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HARNESSING POTENTIAL OF PLANT BREEDING STRATEGIES FOR CLIMATE SMART AGRICULTURE

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ABSTRACT

Climate change, rapid growth of the global population, and limitations in agricultural resources are major challenges to food security. Ensuring food security on a global scale requires a substantial increase in crop yield. Genetic variability and desired traits exploration through genomic research and breeding techniques offer promising pathways for developing crops adapted to climate variations. This all-encompassing examination delves into the dynamic relationship between climate change and agriculture, underscoring the significance of climate-smart practices to address concerns about food security. The investigation encompasses both conventional and genomic breeding methodologies, incorporating Marker-Assisted Selection (MAS), Omics-Led Breeding (OLB), and Genome Selection (GS), as well as the revolutionary CRISPR/Cas9 system for precise manipulation of genomes. By integrating these ingenious strategies, the foundation is established for cultivating climate-resilient crops that effectively mitigate the adverse impact of climate change on agriculture.

Keywords: Climate Change, Agriculture, Genomics, Breeding, Climate-Smart Practices, Marker-Assisted Selection (MAS), Omics-Led Breeding (OLB), Genome Selection (GS), CRISPR/Cas9, Climate-Resilient Crops.

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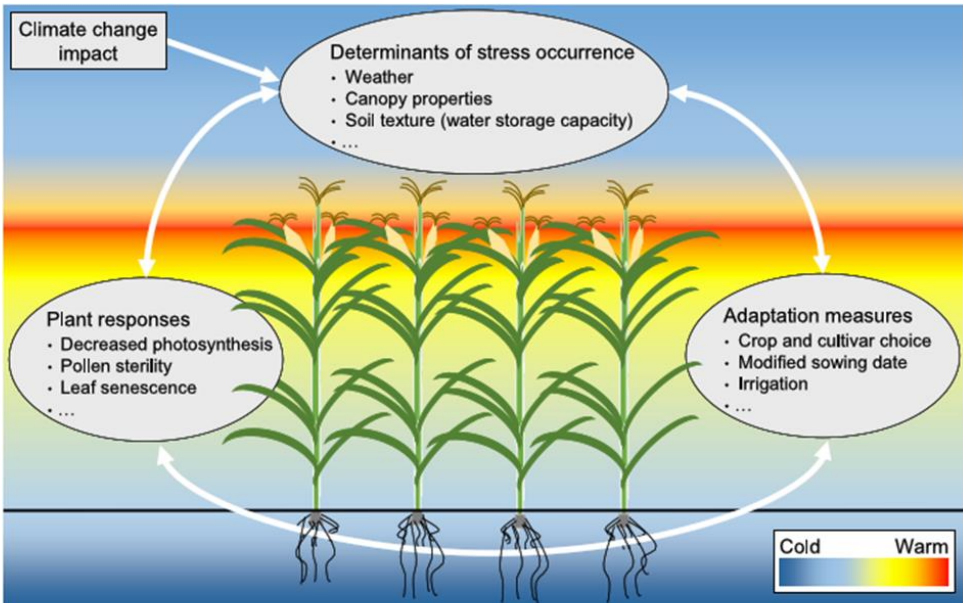
1. INTRODUCTION

Climate change and its association with agriculture is of considerable importance due to their interdependence and reciprocal impacts on each other. Climate change has been found to have both direct and indirect impacts on the agricultural sector, leading to unfavorable consequences. The significant influence of climate fluctuations and changes on food self-sufficiency and security cannot be overstated. While climate change does pose a threat to crop yield, it is crucial to recognize that this phenomenon also presents noteworthy opportunities for enhancement (Thuiller, 2007). The main goal of global agricultural and forestry systems is to ensure food security by cultivating high-yield crops that can adequately meet the projected demands of the worldwide human population. Over the past few decades, there has been a notable decrease in agricultural productivity attributed to the impacts of climate change.

Within the agricultural domain lie a diverse array of hindrances, encompassing factors such as the expansion of human populations, fluctuations in climatic patterns, malnutrition-related issues, poverty, hunger, and numerous other stress-inducing factors. Overcoming these challenges becomes increasingly onerous in the absence of integrating genetic enhancements into plants, which serve to boost agricultural output and effectively address concerns pertaining to yield reduction, pest control, and interactions with climate change. Therefore, it is imperative for the agricultural sector to undergo a significant transformation in order to effectively address the increasing demands of the global population. This transformation entails shifting towards contemporary and efficient agricultural practices (Satterthwaite et al. 2010).

Crop production and productivity encounter substantial limitations on a global scale, which impose a substantial pressure on agriculture. Presently, Earth's global population is experiencing rapid growth, while crop yield is being increased at a more gradual pace. Consequently, the mission of ensuring sufficient sustenance for these swiftly expanding populations presents a considerable hurdle, primarily arising from the disparity between population growth rate and crop yield level (Tomlinson, 2013). This discrepancy's primary cause can be attributed to climate change's substantial impact and its resultant consequences. The assurance of global food security poses formidable challenges due to profound climatic fluctuations, diminishing arable land, and projected population increments to 8.6 billion by 2030 and 10 billion by 2050 (Tacoli, 2010).



Source: Future Crop Production Threatened By Extreme Heat

Understanding the improved crop production as a dire need of time, it is crucial to ensure a 70% rise in grain production in the forthcoming decades to effectively support the global human population (Tomlinson, 2013). The rapid and exponential expansion of the global human population has resulted in a critical and urgent demand for an annual growth rate of 37% in the production of food (Beddington et al. 2011). The stipulation is greatly impacted by the ramifications of climate change and variations in agricultural productivity. Concurrently, climate change has a significant influence on the structure of the Earth, resulting in increased temperatures, altered patterns of precipitation, depletion of the ozone layer, and rising concentrations of carbon dioxide. These changes have adverse consequences for agricultural output. Rapid economic growth is associated with significant increases in income, which in turn accelerates the transition towards a more varied consumption of agricultural products (Tilman and Clark, 2014). According to projections, it is important for the agricultural sector to increase food production by around 60-100% by the year 2050, in comparison to present-day levels. Hence, prioritizing the objective of achieving abundant food production becomes crucial to meet the growing need for nutritional steadiness. This remains relevant regardless of the interconnected connection that exists between changes in climate patterns and the unfavorable outcomes associated with increased temperatures, restricted water availability, and obstacles connected to land utilization. These factors are anticipated to have a substantial impact on the capability to produce an acceptable quantity of nourishment (Basner et al. 2014).

Throughout the years, plant breeders have effectively enhanced food production using a range of breeding strategies and practices. However, the use of monoculture practices has resulted in a decline in agricultural output, resulting in a significant decrease in genetic variety and posing a significant obstacle to reaching sufficient food production (Khoury et al. 2014). The combination of traditional agronomic methodologies and sophisticated plant breeding techniques has been instrumental in achieving significant advancements in crop yields from 1960 to 2015. The increase in productivity witnessed a substantial boost owing to the introduction of improved varieties, along with the utilization of irrigation, mechanized agricultural methods, and widespread adoption of synthetic fertilizers during the initial period of the green revolution. The improvements in productivity linked to the green revolution are now diminishing for several pivotal crops within the agricultural domain due to an assortment of challenges. The current trajectory of yearly production increases for key crops, which ranges from 0.9% to 1.6%, is insufficient to meet future demands. Therefore, it is imperative to attain yearly increments in agricultural yield of 2.4% in order to meet global food demands (Ray et al. 2013).

Hence, the primary focus should be on the cultivation of advanced strains of climate-resilient crops to enhance agricultural output in conjunction with the growing global populace. In order to effectively tackle the urgent global concerns and boost agricultural genetics, it is imperative to smoothly integrate conventional plant improvement methods with marker-assisted breeding techniques (Bellamy et al. 2018). The future of agricultural progress and enhanced production and productivity relies heavily on the integration of marker-assisted plant breeding, which enables quick advancements within a limited timescale. The integration of biotechnology into plant development is crucial for tackling the difficulties posed by global climate change. This integration is essential as it has the potential to enhance crop yields and effectively tackle concerns connected to yield loss. The implementation of sophisticated breeding techniques holds great importance in the improvement of agricultural output, the alleviation of poverty achieving zero hunger goals hunger, and the enhancement of living conditions by means of better crop yields (Gruhn et al. 2000).

From 2012 through 2022, the worldwide yield of vital grains underwent marked shifts. Wheat output surged from 718.4 million tonnes to 775.8 million tonnes, showcasing an unwavering ascendant pattern. Rice production encountered a similar upward trajectory, ascending from 725.1 million tonnes to 783 million tonnes. The most remarkable alteration unfolded within corn cultivation, as production catapulted from 808.9 million tonnes in 2012 to an impressive 1,143.6 million tonnes in 2022, unveiling a momentous upsurge in yield. Correspondingly, soybean output progressed from 319.6 million tonnes to 388.5 million tonnes, exemplifying a persistent upward motion. Sorghum and millet, albeit on a diminutive scale, also displayed expansion, with sorghum production ameliorating from 62.3 million tonnes to 83.7 million tonnes, and millet production escalating from 29.9 million tonnes to 35.6 million tonnes, elucidating propitious inclinations traversing the spectrum of principal grains during the preceding decade (Table 1).

Table 1: Comparison of grain production in the world in the last decade (Source: FAO 2023)

Grain	Production in 2012 (million tonnes)	Production in 2022 (million tonnes)
Wheat	718.4	775.8
Rice	725.1	783
Corn	808.9	1,143.60
Soybeans	319.6	388.5
Sorghum	62.3	83.7
Millet	29.9	35.6

The corn's production has experienced a significant upswing over the last ten years, followed by soybeans and wheat in succession. This transformation stems from a medley of factors, which encompass heightened mechanization, improved irrigation methods, and the advent of fresh crop variants showcasing augmented resilience against pests and maladies. In a global context, the yield of grains has undergone a notable 12.4% increase over the preceding decade. This affirmative unveiling denotes a rise in the production of nourishment to address the burgeoning worldwide populace. Nonetheless, it remains imperative to emphasize that this surge in output has not undergone a uniform dispersion. Several nations, with China and India as instances, have observed considerable elevation in their grain production, whereas others, akin to sub-Saharan Africa, have encountered stagnation or even contraction in their yield. Hence, it remains pivotal to consistently direct investments into agricultural exploration and pioneering to safeguard our capacity to fulfill the imminent nutritional requisites (FAO 2023).

Conventional plant breeding has proven to be effective in meeting individuals' choices for both quantitative and qualitative features. The realm of plant breeding mainly focuses on hereditary biological traits that are transferable across consecutive generations. The objective is to enhance the resilience of crop plants against adverse climatic conditions, thereby intensifying their robustness. The enhancement of the genetic output potential of crops frequently relies on the presence of substantial genetic variety and the effective utilization of this diversity through the practice of selective breeding. The existence of genetic diversity is a fundamental requirement for the successful execution of efficient plant breeding methodologies. The science of enhancing plant traits through scientific techniques constitutes the discipline of plant breeding. To attain this goal, intentional generation of genetic diversity and appropriate selection methods are employed (Galsky et al. 2020). In order to address the increasing needs for crop production, it is much demanding to combine traditional breeding methods with a range of biotechnological approaches. This integration aims to improve crop genetic enhancement and accelerate the breeding process. Molecular breeding encompasses the act of enhancing genetic material via the application of molecular biotechnologies. This procedure involves the utilization of molecular markers combined with genomics and linkage mapping techniques (Gornall et al. 2010).

Genomic research assumes a crucial position in the enhancement of crops, placing specific emphasis on the identification of genetic variability and desired qualities. Additionally, it involves the characterization of diverse genetic materials of crops to develop resilience against abiotic and biotic stressors. The emergence of genome editing tools, particularly CRISPR/Cas9, has created novel opportunities for rapid and accurate genome alterations aimed at advancing, understanding and facilitating enhancement endeavors (Scheben et al. 2017). This technique of genome editing focuses on specific site directed modifications in the desired genomes hence permitting the alteration of observable qualities. Currently, a number of crops improved by genome editing have been introduced into the commercial markets of developed nations such as the United States, with a particular focus on the cultivation of drought and salt-resistant types. The imperative emphasis on enhancing crop plant performance via genomic methodologies is of paramount importance in the advancement of climate-adaptive agricultural cultivars (Waltz, 2018).

Wide-ranging weather patterns are impacted by the worldwide climate change phenomena, which modifies factors like temperature, precipitation patterns, and wind dynamics. The components that form the structure of Earth's climate system, from which climate change arises, involve the atmosphere, hydrosphere, biosphere, cryosphere, and lithosphere. Climate alteration originates from two fundamental causes. In contrast to human-induced influences, such as deforestation, carbon dioxide emissions from industry and agriculture, acid rain, ozone layer depletion owing to Freon gas, and greenhouse gases, natural reasons are the primary and most significant drivers of climate change. (Venterea et al. 2012). Numerous factors, such as variations in solar activity, volcanic eruptions, ocean temperature changes, patterns in the distribution of the ice caps, westerly waves, and atmospheric waves, are responsible for these natural occurrences. The commencement of the Industrial Revolution triggered the genesis of worldwide temperature elevation, characterized by Earth's warmth elevation. The leading impetuses for this transformation are the gases within the greenhouse category. This group includes carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and Sulphur hexafluoride (Christianson et al. 2021).

A variety of difficulties are faced by agriculture in areas with arid and semi-arid climates. The main factors causing these obstacles are the world's constantly expanding population, the ongoing economic changes, the lack of water supply, the pervasive dryness, and the wide-ranging effects of climate change. Genetic diversity must be preserved to ensure the unbroken continuation of species because it promotes the evolution of adaptable responses to a wide range of ecological challenges involving both animate and inanimate components. Furthermore, it enables the capacity to manipulate the genetic composition in reaction to changes in the surrounding milieu. The various limitations imposed on production processes have a direct impact on the stability of crop yields, ultimately contributing to the issue of global food insecurity. The further advancement of agricultural development, characterized by notable enhancements in many morphological and agronomical characteristics, is contingent upon the substantial presence of plant genetic variety (Eigenbrode et al. 2018).

Based on climate modelling research, it is anticipated that climate change will have adverse effects on the agricultural productivity of various tropical and mid-latitude countries, leading to a potential decline in food crop production (Luck et al. 2011). As a result, it is anticipated that the quantity and quality of food crops and forage would diminish as climate change progressively intensifies. The escalation of severe weather phenomena is anticipated to sustain price and yield fluctuations, thereby presenting hazards to livelihoods and the stability of food supplies in forthcoming times. This demand is further compounded by the limited availability of arable land. Therefore, it is imperative for the agricultural sector to prioritize the production and improvement of crop plants in order to augment yields on current agricultural land. This can be achieved by embracing the cultivation of climate-resilient crops (Myers et al. 2014).

1.2. Climate-smart Agriculture

A novel farming strategy, denoted as "climate-smart agriculture," recognizes and confronts the complex challenges presented by shifts in the climate. According to the work of (Lipper et al. 2014), the key aims of this endeavour involve achieving sustainable and increased agricultural output, fostering the development of climate-resilient crops, mitigating emissions, and advocating for national food security and developmental initiatives. Crafted with three interconnected components, this methodology is designed to achieve its central objective by giving precedence to resolving climate-induced dilemmas that obstruct the upsurge in necessities for agricultural production, particularly pertaining to sustenance, energy, and materials. A crucial role is played by climate-smart agriculture (CSA), which provides essential advantages like increased economic growth, food security, reduced poverty, the cultivation of crops that can adapt to changing climates, and increased agricultural productivity (Lipper et al. 2014).

The concepts of climate-smart agriculture endeavor to address existing limitations by emphasizing the gathering of information, addressing climate-related difficulties, advocating for multidisciplinary research, and applying solutions that are supported by empirical data. These topics encompass three primary domains: The study focusing on primarily centers of three key domains: the investigation of farm and food systems, the scrutiny of landscape and regional issues, and the assessment of institutional and policy components ha suggested that the first two aspects of the research involve an analysis of crop physiology and genetics, as well as livestock and agricultural mitigation and adaptation (Scherr et al. 2012).

Moreover, the examination delves into impediments related to adopting climate-smart techniques, managing climate risks, and utilizing energy and biofuels. Furthermore, the research delves into the examination of adaption modelling and uncertainty, the achievement of multifunctionality, the dynamics of food and fishing systems, the preservation of forest biodiversity and ecosystem services, the consequences of climate-induced rural migration, and the utilization of metrics. This emphasizes the importance of constructing multidisciplinary research designs that incorporate stakeholder involvement in order to establish direct connections between scientific investigation, practical application, and governance (Arslan et al. 2014).

1.3. Agricultural Productivity

Climate-smart agriculture endeavors to consistently enhance agricultural productivity and augment money generated by livestock, crops, and aquatic organisms, while minimizing adverse impacts on the environment. The main goal of this undertaking is to get improved nutrition and ensure food security. The significance of agricultural productivity becomes highly relevant in the context of sustainable intensification. The significant impact of food production on environmental changes gains widespread recognition as it is connected with approximately one-third of global greenhouse gas emissions and constitutes 70% of freshwater usage (Willett et al. 2019).

The Table 2 offers insights into the repercussions of climate shifts upon primary crops and potential strategies for acclimatization aimed at alleviating these repercussions. Elevated temperatures and heightening hazards of aridity loom as perils for wheat, rice, corn, soybeans, and maize yields, culminating in 5-10% reductions in output encompassing diverse locales. To counteract these difficulties, cultivators can opt for crop strains resilient to drought, incorporate methodologies for irrigation, and deploy cover crops to augment the retention of soil moisture. Rice confronts supplementary hazards stemming from the ascent of sea levels and infiltration by saline waters, instigating 5-10% dwindles in yield within coastal regions. The process of acclimatization entails the cultivation of rice equipped to endure salt content, the adoption of irrigation techniques prudent in water use, and the calibration of field altitudes. This all-encompassing dataset, derived from academic inquiries;(Juroszek and Von Tiedemann, 2013; Rezvi et al. 2023);(McFadden and Smyth, 2019);(Guo et al. 2022);(Chisanga et al. 2022), accentuates the immediate necessity for agricultural alterations to uphold the global output of crops when confronted with climate shifts.

The outcomes of climate alteration and the approaches for managing it will differ, reliant on the crop and area. The observed decrease in production will also oscillate according to the location and the degree of climate shift. It is of paramount importance to understand that climate transformation is a intricate issue, and a one-size-fits-all solution is absent, adaptable for all crops and regions. Nonetheless, by grasping the potential consequences of climate alteration on agricultural yield, those in agriculture and policymakers can initiate actions to adjust and mitigate the linked risks.

Table 2: Climate-Change Impact on Major Crops

Crops	Climate-Change Impacts	Potential Adaptation Strategies	Observed Decrease in productivity	References
Wheat	Increased temperatures and droughts can reduce yields.	Drought-tolerant varieties of wheat, use irrigation, and plant cover crops to help retain moisture in the soil.	10-20% decrease in yields in some regions	(Juroszek and Von Tiedemann 2013)
Rice	Rising sea levels and saltwater intrusion can damage rice fields.	Saltwater tolerant rice varieties, use water-saving irrigation techniques, and raise the elevation of rice fields.	5-10% decrease in yields in some coastal regions	(Rezvi et al., 2023)
Corn	Increased temperatures and droughts can reduce yields.	Adoption of drought-tolerant varieties of corn, use irrigation, and plant cover crops to help retain moisture in the soil.	5-10% decrease in yields in some regions	(McFadden and Smyth 2019)
Soybeans	Increased temperatures and droughts can reduce yields.	Drought-tolerant varieties of soybeans, use irrigation, and plant cover crops to help retain moisture in the soil.	5-10% decrease in yields in some regions	(Guo et al., 2022)
Maize	Increased temperatures and droughts can reduce yields.	Drought-tolerant varieties of maize, use irrigation, and plant cover crops to help retain moisture in the soil.	5-10% decrease in yields in some regions	(Chisanga et al., 2022)

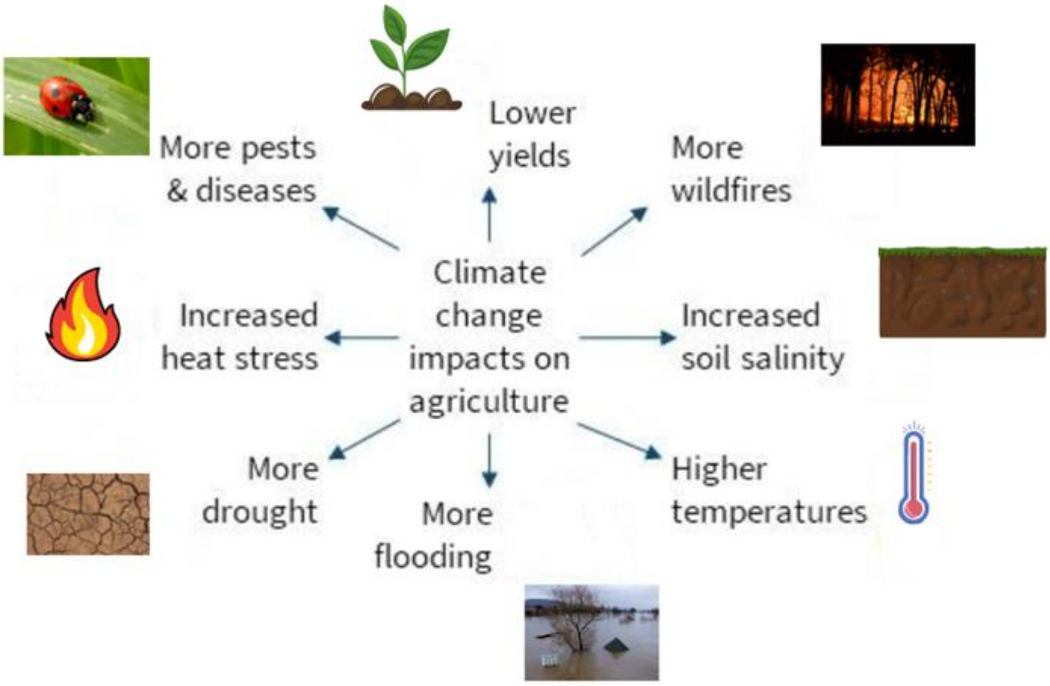


Fig. 2: Climate Change Impact.

1.4. Food Security as a Dire Need of Time

Food security can be perceived as the condition where individuals consistently have the means to obtain an adequate amount of safe and nutritionally balanced food, thus fulfilling their dietary needs and preferences while promoting an active and healthy lifestyle. Food security depends on three essential elements: the availability of sufficient food supplies, accessibility to acquire food, and the efficient utilization of food resources. It encompasses several characteristics, specifically food availability, access, utilization, and stability, as portrayed in academic literature. Evaluating food availability involves utilizing diverse data, including crop output, food production indicators, animal ownership indicators, and national food balance sheets (Renzaho and Mellor, 2010).

The ability to obtain food is contingent upon the range of different combinations of goods and services that an individual can acquire within a given community, utilizing their legal entitlements and available resources. Food utilization encompasses the effective use of food resources by means of a balanced and nourishing diet, access to clean water, proper sanitation practices, and enough healthcare, with the ultimate goal of achieving optimal nutritional well-being. Food stability refers to the consistent availability of sufficient food resources for a population, home, or individual, ensuring their sustained access to an appropriate food supply without interruption (Sen, 2017).

Table 3: Major food security crop plants' adaptations to climate change

Crops	Adaptations	References
WHEAT	• Utilization of heat-resistant strains • Modification of sowing timelines • Optimal populace of plants	(Ahmad, et al., 2018)
RICE	• Application of systematic rice intensification using alternating wet and dry conditions • Direct seed placement	(Weerakoon WMW, et al. 2011)
MAIZE	• Planting on elevated beds • Utilization of cultivars with accelerated maturation • Precise management of nutrients	(CIAT, et al. 2017)
COTTON	• Cultivars with resilience to high temperatures and drought • Augmentation of plant density by 18%	(Rahman, et al. 2018)
SUGARCANE	• Management of ratoons • Indentation-based planting	(Singh, et al. 2011)
CHICKPEA	• Comprehensive regulation of weed proliferation • Incorporation of agro-forestry (Wind break) • Enhancement of crop variants (early maturity)	(Ratnam, et al. 2011)

The Table 3 shows ideas to help important crops deal with changes in the weather. For wheat, this includes using plants that can handle the heat, changing when you plant, and putting plants closer together. For rice, the suggestions are to use a special way of growing with wet and dry times, and planting seeds right in the ground. For maize, it's a good idea to plant on high beds, use plants that grow faster, and manage nutrients carefully. For cotton, it's good to use plants that can handle heat and dryness, and put more plants close together. Sugarcane should be managed well after the first growth, and planted using a specific method. Chickpeas can do better when you control weeds, mix trees with farming to block the wind, and use kinds of crops that grow early.

The vulnerability of food security in the context of climate alteration pertains to the food system's capability to realize security objectives within the context of climate change. This covers diverse dimensions that involve environmental, economic, and social facets. Climate shifts impact distinct dimensions of food security, comprising availability, access, use, and stability. These effects trace both direct and indirect paths, affecting food security and the continuity of livelihoods. The African continent undergoes climate variation outcomes, including food security, water resource availability, and production levels ((Turral et al. 2011).

1.5. Plant Adaptation to Climate Changes

The process of crop adaptation to climate change involves a comprehensive, multi-faceted approach to enhance the resilience of both natural and societal systems. This strategy aims to counter and recuperate from the consequences of climate shifts. The core aim resides in the reduction of vulnerabilities within these intricate systems. The effective implementation of this strategic approach holds immense importance in mitigating the impacts of climate change, notably in areas prone to recurrent drought occurrences (Berrang-Ford et al. 2011).

To effectively handle vulnerabilities in societal and ecological frameworks, the strategic allocation of resources to climate adaptation strategies plays a pivotal part. Such action assists in mitigating the impacts of global warming. Of particular significance, adaptability plays a critical role in food security, relying on genetic diversity within and among diverse crop species. The presence of genetic variety within crop species offers promising potential in bolstering their resilience to ever-evolving climatic circumstances. Emphasizing adaptability can lead to valuable outcomes in maintaining food security amidst the challenges brought by shifting climates (Scott and Becken, 2010).

Severe weather phenomena, such as extreme temperatures during crucial growth phases, can cause sterility in grains and a resulting reduction in output, thus rendering agricultural productivity vulnerable to various challenges associated with climate change. Adaptation methods play a crucial role in preventing climate-linked hazards within the agricultural sector and mitigating their adverse effects. The necessity to uphold productivity under shifting climate circumstances necessitates the creation of cultivars that exhibit early maturation and the ability to withstand drought and heat stress (Fischer et al. 2002).The development of novel cultivars by traditional plant breeding and genomics research is a crucial approach for the adaptation of agriculture to the challenges posed by climate change. The presence of genetic variety is of utmost importance in the enhancement of crops and the creation of varieties that are adaptable to climate change. The incorporation of genetically modified natural variants into breeding programmer boosts the genetic diversity associated with stress tolerance, hence improving agricultural productivity under challenging environmental conditions. Understanding genetic variety is a fundamental aspect in the enhancement of crops, and the process of effective selection becomes important when there exists an ample amount of genetic variation for various attributes (Scheben et al. 2017).

The critical adoption of policies targeted at adapting to climate change is necessary to ensure the long-term sustainability of food security and agricultural productivity in the face of changing climatic conditions. The preservation of genetic diversity is of utmost importance in the advancement of climate-resilient agricultural crops and the alleviation of the adverse effects of climate change on the agricultural sector (Dwivedi et al. 2017).

1.6. Plant Breeding Strategies in the Era Climate Change

To battle the impacts of climate change and curb the atmospheric greenhouse gases like carbon dioxide, nitrous oxide, and methane, various tactics come into play. The key lies in effectively adopting breeding methods to combat greenhouse gas discharges, notably methane and nitrous oxide, originating from diverse origins like grazing creatures and soil. These strategies further possess the potential to actively capture carbon from vegetation and soil, rendering a significant aid in addressing climate change mitigation(Jana et al. 2019).

The genetic modification of crops is of paramount importance in enhancing agricultural productivity and enhancing the overall quality of agricultural commodities. Furthermore, it functions as a mechanism to tackle climate change and mitigate the detrimental environmental impacts linked to agricultural methodologies. The objective of climate-smart agriculture is to effectively reduce and eliminate the release of greenhouse gas emissions, in situations where it is practical and possible. Mitigation measures encompass the avoidance of deforestation resulting from agricultural growth, as well as the enhancement of agriculture's capacity to sequester carbon dioxide from the atmosphere (Senapati and Yager, 2019).

The long-term significance of environmental variability on global agriculture and food security is substantial. The matter of food security and safety is compromised by unfavorable meteorological circumstances, a persistent concern rather than a recent occurrence. However, in the past, no measures were taken to address this issue. Hence, the global imperative lies in effectively managing and adapting to these fluctuations in weather patterns. In order to facilitate the adaptation of crops to evolving environmental challenges, a multitude of ways are necessary (Cowls et al. 2021).

1.7. Cultural Strategies

Farmers have implemented cultural techniques in order to address climatic fluctuations and facilitate plant adaption. Several strategies can be employed to enhance agricultural adaptability under climatic stress conditions. These strategies encompass modifying planting and harvesting schedules, cultivating crops with shorter life cycles, using crop rotation practices, utilizing appropriate irrigation systems, and introducing variations in cropping schemes. Advantages have been observed in the application of these measures to bolster crop resilience when confronted with adverse climate conditions (Henderson et al. 2018).

To enhance agricultural adaptability and guarantee food safety and security amidst climatic uncertainty, essential techniques involve implementing changes to sowing schedules, adopting drought-resistant cultivars, and diversifying crop production. Critical crop management strategies, such as meticulously selecting sowing times, planting densities, and optimal irrigation approaches, hold utmost significance in fostering crop growth and development amid varied environmental pressures (Deutsch et al. 2018).

Fertilizers have a crucial role in mitigating the impacts of global warming and enhancing plant adaptation. Microorganisms have a crucial role in the provision of vital nutrients to plants, the preservation of soil fertility, and the enhancement of productivity. Consequently, their significance in sustaining global nourishment is indubitable (Lyon et al. 2018).

1.8. Conventional Techniques

Historically, plant breeding techniques have been utilized to actively contribute to the progress and improvement of crops in response to various environmental challenges. Genetic divergence analysis is utilized to assess polymorphism, inbreeding, assortment, and recombination in the pursuit of enhancing plant features and cultivating stress-resistant cultivars(Measham et al. 2011).

1.9. Genomics and Genetics Strategies

1.9.1. Omics-Led Breeding (OLB)

The utilization of omics methodologies offers significant contributions to the comprehension of genetic information's biological roles in the context of crop enhancement and development. The integration of population genomics and quantitative genetics facilitates the identification of genes that play a crucial role in determining ecologically significant features. The use of genomic methodologies into breeding programs facilitates the evaluation of superior germplasms possessing a multitude of desirable features. The field of genomics facilitates the exploration of molecular mechanisms that underlie the ability of organisms to withstand abiotic stress(Stougaard, 2001).

1.10. Marker-Assisted Selection (MAS)

Marker assisted selection (MAS) operates as a method employing DNA markers to locate and opt for plants harboring sought-after genes or attributes, spanning disease resistance, drought endurance, or amplified yield (Hasan et al. 2021). Through reducing the need for phenotypic assessment and heightening selection intensity, MAS can expedite the breeding process (Kushanov et al. 2021). The notion of omics-driven breeding is linked to the amalgamation of omics data—encompassing genomics, transcriptomics, proteomics, metabolomics, and phenomics—into the sphere of plant breeding. This approach can yield a holistic grasp of the molecular mechanisms and interactions underpinning intricate traits, such as quality, stress response, and adaptation (Tang et al. 2009).

This important knowledge holds significant value for the progress of climate-adaptive farming, as it contributes to the growth of crops that demonstrate enhanced yield and efficacy in response to shifting weather conditions. The application of marker-assisted selection (MAS) has garnered recognition as a valuable tool to expedite breeding advancements, thus playing a critical role in improving crop attributes and overall productivity.

1.11. QTL Mapping

By employing quantitative trait loci (QTL) analysis to investigate traits associated with yield, the potential emerges to cultivate innovative varieties displaying heightened adaptability to non-living stress conditions. The indispensable role of molecular plant breeding techniques lies in boosting crop production amidst various living and non-living stressors (Zahra et al. 2021).

The emergence of pioneering sequencing technologies has remarkably mitigated the challenges tied to investigating genomic variations, leading to the revelation of a substantial pool of DNA polymorphisms, notably single nucleotide polymorphism (SNP) markers. Progress in linkage maps has significantly enhanced QTL mapping precision, with the typical range reducing from 10–30 centimorgans to less than 1 centimorgan. The utilizations of the high-throughput phenomics approach additionally enhances the precision of quantitative trait loci (QTL) mapping(Garg et al. 2014). Researchers accomplished the successful creation of drought-resistant wheat varieties, like "Ripper,"and superior maize germplasm, sustaining grain yield and quality through QTL mapping. In-depth examinations into bread wheat and durum wheat have taken place to detect QTLs concerning drought stress. Barley QTL investigations have uncovered distinct and dependable genomic regions overseeing malting attributes. Additional QTL research has concentrated on pinpointing crucial genome loci in bread wheat during hyper-temperature scenarios and delving into singular allelic differences in wheat, augmenting the scope for drought-tolerant cultivars (Sagita et al. 2021).

In Table 4, an illustration is presented regarding the introduction of Bt cotton and its consequential impact on notable enhancements in cotton yields across both India and China. It is worth noting that India witnessed a 25% increase in yields between 2002 and 2010, while China experienced an even more substantial surge of 40% during the same time frame.

Table 4: Varieties Developed through Omics-Led Breeding and MAS

Variety	Description	Reference
Drought Gard	• Drought Gard, a maize variety that has improved drought tolerance due to the insertion of a bacterial gene (cspB) that encodes a cold shock protein using genetic engineering. • This variety can maintain higher yields under water-limited conditions and has been commercialized in the USA and Africa.	(McMillen et al., 2022)
Golden Rice	• Golden Rice, a rice variety that has enhanced provitamin A content due to the introduction of two genes (psy and crtl) from daffodil and maize using genetic engineering. • This variety can help prevent vitamin A deficiency, which affects millions of children and pregnant women in developing countries.	(Tang et al., 2009)
IR64-Sub1	• IR64-Sub1, a rice variety that has enhanced tolerance to submergence stress due to the introgression of the Sub1 gene from a landrace using MAS. • This variety can survive up to two weeks of complete submergence and has been widely adopted by farmers in flood-prone areas of Asia.	(Singh et al., 2009)

The driving force behind these heightened yield levels is attributed to the insect-resistant traits inherent to Bt cotton. This particular strain of cotton produces a protein with detrimental effects on specific insects, notably bollworms. As a result, farmers can limit their reliance on pesticides, culminating in amplified yields and reduced financial outlays. Moreover, Table 4 underscores the widespread adoption of Bt cotton in both India and China. The data showcased reveals that Bt cotton constitutes more than 90% of the cotton cultivated in India and exceeds 80% in China. These revelations posit the potential of biotechnology to exert a significant influence on elevating cotton productivity in the foreseeable future (Tabashnik and Carrière, 2020).

1.12. Genome Selection (GS)

The crop improvement realm employs a cutting-edge method called Genomic Selection (GS), utilizing high-throughput phenotyping and dense markers to assess prime germplasm, elevate polygenic traits, and accelerate breeding line development. Various statistical models have surfaced to tackle genome estimation in multi-environment setups. This study introduces a linear mixed model to explore genotype × environment (G × E) interactions within a high-dimensional framework, encompassing genetic markers and environmental elements for the G × E analysis (Heffner et al. 2009). The proposed model is a GBLUP-type model that incorporates phenotypic regression to account for the interaction between markers and environments (M × E). A contemporary Bayesian-based model that encompasses several environments. The aforementioned methodologies have been utilized in the examination of wheat and maize cultivars, whereby the G × E model has exhibited notable levels of significance and superior genomic predictions in comparison to alternative models(Crossa et al. 2017).

Among the technologies showing promise in genomic selection (GS) are Diversity Arrays Technology (DArT) markers, succeeded by Single Nucleotide Polymorphisms (SNPs) and Genotyping-by-Sequencing (GBS) techniques (Wang et al. 2017). Grains, namely wheat, barley, oat, and durum wheat, have served as primary focal points for genomic selection (GS) studies. Notably, GS strategies have been devised in the context of wheat breeding to identify germplasms demonstrating heightened adaptability to climate fluctuations. The integration of high-throughput phenotyping and genomic data has been employed to investigate the impacts of heat and drought conditions on elite wheat cultivars (Cabrera-Bosquet et al. 2012).

Table 6 shares insights on the link between disease resistance in different crops and specific parts of their genes or markers. For wheat, protection against diseases like Rusty leaves, Rusty stems, and Rusty patterns is connected to Lr34, Sr31, and Yr15 markers. In rice, the ability to resist Exploding rice and Attacking midges is related to the Pi5(t) part and Gm7 unit. In maize, defense against Sugary viruses involves Scm1 and Scm2 molecules. For Barley, fighting Pale mosaic virus uses the rym4/rym5 genes, and Rusty leaves defense has the Rph7 symbol. To find these parts, scientists use techniques like DNA Fingerprinting, Molecular Barcoding, Genetic Sequences, and more. The sources (Suenaga et al. 2003; Mago et al. 2002; Chague et al. 1999; Jeon et al. 2003; Sardesai et al. 2002; Dussle et al. 2002; Williams, 2003; Graner et al. 2000) give more information on these methods. This info shows how important genes and markers are for making crops more resistant to diseases.

1.13. Crop Improvement using the Crispr/Cas9 System

Taking cues from prokaryotic defense mechanisms activated by type II RNA organization to fend off viral invasions, CRISPR/Cas9, a contemporary genome editing method, has revolutionized the field of genome editing. This technology has paved the way for generating gene mutants and specifically modifying individual nucleotides within a genome, offering immense potential in supporting crop breeding initiatives for the development of high-yield and stress-tolerant cultivars. Recognized as an environmentally sustainable approach for creating genetically modified plants, the CRISPR/Cas9 tool is gaining widespread acclaim, escaping transgenic classification. Its capabilities hold a bright future in addressing environmental challenges and ensuring food security. (Mahfouz et al. 2014).

Table 5: Transgenic Bt cotton has increased cotton productivity in relation to the integration of biotechnology over the last two decades.

Country	Year	Yield (kg/ha)	% Increase
India	2002	200	10
India	2010	250	25
China	2002	220	5
China	2010	300	40

Table 6: Disease resistance in various crops is correlated with genes and markers.

ORGANISMS	CHARACTERISTIC	GENETIC ELEMENTS	DNA TAG	SOURCE
WHEAT	Rusty leaves (Puccinia recondita f.sp. tritici)	Lr34 extracted from T. aestivum	Sequence Specific	(Suenaga et al., 2003)
WHEAT	Rusty stems (Puccinia graminis f. sp. tritici)	Sr31 element	DNA Fingerprint	(Suenaga et al., 2003)
WHEAT	Rusty patterns (Puccinia striiformis f. sp. tritici)	Yr15 markers	Random Amplification	(Chagué et al., 2010)
RICE	Exploding rice (Pyricularia oryzae)	Pi5(t) factor	Molecular Barcoding	(Jeon et al., 2003)
RICE	Attacking midges (Orseolia oryzae)	Gm7 unit	Specially Altered	(Jeon et al., 2003)
MAIZE	Sugary viruses (SCMV)	Scm1 and Scm2 molecules	Genetic Labels	(Jeon et al., 2003)
BARLEY	Pale mosaic virus	rym4/rym5 genes	Genetic Sequences	(Williams, 2003)
BARLEY	Rusty leaves (Puccinia hordei)	Rph7 symbol	DNA Barcoding	(Graner et al., 2000)

CRISPR/Cas9 technology has found extensive application in editing plant genomes to confront abiotic and biotic stresses. The study delved into CRISPR genome editing's utilization, targeting the genes TaERF3 and TaDREB2, with the objective of bolstering abiotic stress resilience. Similarly, 21 KUP genes were identified in cassava, displaying heightened expression in reaction to abiotic stress factors, showcasing their potential to impart drought resistance. To explore drought tolerance research, a genome-wide analysis examined the role of MAPKKK genes. Rice cultivation saw the implementation of the CRISPR/Cas9 system to create triplet mutants, impacting the genes TGW6, GW5, and GW2, pivotal in seed size regulation. Gene mutation yielded a notable 30% increase in seed size. (Ahmad et al. 2020).

Employing a similar technique, the researchers aimed to enlarge wheat seeds by inhibiting the TaGW2 gene, which limits seed size. Utilizing CRISPR/Cas9 technology, wheat was engineered to achieve reduced gluten levels without genetic alteration. The tomato mutant lines displayed heightened vulnerability to oxidative stress amid drought conditions. This study's outcomes emphasized the importance of the SlMAPK3 gene in drought tolerance pathways. Additionally, enhancing drought tolerance can be attained through genetic engineering to overexpress this gene (Zhang et al. 2021).

Table 7: An overview of the research on crispr-mediated plant disease resistance

Disease Agent	Cultivated Plants	Desired Alteration	Targeted Genetic Material	Targeted Maladies	Outcomes	Source
Fungus	Rice	Imitating natural processes	Eif4g	Malady caused by Rice tungro spherical virus	Attainment of resistance to the virus	(Macovei et al., 2018)
	Rice	Disruption of genetic sequence	Employment of singular and multiple gRNA at OsERF922	Rice blast caused by Magnaporthe oryzae	Significant reduction in blast lesions	(Wang et al., 2016)
	Rice	Disturbance of genetic structure	OsMPK5	Pathogenic agents Magnaporthe grisea (fungus) and Burkholderia glumae (bacteria)	Identification of indels within the objective; unconfirmed resistance	(Xie and Yang, 2013)
	Wheat	Genetic sequence modification	TaMlo-A1, TaMloB1, and TaMlo-D1	Powdery mildew	Development of heightened resistance to the ailment	(Wang et al., 2014)
	Wheat	Genomic alteration	TaMlo	Pathogen causing powdery mildew	Identification of indels within the objective; resistance unconfirmed	(Shan et al., 2013)
	Wheat	Genetic restructuring	TaEdr1 (three homologs)	Condition of powdery mildew	Acquisition of resistance to powdery mildew	(Zhang et al., 2017)
	Tomato	Disruption of genetic sequence	Multiplex gRNA at Pmr4	Malady caused by Oidium neolycopersici	Notable reduction in symptoms of the malady	(Santillan Martinez et al., 2020)
	Tomato	Genetic mutation	SlMapk3	Disease induced by Botrytis cinerea	Heightened resilience against B. cinerea	(Zhang et al., 2018)
Bacteria	Rice	Genetic alteration	OsSWEET13	Ailment brought about by Xanthomonas oryzae pv. Oryzae (Xoo)	Resistance not ascertained	(Zhou et al., 2015)
	Rice	Genetic reconfiguratio n	OsSWEET11	Problem of bacterial blight	Elevation of resistance to Xoo	(Kim et al., 2019)
	Rice	Modification of gene and promoter	TALE-binding elements (EBEs) in OsSWEET13 promoter, OsSWEETT11, and OsSWEEt14 genes	Condition of bacterial blight provoked by Xoo	Wide-ranging enhancement of resistance across multiple Xoo strains	(Xu et al., 2019)
	Rice	Disruption of promoter	OsSWEET11, OsSWEET13 and OsSWEET14	Case of bacterial blight	Heightened resistance; verification observed through field assessments	(Oliva et al., 2019)

The collection of studies emphasizes genetic modifications meticulously designed to amplify plant resilience against an array of pathogens. Notable illustrations are found in rice, wherein approaches encompass RNA genome disruption as a countermeasure to Rice tungro spherical virus, gene disruptions of OsERF922 and OsMPK5 to mitigate Magnaporthe oryzae-triggered blast lesions, and gene disruptions of OsSWEET genes with potential to *counter Xanthomonas oryzae* pv. Oryzae. Wheat similarly affirms augmented resistance to powdery mildew through gene disruptions of TaMlo genes (Xu et al. 2019, Oliva et al. 2019). Furthermore, tomato manifests bolstered resistance through gene disruptions targeting Pmr4 against powdery mildew and SlMapk3 against Botrytis cinerea. In unison, these studies serve as exemplars of the latent capability of genetic modifications to fortify plant defenses against an array of fungal and bacterial adversaries, thereby enhancing agricultural sustainability and crop well-being (Kim et al. 2019).

Following the mutation process, the tomato lines displayed resemblant attributes to the control group, showing similar shape and weight. To develop improved resistance to cold stress, mutant rice lines were generated using CRISPR/Cas9 technology. This research underlines the effectiveness of the OsANN3 gene in conferring cold tolerance, making it a promising candidate gene for augmenting cold tolerance in transgenic rice varieties. Furthermore, the CRISPR/Cas9 system was employed to attain herbicide tolerance in mutant rice lines through targeted suppression of the PmCDA1 gene. These breakthroughs in genome editing pave the way for novel agricultural advancements, fostering resilient crops capable of withstanding various environmental challenges. As scientists continue to explore the potential of CRISPR/Cas9 technology, the future holds exciting prospects for creating sustainable and resilient plant varieties that cater to the needs of a changing world. (Liu et al. 2017).

1.14. Conclusion

The far-reaching consequences of climate change on worldwide farming and sustenance distribution exert significant sway on a wide range of individuals, especially those who are most defenseless to its outcomes. The rise in the frequency and gravity of extraordinary weather incidents, together with a concurrent upsurge in pest and ailment outbreaks, has been acknowledged as the foremost causes behind the downturn in agricultural yield and ensuing populace displacement. The pressing need to tackle these challenges and ensure sustenance security for the ever-expanding global populace calls for the development of crops that can withstand climate variations. The practice of plant breeding is crucial for the purpose of cultivating crop varieties that exhibit enhanced genetic characteristics and demonstrate optimal adaptation to specific ecological conditions. The development and use of climate-smart cultivars is imperative to effectively address the demands and preferences of producers and consumers, while also exhibiting adaptability under adverse environmental circumstances. There exists a necessity to do research on agricultural species that are presently underutilized, with the aim of augmenting their capacity for climatic resistance. The amalgamation of conventional plant breeding techniques with technological advancements, such as the utilization of molecular markers, presents substantial prospects for the progression of genetic research and the facilitation of agricultural growth. Through the implementation of advanced breeding methods, the possibility arises to foster plants showing enhanced resilience against adverse weather conditions, encompassing, yet not restricted to, drought, extreme temperatures, and the repercussions of environmental shifts. To comprehensively explore the research question, diverse methodologies need consideration, like genome-wide association studies (GWAS), high-capacity phenotyping, and genotyping methodologies. Application of genetic engineering techniques has been instrumental in producing transgenic flora displaying augmented endurance to both living organisms and non-living stressors.

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