using a qualitative descriptive research methodology, the study analyzes the impact of climate change on global maize production and proposes innovative strategies for sustainability and food security. The agricultural environment is vulnerable to heavy metal toxicity, which is linked to the relationship between soil health and climate change. From 1850 to 2020, the Earth's temperature increased by 1.1 °C, with projections indicating continued warming. This trend has significant economic implications, particularly in developing countries where agriculture employs 69% of the population. Heat waves and droughts represent abiotic stresses faced by maize. Research suggests that high greenhouse gas emissions could lead to a 24% reduction in maize yield by 2030. The study highlights the need to focus on breeding and phenotyping technologies to develop heat- and drought-tolerant maize varieties that use water efficiently. Additionally, strategies such as genomic editing, transcriptome analysis, and maize quality mapping are crucial to addressing these challenges. Developing insect-resistant maize is another objective. This study emphasizes the necessity of ongoing research to improve agricultural productivity and ensure food security, especially in light of global population growth. It also advocates for new regulations to reduce greenhouse gas emissions, which contribute to global warming.

Keywords: Abiotic Stresses; Climate Change; Food Security; Sustainability; Zea mays

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1. Introduction

Maize (Zea mays), widely referred to as corn, is an important cereal grain that has been grown for more than 7,000 years, originating in Central Mexico. This crop exemplifies global stability and is vital for food security, supplying critical calories and protein to almost 4.5 billion individuals in poor nations [1]. Maize is crucial to the food supply, providing a minimum of 30% of caloric intake, in conjunction with rice and wheat. This food source is deemed vital for supplying calories and proteins to a substantial segment of the global population [2]. It is utilized in multiple ways, including raw materials for starch, oil, sweeteners, and fuel [3]. Maize is crucial for subsistence agriculture in sub-Saharan Africa and for intensive farming in the United States [4]. This crop demonstrates considerable tolerance to various temperatures, ranging from tropical to temperate, making it a suitable option for farmers worldwide. This crop is essential for human consumption and greatly contributes to animal feed. This highlights its significance in our agricultural system. Climate change poses substantial problems to the agricultural industry, which employs 69% of the population in developing nations [5].

Climate change constitutes a significant barrier for modern agriculture. Human activities are regarded as the primary source of greenhouse gas emissions, which modify global temperature, precipitation, and wind patterns, resulting in increased soil degradation and heightened heavy metal toxicity in the soil. The combined impact of these factors affects food security, crop output, and agricultural sustainability. Maize, an essential global crop and staple food for millions, is considerably endangered by climate change due to its susceptibility to extreme environmental conditions, such as heat waves and droughts, which are anticipated to escalate in frequency and intensity over time. Future weather patterns are expected to cause a substantial decline in maize yield, threatening food stability due to predicted population expansion. Adverse weather conditions present a considerable risk to maize production, with forecasts suggesting a 24% decrease under greenhouse conditions by 2023 and a drop of 39–68% by 2050 in the United States compared to the period of 2013–2017, depending on the climatic scenario. Moreover, extreme weather events pose a substantial risk to maize yield, with forecasts indicating a 24% decrease under greenhouse conditions by 2023 and a drop of 39–68% by 2050 in the United States, contingent upon the climatic scenario [6, 7].

Maize has been cultivated in a variety of climates, from temperate to tropical locales, illustrating its considerable tolerance to many environmental conditions [4]. The swift progression of climate change hinders the continuous adaptation of agricultural crops to meteorological circumstances. Studies suggest that impending climate circumstances will lead to reduced output, diminished yields, a substantial increase in world temperatures relative to historical records, and a decline in the nutritional content of maize. Heat stress affects the reproductive stage of maize growth, negatively impacting pollination and kernel formation. It also affects developmental phases, resulting in alterations to their morphological, physiological, and biochemical processes. The ramifications of these stressors are considerable, as global temperatures are anticipated to markedly increase by the century's conclusion, exceeding the greatest temperatures recorded historically. Moreover, the ramifications of this stress are alarming [8, 9].

In addition to the major effect of heat stress, climate change influences maize production through factors such as drought, waterlogging, heavy metal toxicity, and the distribution of pests. Drought stress can significantly affect maize growth by diminishing water availability during essential growth phases [9]. Conversely, waterlogging may result in root decay [8]. Soil acidification and pollution due to climate change can lead to the accumulation of heavy metals, including cadmium (Cd), which inhibits maize growth, diminishes its nutritional quality, and raises concerns regarding food safety and public health [10]. Climate variability is increasing the spread of pests, which poses a significant threat to essential crops critical for food security, including maize. The success of maize cultivation through the long run relies mainly on the implementation of effective strategies to improve resistance to diseases and pests. CIMMYT conducts research initiatives aimed at identifying effective solutions to this issue by locating stable sources of resistance to maize diseases [8]. Factors associated with climate change represent a substantial risk to food security, which is an increasingly pressing global issue.

This article aims to underscore the crucial role of maize in ensuring food security for both humans and animals, scrutinize the obstacles posed by climate change on maize production, and explore potential solutions to alleviate the food security predicament associated with maize. This debate examines three critical questions that clarify distinct facets of the issue and the possible effects of alternative solutions for improving maize production. This article seeks to address three primary questions: The articles are:

Q1: In ensuring the safety of food for both humans and animals, what part does maize play?

Q2: What is the impact of climate change on the production and economic cost of maize on a worldwide scale?

Q3: What strategies have been proposed to address climate change and enhance the efficiency and sustainability of global maize production?

Understanding the current challenges and examining the barriers to establishing sustainable maize production and economic resilience in the context of climate change is essential for achieving sustainable food security. The maize sector plays a crucial role in providing a staple food source and supporting global food security. However, climate change, including rising temperatures and changing weather patterns, poses significant risks to maize production, potentially leading to economic losses and impacting food security. This research aims to provide a comprehensive analysis of the challenges facing the maize industry due to climate change and rising temperatures, along with strategies to address these issues. It seeks to contribute to the literature with insights on the effects of climate change on maize sustainability and food security, a topic that remains a critical focus worldwide. Additionally, maize producers must adopt measures to mitigate the impacts of temperature stress and reduce economic losses. This study will explore the role of maize in ensuring global food security and the implications of climate change for the sector, highlighting the importance of implementing strategies to combat climate change and safeguard long-term food security and sustainable maize production.

2. Materials and Methods

This study employs a qualitative descriptive research methodology, focusing on analyzing the impact of climate change on global maize production to develop innovative strategies for sustainability and ensuring global food security. Furthermore, descriptive research, as described by Neuman[11], is characterized by its ability to "present a picture of the specific details of a situation, social setting, or relationship" and "begins with a well-defined issue or question and endeavors to describe it accurately." "...concentrates on 'how' and 'who' inquiries...". Moreover, contend that qualitative research designs, including phenomenology and grounded theory, can serve both descriptive and explanatory purposes[12]. Lambert and Lambert suggest employing the term "qualitative descriptive research" to avoid mislabeling the research approach with other methodologies, such as phenomenology, grounded theory, and ethnography[12]. "Naturalistic inquiry" by Lambert and Lambert, says that qualitative descriptive research "strives to look at things in their natural state as much as possible within the research context"[12]. The study is qualitative because it looks at the impact of climate change on global maize production to develop innovative strategies for sustainability and ensuring global food security. It is, therefore, qualitative descriptive research.

Furthermore, the present study's objectives necessitate a thorough content analysis of both electronic and printed materials regarding the occurrences or events under investigation[13]. Furthermore, Bowen asserts that it has three phases: skimming, comprehensive reading, and interpretation[13]. By breaking down large amounts of text into smaller, more manageable pieces, content analysis helps us find the most important meanings within them[14]. It does this by looking for recurring themes and patterns in the text[15].

3. Results and Discussion

3.1. Maize Plays a Vital Role in Ensuring the Safety of Food for Both Humans and Animals

At least seven thousand years ago from now, it was thought that farmers in Central Mexico were the ones who domesticated maize, also known as Zea mays, which is also known as corn. Because of its great productivity and outstanding regional adaptations, maize is considered one of the most significant annual plants in many countries. It is also an essential crop in numerous regions of the world, because it is an essential cereal crop for both human and animal consumption. Besides industrial applications, it also significantly contributes to global food security[1]. Maize is used as a raw ingredient in a wide variety of important goods, such as starch, oil, alcoholic drinks, food sweeteners, and fuel [3]. Along with rice and wheat, it contributes at least thirty percent of the total calories in the food supply. Furthermore, it serves as a source of protein for more than four and a half billion people in more than ninety developing nations [2].

There are a wide range of growth conditions that can be used to cultivate maize, including tropical climates, temperate climates, and elevations ranging from sea level to 3,000 meters above sea level. Due to the fact that it is cultivated on every continent, maize may be converted to a subsistence farming system. One example of this is the cultivation of maize in sub-Saharan Africa. On the other hand, it is grown in the United States to a significant extent [3]. In spite of the fact that there are numerous hybrids of maize, each of which possesses its own unique characteristics and kernels, maize is typically divided into two broad categories: yellow maize and white maize. These distinct categories are determined by the color and flavor of the corn. Yellow corn accounts for the majority of the world's production as well as the majority of international trade. Traditionally, it has been utilized for the purpose of animal feeding in the countries that are located in the northern hemisphere. In addition to this, it can be utilized in a broad variety of industrial applications, one of which is the cultivation of ethanol. White maize cultivation, which is widely considered to be a food crop, is mostly produced in the United States of America, Mexico, and a few nations in southern Africa. White maize cultivation requires more favorable climatic conditions than yellow maize cultivation does [10].

Experts predict that the global population will surpass 9 billion by 2050, with developing countries experiencing the highest rate of population growth. Developing countries anticipate a twofold increase in maize demand, and present productivity levels and growth in population will not suffice to meet future demands. Moreover, maize is the primary staple crop for a significant fraction of people in Africa. In Eastern and Southern Africa, maize accounts for approximately 32 percent of calories consumed, with projections indicating an increase to 51 percent in certain nations by 2050. The Food and Agriculture Organization (FAO) predicted that worldwide cereal production for our current year 2024 will reach 2848 million tons. Although there is a decline of 0.4% from the previous year, it remains the second highest output ever documented [16]. After reaching the peak in 2023, global coarse grain production was expected to decrease to the second highest level on record in 2024. The decline in maize production worldwide is thought to be mainly driven by unfavorable meteorological conditions that maize couldn't tolerate [8]. Moreover, more than half of the world's maize is produced in China and the United States (**Figure 1**) [17]. Approximately 90% of all countries are AMIS countries. Additionally, maize is a major commodity for trade, particularly for AMIS nations, which make up over 60% of global imports and approximately 95% of global exports, respectively. Moreover, by 2024/25, worldwide maize production will fall by 1.79% while wheat, rice, and soybean production will rise [18].

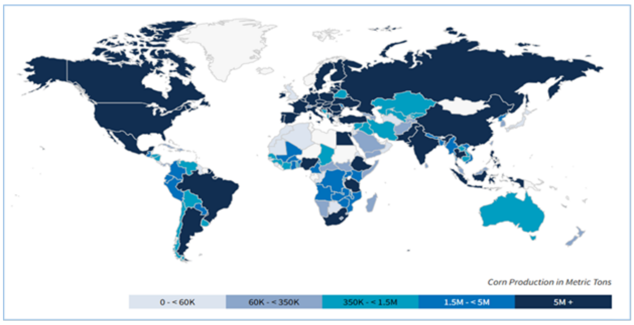

Figure 1. Global corn production by metric tons in 2023/2024 [17].

As shown in **Table 1**, the data reveals significant disparities in agricultural production and consumption among major countries during the period from 2020 to 2025, reflecting variations in agricultural capacities and challenges, including the impact of climate change. In the United States, there has been substantial growth in agricultural production, reaching levels that bolster its export capabilities. However, this growth remains vulnerable to potential climate disruptions, such as droughts or storms. Conversely, China continues to face a persistent gap between production and consumption, as its domestic output falls short of its growing demand, leading to increased dependence on imports a situation that could worsen with climate-induced production challenges. Moreover, Brazil and Argentina have shown resilience in maintaining production balance despite fluctuations, highlighting their strong export potential. However, they remain susceptible to climate phenomena such as flooding or shifts in rainfall patterns that could affect their crops. In the European Union, consumption remains high, while production demonstrates notable volatility, resulting in heavy reliance on imports to bridge the gap—a dependency that could be exacerbated by the global impact of climate change on agricultural output.

On the other hand, climate change plays a pivotal role in this context, affecting agricultural stability worldwide through factors such as droughts, excessive rainfall, and rising temperatures, which contribute to significant fluctuations in crop yields. This underscores the urgent need for sustainable agricultural strategies, including advanced irrigation techniques, the use of climate-resilient seeds, enhanced agricultural research, and strengthened international cooperation to ensure global food security and mitigate the adverse effects of climate change on agricultural production.

Table 1. Top countries in corn production and consumption as “1,000 metric tons” from 2020 to 2025 [17].

Country	2020/2021		2021/2022		2022/2023		2023/2024		2024/2025 “Nov”		Dec., 2025	
	Production	Consumption	Production	Consumption	Production	Consumption	Production	Consumption	Production	Consumption	Production	Consumption
USA	357,819	308,215	381,469	315,665	346,739	305,928	389,667	321,995	384,644	321,706	384,644	322,976
China	260,670	285,000	272,552	291,000	277,200	299,000	288,842	307,000	292,000	313,000	292,000	313,000
Brazil	87,000	70,500	116.000	71,000	137,000	78,000	122,000	84,000	127,000	83,500	127,000	85,500
European Union	67,440	77,700	71,672	81,700	52,329	74,800	61,868	75,800	58,000	75,100	58,000	75,700
Argentina	55,000	16,800	52,000	15,700	37,000	14,200	50,000	15,250	51,000	16,300	51,000	16,300
India	31,647	27,850	33,730	30,000	38,085	34,700	37,665	37,900	38,000	39,100	38,000	39,100
Ukraine	30,297	——	42,126	——	27,000	—	32,500	——	26,200	—-	26,500	——
Mexico	27,346	43,800	26,762	44,000	28,007	46,000	23,500	48,100	24,500	48,700	23,700	48,500
South Africa	16,951	13,220	16,137	12,655	17,100	13,239	13,400	13,600	17,000	13,600	17,000	13,600
Canada	13,563	13,976	14,611	17,984	14,539	14,927	15,421	15,779	15,200	15,600	15,345	15,600

3.2. The Impact of Climate Change on the Production and Economic Cost of Maize on a Worldwide Scale Is Significant, Affecting Yield Levels, Market Prices, and Global Food Security

The release of greenhouse gases is the primary driving force behind global warming, which is produced by human activities. The average temperature of the Earth’s surface rose by 1.1 degrees Celsius between the years 1850 and 2020. The consequence of this is that it has led to broad negative repercussions, such as the destruction of natural resources and the harming of people [19]. Changes in the climate have had a detrimental effect on the agriculture sector. In countries that are still in the process of developing, agriculture employs 69% of the population. Environmental impacts from climate change will affect food production and the nation’s economy. The influence of global warming on crop output differs depending on the geographical area and the crop. Additionally, climatic parameters such as humidity, precipitation, and temperature all have an effect on the development of crops as shown in **Figure 2** [5]. As shown in **Figure 3**, increasing concentrations of carbon dioxide in the atmosphere and rising temperatures can have an effect on photosynthesis in plants, which can result in slower growth rates and less efficient use of water. This has a direct influence on crop productivity [9].

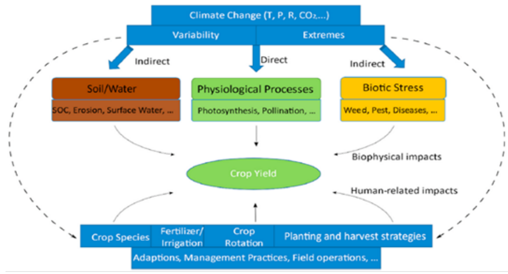

Figure 2. Main pathways that climate change influences crop yields [5].

Maize production can be influenced by abiotic stresses, which are characterized by extreme weather events, including heat waves and drought. Research by NASA, published in the journal Nature Food, predicts a 24 percent decrease in maize yields by 2030 under a scenario of significant greenhouse gas emissions. On the other hand, climatic change is projected to cause a 20% reduction in maize yields in Europe by 2050 [6]. Predictions of climate change will hinder the ability to stimulate economic growth and maintain food security in extensive regions that produce maize, exacerbating the situation. In areas where maize cultivation occurs, there is an urgent necessity to determine future breeding objectives and identify major vulnerabilities to climate change. Identifying prospective breeding goal settings and mitigating uncertainty in climate forecasts are essential tasks for researchers and policymakers to establish priorities. Climate change will produce varied effects across regions, and there will be a delay before farmers adopt improved germplasm[4].

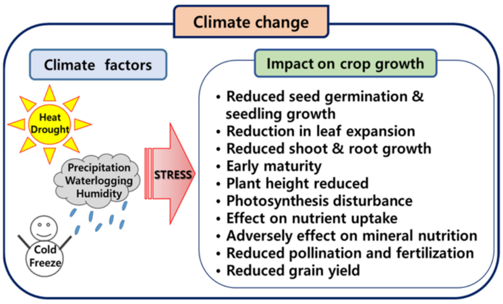

Figure 3. Effect of climate changes on crop productivity[8].

Maize, as a globally essential food crop, faces increasing challenges due to the rising frequency and severity of abiotic stresses driven by climate change. These stresses disrupt physiological and structural processes, posing a significant threat to food security not only in regions directly affected but also on a global scale, thereby becoming a concern for global food security. Therefore, understanding the impact of these climatic challenges on maize is crucial for developing adaptive strategies and enhancing crop resilience to ensure sustainable production in a constantly changing environment. Consequently, the impact of these factors can be outlined as follows:

3.2.1. Drought

Reduced precipitation and shifting patterns are increasing the prevalence of stress due to drought, an abiotic factor that reduces maize development and productivity. Because it affects plant physiology, development, and reproduction, drought stress has a major influence on agricultural output. This is due to the rapid loss of water by plants and soil, as well as the vulnerability of crops to the direct effects of hot weather. Droughts during the seedling or developing stages of tall, broad-leaved maize can cause the leaves to curl and hinder the plant's development[20, 21].

Drought stress is detrimental to maize development and yield at any stage, but it is especially noticeable during the reproductive phase, encompassing tassel emergence to the initial grain filling. This results in lower kernel size and a marked drop in grain yield. Maize is particularly vulnerable to drought stress since its male and female flowers are typically located in different parts of the plant. It can also remove moisture from exposed silk, which prevents it from absorbing pollen grains. Daily yield losses of up to 8% are possible when silk and pollen growth is under high stress. Per day yield reductions of up to 6% are possible if stress caused by drought continues for two weeks following silking[9]. Drought stress decreased grain yield by 15–30% compared to the well-watered control[8].

3.2.2. Water Deficit (Precipitation Stress)

Precipitation is the meteorological variable that most significantly influences maize productivity. Water deficit in the week subsequent to silk development markedly reduces grain weight, resulting in a continued decline in maize yield of approximately 30%. The stress caused by moisture during the grain-loading phase leads to a daily yield drop rate of 3–5.8%. During the period of severe moisture stress, maize yield may decrease by 20–30%[9]. Following 2010, the Czech Republic experienced a reduction in precipitation, resulting in diminished total maize yields[22]. Projections in the United States indicate that maize yields may decline by 39 to 68 % by 2050 compared to the 2013–2017 period, depending on the climatic scenario[7].

3.2.3. Heavy Metal Toxicity in Soils

Climate change may lead to soil acidification and contribute to heavy metal pollution in the soil. This poses a significant environmental and ecological risk, as it increases the contamination of agricultural land with heavy metals, such as cadmium ("Cd"), which in turn introduces these metals into crops[10]. Declines in maize production are attributed to the accumulation of harmful metals in soil. Elevated cadmium levels diminished maize growth and biochemical characteristics, as cadmium accumulation was predominantly observed in the roots rather than in the leaves[9].

3.2.4. High Environmental Temperature

Temperatures outside the optimal range adversely impact the growth and development of all plant species[9]. By the century's end, temperatures during the growth season are projected to reach historical highs. Heat stress is defined by its intensity, duration, and the rate of temperature increase beyond a threshold level, which irreversibly impairs crop growth and development. Heat stress impacts plant tissues, organs, and developmental stages variably, contingent upon the vulnerability of the principal metabolic mechanisms. High temperatures can induce morphological, anatomical, physiological, and biochemical changes in maize[8]. The primary factors contributing to the decline in maize yield are a shorter life cycle, reduced light interception, and increased sterility [23]. Moreover, under optimal rain-fed and drought conditions, each degree above 30 °C resulted in a decrease in grain yield of 1% and 1.7%, respectively. Elevated reproductive temperatures diminish the number of fertilized ovules that develop into grains and reduce kernel weight, consequently decreasing yield. Heat stress negatively impacts pollen viability, germination rates, water potential, pollen shedding, and tube germination under elevated temperatures. Pollen exhibits increased vulnerability to injury or mortality at temperatures exceeding 32 ºC and under conditions of low humidity [23]. In order for grains to form in maize, viable pollen has to be made and then captured by sensitive silks. The male gamete must thereafter be delivered to the female gamete, and the embryo and endosperm have to grow. Elevated temperatures during the initial stages of kernel formation adversely affect kernel development, grain quantity, and final kernel mass. Heat stress alters carbon utilization and distribution but does not affect the carbon supply to the kernel. Heat stress diminishes sink activity by reducing the conversion of sugar to storage products, rather than affecting kernel uptake [9].

3.2.5. Flood and Waterlogging

In the context of plant growth and development, the term "waterlogging stress" refers to the stress that occurs when the soil's water table is higher than its field capacity. Numerous factors influence the plant's ability to exchange gases and absorb nutrients, causing this stress. The rate of gas diffusion in the inundated soil may be 100 times diminished compared to the rate of gas diffusion in the air, which would result in a reduction in the amount of gas exchange that occurs between the root tissues and the atmosphere. Because of the steady decrease in oxygen concentration inside the rhizosphere, the roots of the plant experience hypoxia, which is characterized by low oxygen levels, followed by anoxia, which is characterized by a lack of oxygen [8]. On the other side, when there is waterlogging, the rhizosphere also accumulates ethylene, carbon dioxide, and poisonous gases such as methane, ammonium, and hydrogen sulfide. This occurs during periods of waterlogging. Furthermore, waterlogging leads to a deficiency in key macronutrients like nitrogen, phosphorus, and potassium, as well as an accumulation of hazardous elements like iron and magnesium. This is a consequence of the buildup of these nutrients. Moreover, this situation arises as a result of a decrease in absorption by plant roots and variations in the redox capacity. The accumulation of water situations necessitates a significant quantity of carbohydrates due to the inefficiency of anaerobic respiration in plant roots [8]. During times of waterlogging, increased anaerobic respiration leads to a rapid depletion of carbohydrates in roots, which results in "carbohydrate starvation" for the plant. The generation of ATP per glucose molecule is decreased under anaerobic conditions, which results in a reduction in the amount of energy that is available for the uptake of nutrients. When there is too much water in the soil, leaves wilt and roll over, stomatal conductance drops, root growth is slowed down, alterations in both shoot and root morphology, modifications in the ratio of root-to-shoot, leaf senescence, and the growth of roots from aerial nodes [24]. These symptoms were observed in plants that were subjected to significant amounts of waterlogging. Furthermore, it was discovered that root degradation and wilting were connected with a decrease in the amount of water that was available in maize when it was subjected to waterlogging. It is estimated that floods and waterlogging problems affect over eighteen percent of the overall maize cultivated area within South and Southeast Asia, leading to annual losses in yield between 25−30%. Significant genotypic diversity has been discovered in maize with regard to its tolerance to flooding. This variability has the potential to be utilized in the development of maize varieties that are able to withstand periodic stress caused by waterlogging during the monsoon season in tropical regions [25].

3.2.6. Pests and Diseases

Insect diseases and pests vary significantly across different environments. The preservation of genetic resistance to diseases and pests represents a significant challenge in the adaptation of crops to climatic change. Climate change will affect the diversity of agricultural diseases and pests, along with their stress response capabilities. To mitigate the adverse impacts of pests and plant diseases on maize yield, it is essential to investigate and comprehend the factors that drive change. Environmental factors, including rainfall, relative humidity, temperature, and sunlight, significantly affect disease development. Alterations in these parameters due to climate change are highly probable to influence disease prevalence and the emergence of new diseases. Global climate changes can influence host physiology and resistance, as well as affect the phases and rates of pathogen progression. Ecological circumstances significantly influence the disease infection cycle, encompassing inoculum survival, infection, latent period, formation of new propagates, and dissemination [8]. Moreover, the various components of the cycle are governed by environmental variables. Fungi require moist leaf surfaces or high relative humidity to initiate infection. Modifications to these conditions will lead to an explosion in infections. When relative humidity falls below 80%, pathogen proliferation ceases, leading to the termination of infection. Variations in rainfall patterns, humidity, and temperature may increase the prevalence of pathogens capable of infecting maize [26]. Climate change may influence gene flow, which is the transfer of specific alleles or individuals between populations. This will increase the diversity of the pathogen population, resulting in variations in pathogen virulence, host resistance, and potentially novel certain interactions which may lead to the emergence of newly developed diseases or infections and the introduction of microbes into previously uninhabited ecosystem niches [8].

Mycotoxin contamination poses a significant threat with potential prolonged implications for both animal and human health. The effects encompass immune system suppression, an increase in infectious diseases, diminished infant development, and a decline in the effectiveness of immunization programs. In 2004, the consumption of maize with aflatoxin B1 levels reaching 4,400 ppb resulted in the deaths of over 125 individuals in Kenya. On the other hand, the maize harvested during this outbreak was collected after early and unseasonable heavy rains, and it was stored in damp conditions [27]. The environment affects the diversity and abundance of aflatoxin-producing organisms. The geographical distribution and prevalence of F. verticillioides are likely to change due to increasing temperatures in maize-growing areas. This is particularly applicable in regions currently undergoing lower temperatures, where it will supplant F. graminearum. The transition in species of Fusarium will lead to a transformation of mycotoxins, changing from fumonisin, produced by Fusarium verticillioides, to deoxynivalenol and zearalenone, which are generated by Fusarium graminearum [28]. Temperature is a critical environmental factor that significantly influences the behavior, distribution, development, survival, and reproduction of insects. An increase in temperature can accelerate the insects' life cycle, resulting in accelerated increases in populations of pests. However, a temperature increase of two degrees Celsius can increase the number of insect life cycles during the crop season by one to five times [29]. In addition, rising global temperatures and increased drought frequency will promote insect proliferation and herbivory, potentially leading to heightened incidence and severity of insect-related damage, as well as increased levels of aflatoxin and fumonisin mycotoxins in maize. This is expected to enhance the probability of insect-related damage [8].

3.3. Strategies Have Been Proposed to Enhance Maize Production Sustainability and Address Climate Change Effectively

Field experiments, process-based modeling, and statistical modeling represent three broad categories of scientific approaches employed to examine the impact of climate change on agricultural yields. Field experiments allow for the direct observation of the effects of interest. Process-based modeling employs fundamental principles from diverse fields such as biophysics, plant sciences, and agronomy to develop computer models that simulate crop growth. Statistical modeling is employed to analyze historical observations and identify correlations between agricultural yield and climate [5]. Moreover, understanding the molecular and physiological responses of crop yield to individual and combined stresses, such as drought and heat or drought and waterlogging, is crucial for making significant progress [30]. Maize plants often encounter multiple stressors in agricultural fields. Strategies are required to develop drought-resistant maize and genetically modified crops that can effectively adapt to climate change [9].

For sustained success, it is essential to understand the following: (1) the type of disease or insect pest that is present and how strong it is in different populations, (2) the different types of genetic resistance that are available and how they work, (3) finding the best places (hot spots) and using screening methods and protocols to make sure there are enough disease and pest pressures, as well as keeping an eye on resistance, and (4) the fastest ways to make multiple stress-resistant inbred lines and how they can be used in hybrid or variety development [8]. Moreover, CIMMYT conducted a study examining 500 inbred lines of maize across over 15 locations in Asia, Latin America, and Sub-Saharan Africa.

This study aimed to determine reliable sources of resistance to widespread diseases and critical phenotyping sites. The researchers investigated diseases including ear rots, maize streak virus (MSV), turcicum leaf blight (TLB), and gray leaf spot (GLS). The utilization of a similar genotype ensemble in various settings facilitates the monitoring and detection of emerging pathogen strains. These strains are going to be documented for alterations in disease burden and the onset of novel diseases. Furthermore, it is feasible to assess the impact of environmental characteristics on the biology and prevalence of pests. Through initiatives such as Insect-Resistant Maize for Africa [8], the Center for International Molecular Biology and Genetics (CIMMYT) has also generated a number of varieties, inbred lines, and populations of insect-pest-resistant maize. These have demonstrated notable efficacy against post-harvest insect pests and stem borers, including grain borers and weevils [8].

On the other hand, breeding was the primary factor contributing to the triumph of the green revolution, resulting in substantial increases in cereal production. Conversely, given the reality of climate change, it is crucial to improve breeding pipelines to meet the requirements of coming generations. Breeding programs frequently conduct independent stress assessments recognized in the desired environment. The objective of these screenings is to select genotypes that demonstrate effective performance under diverse pressures. Conversely, as illustrated in **Figure 4** [5], the aggregation of individual stresses fails to accurately forecast the highly diverse results generated by multi-stress conditions.

Figure 4. Crop yield as a function of multiple stresses [5].

On the other hand, a combination of transgenic breeding, molecular, and conventional methods is anticipated to be necessary to enhance the efficiency of breeding pipelines [8] as effective strategies to improve maize's heat stress tolerance while ensuring high productivity. The following strategies are utilized:

3.3.1. Conventional Breeding

The advancement of drought-tolerant tropical maize is largely due to the application of established drought breeding methodologies in controlled stress screening, leading to significant enhancements in grain yield under drought conditions. Traditional drought breeding methods have been employed to attain this achievement. Several organizations, particularly in the commercial sector, have focused their efforts on implementing doubled haploid (DH) technology in breeding programs. It is estimated that eighty percent of businesses utilize this technology. In 2008, Phillips defined DH as a genotype resulting from the chromosome doubling of haploid cells. This method facilitates the creation of a homozygous line after one cycle of recombination [31]. The utilization of DH technology for breeding can reduce the time needed to achieve homozygosity from approximately six seasons to one season, thereby enhancing the efficiency of line development [32]. This may lead to enhanced efficiency in line development processes. In addition, the use of DH technology in tropical maize breeding has the potential to enhance genetic improvements of breeding programs. The advancement of breeding techniques relies on the availability of genetic diversity. SeeD is an initiative designed to assess the extent of allelic variation between the genetic resources of maize and wheat, establish core sets through genotyping and phenotyping, and employ marker-assisted breeding to integrate rare yet beneficial alleles into breeding programs for the development of new genotypes [8]. SeeD is a project focused on the creation of core sets. On the other hand, traditional breeding methods, which depend on significant phenotypic evaluation, are effective, but they are a slow process for producing genetic material resilient to existing climatic conditions. Moreover, these methods are suboptimal for quickly improving resistance to various stresses [33].

3.3.2. Molecular Breeding

The integration of molecular techniques within breeding pipelines is a prevalent and effective strategy in both public and private sectors. Recent advancements in molecular breeding have enabled the creation of advanced tools that enhance breeding efficiency and facilitate the analysis of plant responses to stress. The early 1980s marked the emergence and utilization of molecular technologies in plant breeding. Plant breeding might be made more efficient and rapid with the help of molecular breeding [33]. A general term is used to describe the process of modern breeding by Whitford, Gilbert and Langridge. To expedite the release of improved germplasm, DNA markers are utilized in place of phenotypic selection [33]. Moreover, the main techniques of molecular breeding include marker-assisted selection (MAS), marker-assisted backcrossing (MABC), marker-assisted recurrent selection (MARS), and genome-wide selection (GWS)[34]. However, the integration of these methods facilitates the efficient incorporation of quantitative trait loci (QTL) and essential traits governed by large genes into breeding pipelines. A considerable number of quantitative trait loci (QTLs) with minor effects have been identified in maize concerning yield and abiotic stresses. In contrast, for various biotic challenges, only a limited number of QTLs with moderate to substantial effects have been documented[8].

Identifying genomic regions associated with the trait of interest is essential for the implementation of molecular breeding. Advancements in DNA marker technology have led to significant progress in the development of markers, genetic mapping, genome sequencing, and the scalability and affordability of technological applications. QTL mapping allows for the analysis of the genetic basis of complex traits, providing a foundation for marker-assisted selection (MAS). It is possible to find the link between a chromosomal fragment situated between two specific breakpoints and a certain phenotype using QTL mapping. Quantitative trait loci (QTL) mapping seeks to identify the genes or sequence alterations responsible for quantitative trait nucleotides (QTN). Research has identified more than 1,080 QTLs associated with yield, yield components, and flowering factors. This study primarily aims to identify genomic regions linked to drought stress resistance in maize. Conversely, there has been a limited amount of research conducted on QTLs associated with various abiotic stimuli, especially heat stress. Multiple QTLs exhibiting modest effects have been identified in maize to assess seedling stage tolerance to waterlogging[35, 36]. Furthermore, quantitative trait loci conferring resistance to significant maize diseases, including TLB, downy mildews, SLB, rust, and GLS, as well as insect pests, have been identified[37, 38]. These loci confer resistance to diseases and pests. Furthermore, implementing an additional round of marker-based selection in the later stages of the process results in inefficiency. Nine to twelve unlinked QTLs may be targeted for F2 enrichment. MARS effectively addresses the challenges associated with F2 enrichment techniques; however, the resulting products, which are recombinant inbreds, may not be fixed for the beneficial allele at all target loci[39].

Genome-wide selection, commonly known as genomic selection, represents an alternative strategy that does not necessitate prior knowledge of quantitative trait loci (QTLs). In addition, decisions are based on performance forecasts rather than intuition[40]. Genomic estimated breeding values (GEBVs) are calculated for each individual in the population by incorporating all polymorphic markers as random effects within a linear model. GEBVs provide the basis for selection. Moreover, rapid-cycle genomic selection for abiotic stresses may enhance genetic gains in stress tolerance breeding by a factor of two to three[41]. Genome-wide selection can address challenges related to the number of QTLs influencing a trait, the distribution of QTL allele effects, epistatic interactions arising from genetic background, and the integration of genetic effect information for multiple stresses in selection processes. A gene encoding β-carotene, designated as crtRB1, has been recently identified in maize. The introduction of this gene into tropical germplasm is being conducted via marker-assisted selection to address vitamin A deficiency in the developing world, as reported[42].

3.3.3. Precision and High Throughput Phenotyping

The integration of newly developed phenotyping techniques with advancements in molecular technologies will significantly accelerate the improvement of germplasm. Without standardized phenotyping field sites, the expected advantages of molecular breeding will remain unachieved. Highly variable field sites yield highly variable data, potentially obscuring genetic variation for essential traits. This holds true irrespective of the cost and accuracy of a specific phenotyping tool. Phenotypic variance among individuals can arise from various factors, including genetic and environmental influences. Heritability estimates (H) in a broad sense quantify the proportion of variance attributed to genotypic effects relative to the variance arising from environmental influences. Identifying and implementing strategies to minimize environmental variation in agricultural trials can enhance overall heritability. This may result in improved selection gains for the researchers. To enhance the cost-effectiveness of phenotyping and accelerate genetic progress in the development of climate-ready germplasm, it is crucial to improve trial heritability by minimizing environmental errors. In the context of abiotic stress tolerance breeding, optimal conditions may obscure variability. Soil sampling, soil sensors, and measurements of plant growth serve as methods for mapping variability within field sites. These methods are recognized as part of the numerous available techniques [8].

Conservation agriculture represents a crop management strategy aimed at enhancing the resilience of maize systems to climate change-related stressors. Conservation agriculture is proposed as a collection of management strategies that ensure more sustainable agricultural production, reduce production costs, and enhance profitability. The implementation of conservation agriculture is contingent upon variables including climate, biophysical soil characteristics, management conditions, and the circumstances of farmers. The principles of conservation agriculture are relevant to numerous crop production systems. New agricultural methods must not only halt further soil degradation but also enhance system resilience while reducing production costs [8]. Moreover, enhanced agronomic management can improve soil quality and increase the resilience of cropping systems to changing environmental conditions. Conservation farming, which incorporates crop rotation, minimal tillage, and crop residue, enhances water infiltration and reduces evaporation compared to conventional tillage or zero tillage methods that do not adequately preserve crop residue [43]. Conservation farming includes the practice of crop rotation. Conservation agriculture leads to increased infiltration and reduced evaporation, thereby enhancing water availability for crop production compared to conventional tillage and zero tillage with residue removal. In conservation agriculture, elevated soil water content serves as a buffer against short dry periods that may arise during the growing season. Conservation agriculture can significantly enhance crop yields during periods of inadequate rainfall distribution, particularly when contrasted with conventional tillage or zero tillage practices that do not incorporate crop residue retention. Conservation agriculture and planting techniques that raise the rooting zone above standing water, such as raised bed planting, exemplify management practices that mitigate the risk of waterlogging. Strategies that enhance infiltration can also mitigate waterlogging [8].

3.3.4. The Future Direction of Research Concerning Maize Breeding Response to Climate Change

On the other hand, it emphasizes the necessity of developing and enhancing maize varieties that exhibit resistance to stressors like drought and elevated temperatures, as well as those capable of adapting to evolving ecosystems, including climate change. This is essential for minimizing yield losses and sustaining maize production in arid regions [44]. Researchers have examined various studies in order to understand the genetic structure and regulatory mechanisms underlying maize's drought resistance. Drought-related QTL analysis has specifically pinpointed the genomes that are capable of selecting particular alleles. A significant number of genetic variations associated with drought in maize have been identified using GWAS. In addition, most of these represented genes through GWAS are still unidentified and warrant additional genetic research [9]. Recent advancements in maize breeding have employed proteomics analysis to elucidate functional insights regarding variations in gene expression [45]. The classification of subtypes within the proteome demonstrates a higher accuracy level compared to the transcriptome, aligning closely with that of genetic subpopulations. Grasping the concept of the molecular control mechanisms of drought responses through these analytical approaches can yield valuable insights for maize breeding and aid in developing new maize varieties that are more resilient to water scarcity. When breeding maize for climate change adaptation, several factors must be considered. Given the potential for accelerated climate change in the future, it is imperative for researchers to ensure the adaptation of all crops to the emerging conditions [9].

4. Conclusions

Climate change, characterized by rising temperatures and altered rainfall patterns, poses a significant threat to crop yields and food security, further aggravated by population growth, increased consumption, and heightened greenhouse gas emissions. The decline in maize growth and yields caused by recent drought stress has disrupted food supply chains globally. Advances in understanding the genetic structure and regulatory mechanisms of maize have enabled the development of temperature-resistant varieties. However, addressing future demands requires integrating innovative molecular breeding techniques and phenotyping tools to combat climate-induced challenges. Moreover, significant progress has been made in utilizing transformation studies, QTL mapping, transcriptome analysis, and genome editing to enhance drought resistance in maize. The rising production of genetically modified maize underscores its critical role in meeting food security goals. Yet, gaps remain in the introduction of adaptive cropping systems and cultivation techniques tailored to changing environments. In addition, future efforts should prioritize fostering interdisciplinary research and policy initiatives to enhance crop adaptability. Suggestions include strengthening global collaborations, promoting the adoption of sustainable practices, and reducing greenhouse gas emissions. These measures will not only mitigate climate impacts but also ensure a sustainable and resilient agricultural future.

Author Contributions

This work was carried out in collaboration with all authors. All authors read and approved the final manuscript

Data Availability Statement

The data used for this study are available upon request from authors.

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Conflicts of Interest

All authors disclosed no conflict of interest.

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