Scholars Academic Journal of Biosciences
Abbreviated Key Title: Sch Acad J Biosci
ISSN 2347-9515 (Print) | ISSN 2321-6883 (Online)
Journal homepage: https://saspublishers.com
National Library of Medicine
National Center for Biotechnology Information
NLM ID: 101629416

OPEN ACCESS

Botany

Plant Science in the Face of Global Crises: Biotechnological Innovations for Climate Resilience, Food Security, and Medicinal Plant Conservation

Hafiza Shafaq Ishaq[1*], Muhammad Akif[2], Ali Hasan[3], Ammara Khalid[4], Maha Fatima[5], Muhammad Mohsan[6], Aizaz Haider Khan[7], Misbah Afzal[8], Mariam Abbas[9]

[1]Department of Botany, Government College University, Faisalabad, Punjab, Pakistan
[2]Department of Agronomy, Huazhong Agricultural University, Wuhan, Hubei 430070, China
[3]Department of Botany, Government College University, Faisalabad, Punjab 38000, Pakistan
[4]Centre of Agricultural Biochemistry and Biotechnology (CABB), University of Agriculture, Faisalabad, Pakistan
[5]Department of Botany, University of Agriculture, Faisalabad, Punjab, Pakistan
[6]Hubei Key Laboratory of Plant Pathology, Huazhong Agricultural University, Wuhan, China
[7]Department of Entomology, University of Layyah, Punjab, Pakistan
[8]Department of Environmental Sciences, Institute of Agro-Industry and Environment, The Islamia University of Bahawalpur, Punjab 63100, Pakistan
[9]Department of Environmental Sciences, Institute of Agro-Industry and Environment, The Islamia University of Bahawalpur, Punjab 63100, Pakistan

DOI: https://doi.org/10.36347/sajb.2025.v13i09.007 | **Received:** 06.07.2025 | **Accepted:** 28.08.2025 | **Published:** 12.09.2025

***Corresponding author:** Hafiza Shafaq Ishaq
Department of Botany, Government College University, Faisalabad, Punjab, Pakistan

Abstract **Review Article**

The increasing number of anthropogenic and environmental stresses is leading to multiple global crises, including climate change, food insecurity, soil degradation, and alarming rate of loss of biodiversity of medicinal plants. These issues are challenging the long-term stability of the ecosystem and well-being of humans. In order to mitigate these challenges, plant science is at the forefront to provide answers to the rapidly emerging problems of the world. Keeping this context, this review article primarily focuses on the recent updates in plant biotechnology and its application to understand the impact of climate change, environmental stresses, and anthropogenic activities on the physiological, biochemical, and molecular mechanisms of plants, photosynthesis, and biodiversity of medicinal plants. This is followed by approaches to develop climate-resilient plants with the help of modern biotechnology tools, such as genetic engineering, CRISPR/Cas-mediated gene editing, and manipulation of plant growth-promoting rhizobacteria (PGPR) that also ensure food security in the context of increasing population pressure and declining soil health. With decreasing biodiversity of medicinal plants due to overexploitation and land use changes, recent tools to conserve them and their sustainable production, such as in vitro plant propagation, engineering of metabolic pathways, and cryopreservation, are also discussed. This is followed by the beneficial role of plant–microbiome interactions in nutrient dynamics, amelioration of plant stress, and sustainable agriculture through biofertilizers and biocontrol agents. This is rounded up with a focus on the biosafety, public perception, and policy issues related to biotechnology approaches and the need to address these, along with the issues related to the intellectual property rights of genetic resources, through appropriate policies. This review article, thus, provides an overview of the current progress in plant science, ranging from the various aspects of plant physiology, biochemistry, microbiology, and biotechnology. It also aims to provide an integrated approach to understand the impact of environmental stresses, including climate change, and to find possible solutions for the same. The focus is to understand the interaction between the plant and the abiotic environment and how it can be harnessed to address the abiotic stresses that are of prime importance in the present-day world and work toward food security, sustainability, and conservation of medicinal plants.
Keywords: Plant biotechnology; Climate change; Environmental stress; Medicinal plant conservation; Genetic engineering; Plant–microbiome interactions.

1. INTRODUCTION

The twenty-first century is marked by complex global challenges that profoundly affect ecosystems, human societies, and agricultural systems. Climate change, biodiversity loss, land degradation, and food insecurity are among the most pressing crises threatening the stability of natural resources and human well-being. Agricultural systems, which depend fundamentally on plants, are at the core of these challenges. Plants not only serve as the foundation of food production but also contribute to global carbon sequestration, water regulation, and the preservation of ecosystem functions. However, rising global temperatures, erratic precipitation patterns, increasing pest and pathogen outbreaks, and the overexploitation of natural resources have placed plant systems under unprecedented pressure. Consequently, plant science has emerged as a critical field of study, offering strategies to address these intertwined issues through advances in genetics, biotechnology, ecological management, and sustainable agricultural practices (McKay, 2025).

Climate change is a central driver of agricultural vulnerability. Global models estimate that under a warming scenario of 2 °C, between 10% and 31% of current cropland areas could fall outside suitable climatic ranges for major staple crops, particularly in low-latitude regions where food insecurity is already prevalent. At 3 °C warming, this risk could extend to between 20% and 48% of croplands, with reductions in potential crop diversity across more than 50% of cultivated land (Heikonen *et al.,* 2025). These findings underscore the looming risks to global food security, particularly as the human population continues to grow, with projections suggesting a demand increase of more than 50% in food production by 2050. At the same time, sub-Saharan Africa and South Asia—regions highly dependent on rain-fed agriculture—are predicted to experience yield declines of over 30% due to increasing climatic variability, water scarcity, and soil degradation (Muluneh, 2021). These impacts threaten to exacerbate malnutrition, poverty, and socio-political instability in vulnerable regions.

Another urgent challenge lies in biodiversity loss, which significantly undermines agricultural resilience. Modern agriculture has increasingly focused on a narrow genetic base of staple crops, with only four—rice, maize, wheat, and potatoes—providing about 60% of global dietary energy (FAO, 2010). Such reliance on limited crop diversity makes food systems more vulnerable to disease outbreaks, pest invasions, and climatic stresses. Moreover, habitat destruction, monoculture expansion, and chemical overuse have accelerated the decline of pollinators, soil biodiversity, and wild relatives of crops—resources that are essential for breeding future varieties capable of withstanding environmental challenges. Biodiversity thus serves as a natural insurance mechanism, yet current trajectories indicate accelerating losses that compromise long-term sustainability. Addressing this crisis requires integrating biodiversity conservation into agricultural strategies and deploying plant science innovations to expand the genetic resources used in food production (Muluneh, 2021).

Plant science is uniquely positioned to mitigate these global challenges through innovative approaches that enhance crop productivity, resilience, and sustainability. Advances in genomics, transcriptomics, proteomics, and metabolomics have revolutionized the ability to dissect plant responses to environmental stressors at molecular and cellular levels (Li *et al.,* 2025). Genome editing technologies, particularly CRISPR/Cas systems, allow precise modification of genes controlling traits such as drought tolerance, salinity resistance, pest resistance, and nutrient efficiency. These tools provide plant scientists with unprecedented capacity to accelerate breeding processes that once required decades. Complementing these advances, biostimulants and microbial inoculants are being explored to enhance plant stress tolerance and nutrient acquisition, offering environmentally friendly alternatives to conventional chemical inputs (Li *et al.,* 2025). Such developments illustrate the multifaceted role of plant science in developing both high-tech and nature-based solutions for agriculture.

Beyond technological breakthroughs, systems-based frameworks such as climate-smart agriculture (CSA) provide an integrative approach to food security and environmental sustainability. CSA emphasizes three interrelated goals: sustainably increasing productivity, building resilience to climate change, and reducing greenhouse gas emissions (FAO, 2010; World Bank, 2024). This framework has been widely adopted in international agricultural policy discussions and is supported by national strategies in multiple regions. CSA interventions include stress-tolerant crop varieties, improved soil and water management practices, diversified cropping systems, and digital technologies for precision agriculture. Importantly, CSA highlights the need for both local innovation and global cooperation to achieve sustainable outcomes. As such, plant science contributes not only at the level of laboratory research but also in shaping practical strategies for farmers and policymakers.

The rationale for reviewing plant science's role in addressing global challenges is therefore twofold. First, there is an urgent need to consolidate knowledge across rapidly evolving domains, including molecular biology, crop physiology, ecological management, and climate adaptation strategies. The accelerating pace of discovery, particularly in genomics and biotechnology, requires synthesis to guide coherent strategies for implementation. Second, there is a critical need to identify gaps and barriers in translating scientific knowledge into practice. While advanced technologies offer immense promise, their accessibility and adoption are limited by socio-economic constraints, policy frameworks, and institutional capacity in many developing regions (McKay, 2025). Furthermore, ethical and regulatory considerations surrounding genetic modification and biotechnology remain points of contention that influence public acceptance and market viability.

The objectives of this review are therefore to clarify the specific global challenges undermining plant-based systems, evaluate the most recent innovations in plant science that address these challenges, and highlight integrative approaches for sustainable agriculture. The article also aims to discuss barriers such as regulatory frameworks, technological accessibility, and socio-economic inequalities that may hinder the effective implementation of scientific advances. Finally, the review identifies future directions for plant science research and innovation, emphasizing the need for interdisciplinary collaboration that integrates biological sciences, engineering, social sciences, and policy-making.

The scope of this article extends across environmental, technological, and socio-political dimensions of plant science. It begins with an analysis of global environmental challenges, including climate variability, biodiversity erosion, and land degradation, all of which pose threats to food security. It then evaluates scientific and technological innovations, from omics technologies to genome editing, stress-response modulation, and the development of sustainable cropping systems. Following this, the article addresses integrative strategies such as climate-smart agriculture and ecosystem-based management, exploring how these approaches can bridge the gap between laboratory research and real-world application. Case studies of successful implementation are presented to illustrate practical pathways for achieving resilience. The article concludes with a forward-looking discussion of research priorities and policy reforms needed to ensure plant science fulfills its potential in contributing to sustainable development goals.

By synthesizing these diverse strands, this review underscores the indispensable role of plant science in addressing some of the most critical challenges of our time. In a century defined by ecological uncertainty and growing human demands, the capacity to harness plant biology for food security, climate adaptation, and ecosystem sustainability represents not only a scientific imperative but also a moral responsibility. Plant science must therefore evolve as both a cutting-edge discipline and an applied solution framework, guiding global societies toward resilient, equitable, and sustainable futures.

2. CLIMATE CHANGE AND ITS IMPACT ON PLANT SYSTEMS

2.1. Temperature Extremes and Photosynthetic Efficiency

Temperature is one of the most important abiotic factors influencing plant growth, development, and productivity. Extreme heat or cold disrupts photosynthesis by altering enzymatic activity, stomatal conductance, and chloroplast integrity. Elevated temperatures accelerate photorespiration in C_3 plants such as wheat, rice, and soybeans, leading to significant yield losses (Zhao *et al.,* 2017). Experimental studies have shown that a 1 °C rise in average growing-season temperature can reduce wheat and maize yields by 6% and 7%, respectively (Zhao *et al.,* 2017). Furthermore, heat stress damages the thylakoid membranes of chloroplasts, causing impaired electron transport and reduced photosystem II efficiency (Hasanuzzaman *et al.,* 2013).

Cold extremes are equally detrimental, causing membrane rigidification, oxidative stress, and reduced Rubisco activity. Many tropical crops such as rice and maize are highly sensitive to chilling injury during early growth stages, which limits their geographic expansion. As illustrated in Figure 1, global warming scenarios project significant reductions in photosynthetic efficiency across both C_3 and C_4 plants, particularly under heatwave conditions (Heikonen *et al.,* 2025).

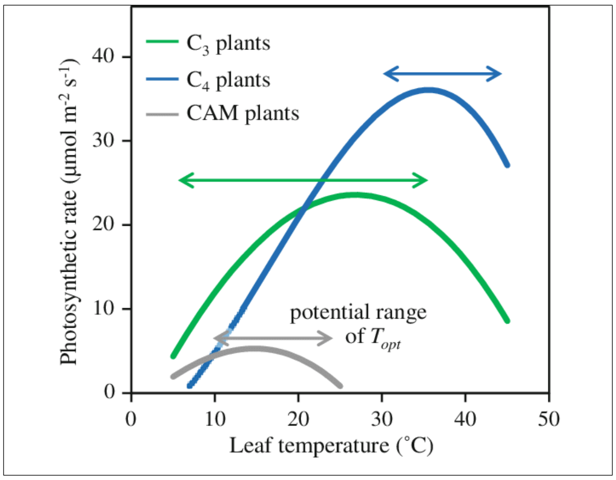

Figure 1: Projected impact of increasing temperature on photosynthetic efficiency and yield reduction in major crops under climate change scenarios

This figure illustrates how rising temperatures are projected to reduce photosynthetic efficiency in major crops, leading to significant declines in yield. As temperature exceeds the optimal range for photosynthesis, enzyme activity and stomatal function are impaired, causing stress-induced productivity losses. The trend highlights the vulnerability of global food systems to climate change.

2.2. Drought, Salinity, and Flood-Induced Stress

Water availability represents another critical determinant of plant performance. Climate change intensifies hydrological extremes, resulting in recurrent droughts, salinity accumulation, and flooding events. Drought stress reduces turgor pressure, closes stomata, and restricts carbon dioxide uptake, ultimately decreasing photosynthesis and biomass production (Farooq *et al.,* 2012). Prolonged water scarcity triggers oxidative stress through the accumulation of reactive oxygen species (ROS), which damage proteins, lipids, and DNA.

Salinity stress, often exacerbated by sea-level rise and irrigation mismanagement, disrupts ionic balance and osmotic potential in plant cells. Excess sodium and chloride ions interfere with potassium uptake, impair enzyme function, and inhibit photosynthetic activity (Munns & Tester, 2008). Crops like wheat and rice, which feed more than half of the world's population, are particularly vulnerable to soil salinity, threatening global food security.

In contrast, excessive rainfall and flooding create anaerobic conditions that severely limit root respiration. Hypoxia during floods restricts energy production and nutrient uptake, while also stimulating the accumulation of ethylene and ROS that impair cellular function (Bailey-Serres *et al.,* 2012). As depicted in **Figure 2**, projections indicate an increasing frequency of both drought and flooding events across major agricultural regions by 2050, posing severe risks to crop yields and food availability.

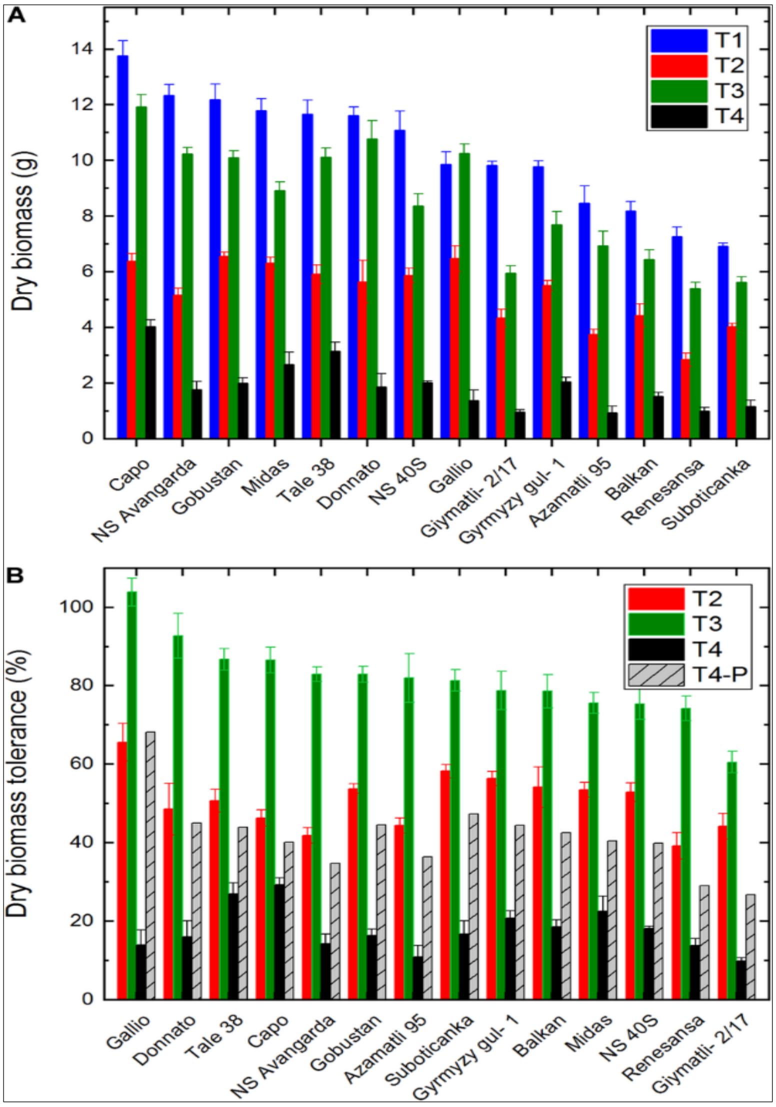

Figure 2: Effects of Drought on Plant Shoot Biomass

This figure shows the effects of different treatments (T1–T4) on dry biomass (A) and biomass tolerance (B) across various crop genotypes. Panel A indicates a decline in biomass with increasing stress severity, while Panel B highlights variation in tolerance levels among genotypes, with some exhibiting higher resilience under stress. The data demonstrate significant genotype-dependent differences in stress responses.

2.3. Shifts in Plant Biodiversity and Ecosystem Dynamics

Beyond individual crop physiology, climate change disrupts biodiversity patterns and ecosystem dynamics. Species distributions are shifting poleward and upward in elevation as plants seek suitable climatic niches. However, not all species are equally capable of migration, leading to local extinctions and altered community compositions (Pecl *et al.,* 2017). Changes in flowering time, pollination interactions, and seed dispersal dynamics further destabilize ecosystems.

For instance, alpine and Arctic ecosystems face rapid vegetation turnover, with shrubs expanding into tundra regions, thereby altering carbon storage capacity and surface albedo (Bjorkman *et al.,* 2018). In tropical forests, increased temperatures and drought stress reduce tree survival and recruitment, weakening their role as carbon sinks (Hubau *et al.,* 2020). Agricultural biodiversity is also at risk: the narrowing genetic base of modern crops makes them highly vulnerable to pest outbreaks and climatic shocks, further emphasizing the need to conserve wild relatives and landraces as genetic reservoirs (FAO, 2010).

As illustrated in **Table 1**, the impacts of climate change on plant biodiversity extend across physiological, population, and ecosystem levels, underscoring the interconnectedness of plant science and ecological resilience.

Table 1: Impacts of climate change on plant biodiversity and ecosystem functions

Level	Impact	Example
Physiological	Altered flowering, photosynthesis, and reproduction	Drought-induced flowering shifts in cereals
Population	Range shifts, local extinctions	Alpine species moving to higher altitudes
Community	Altered species interactions, competition, and pollination networks	Pollinator-plant mismatches in temperate regions
Ecosystem	Changes in carbon storage, nutrient cycling, and albedo	Shrub expansion in Arctic tundra

3. BIOTECHNOLOGICAL STRATEGIES FOR CLIMATE RESILIENCE

3.1 Genetic Engineering for Abiotic Stress Tolerance

Abiotic stresses such as drought, salinity, heat, and cold are major factors limiting global crop productivity. Genetic engineering has emerged as a key approach to improve plant resilience by introducing stress-responsive genes from diverse sources. Transgenic approaches have successfully incorporated genes encoding osmoprotectants (e.g., proline, glycine betaine) that enhance osmotic adjustment under drought or salinity (Bhatnagar-Mathur *et al.,* 2008). Similarly, overexpression of heat-shock proteins (HSPs) and late embryogenesis abundant (LEA) proteins has been shown to stabilize cellular structures and improve thermotolerance in crops such as rice and wheat (Wang *et al.,* 2004).

Additionally, transcription factors such as DREB, NAC, and WRKY families play central roles in regulating stress-inducible genes. Transgenic rice overexpressing DREB1A exhibited enhanced drought and cold tolerance without significant yield penalties (Kasuga *et al.,* 1999). Likewise, overexpression of the NAC transcription factor SNAC1 in rice improved drought resistance while maintaining productivity (Hu *et al.,* 2006). Collectively, these findings illustrate that genetic engineering of stress-responsive pathways provides an efficient route to develop climate-resilient crops.

3.2 CRISPR/Cas-Mediated Genome Editing in Stress Response Genes

The advent of CRISPR/Cas genome editing has revolutionized crop improvement, enabling precise modification of genes involved in stress signaling and adaptation. Unlike conventional genetic engineering, CRISPR/Cas allows targeted gene knockout, replacement, or activation, thereby avoiding transgenic concerns in many regions (Zhang *et al.,* 2018).

In rice, CRISPR-mediated disruption of OsRR22, a negative regulator of salt tolerance, resulted in enhanced salt resistance (Zhang *et al.,* 2019). Similarly, editing of SlMAPK3 in tomato conferred improved drought tolerance by modulating ABA-responsive pathways (Wang *et al.,* 2020). Multiplex editing has also been applied to target several stress-responsive genes simultaneously, creating plants with broad-spectrum stress resilience (Li *et al.,* 2020).

Moreover, CRISPR-based base editing and prime editing technologies provide new opportunities to fine-tune stress regulatory genes without inducing double-strand breaks, thus ensuring higher precision. These advances highlight the promise of CRISPR/Cas as a transformative tool for developing climate-smart crops.

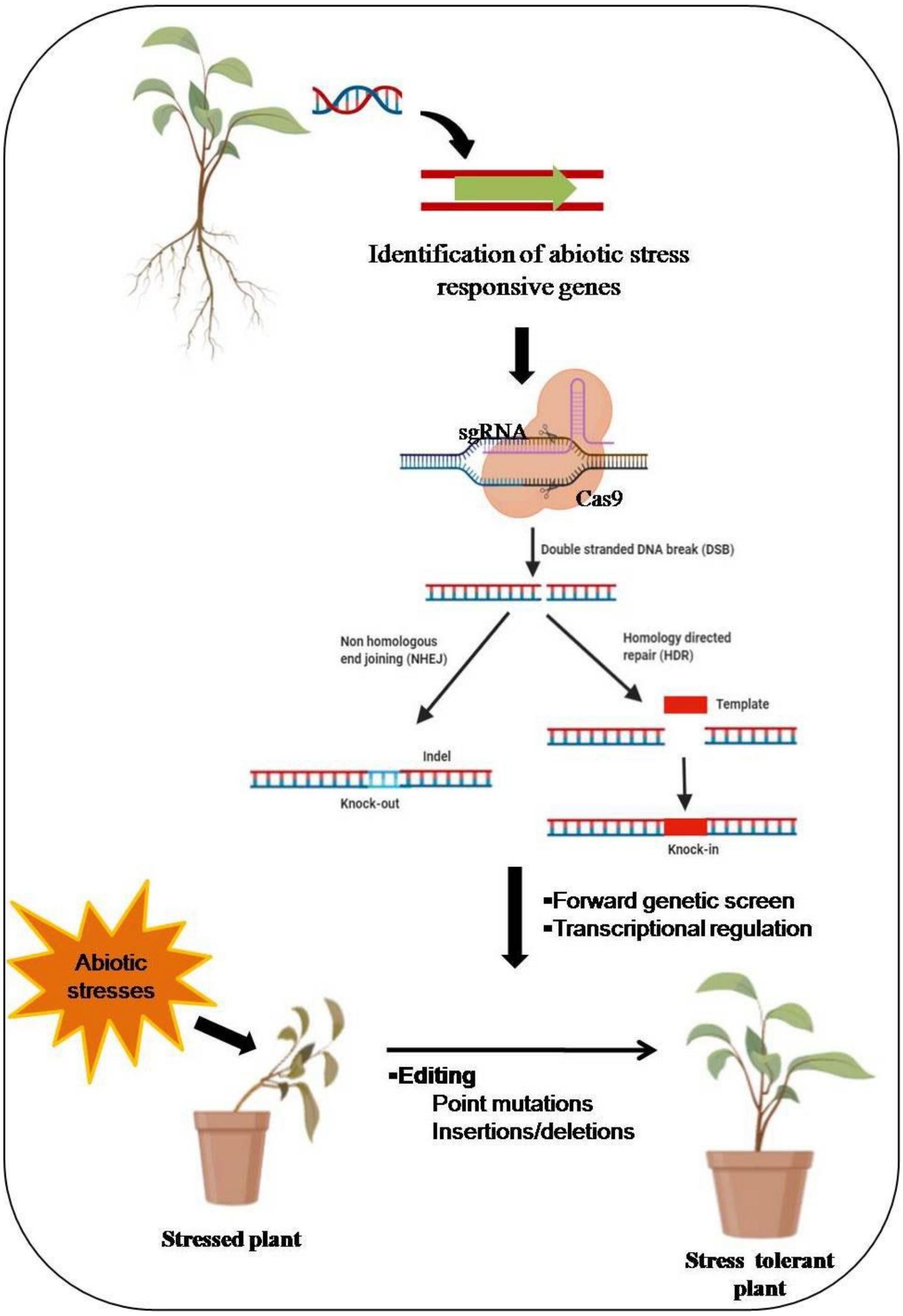

Figure 2: Schematic representation of CRISPR/Cas9-mediated genome editing of stress response genes to improve abiotic stress tolerance in plants.

Schematic display of CRISPR/Cas9-based genome editing in plants. The Cas9 endonuclease, guided by a specific single-guide RNA (sgRNA), introduces a double-strand break (DSB) at the target DNA site. The plant cell then repairs the DSB via either non-homologous end-joining (NHEJ), often resulting in gene knockouts, or homology-directed repair (HDR), enabling precise insertions or gene replacements. This mechanism forms the foundation for editing stress-response genes to enhance abiotic stress tolerance in crops.

3.3 Use of Plant Growth-Promoting Rhizobacteria (PGPR) and Endophytes

Beyond genetic modification, leveraging beneficial microbes represents an eco-friendly strategy for enhancing crop stress tolerance. PGPR and endophytic microorganisms improve plant resilience by modulating hormonal balance, producing antioxidant enzymes, and enhancing nutrient acquisition (Vurukonda *et al.,* 2016). For example, PGPR strains producing 1-aminocyclopropane-1-carboxylate (ACC) deaminase lower stress-induced ethylene levels, thereby promoting root growth under drought and salinity (Glick, 2014).

Endophytes, residing within plant tissues, further contribute by synthesizing osmoprotectants and stress-related metabolites. Inoculation of wheat with Bacillus subtilis enhanced drought tolerance by increasing root hydraulic conductivity and activating antioxidant defenses (Khan *et al.,* 2020). Similarly, arbuscular mycorrhizal fungi (AMF) improve phosphorus uptake and mitigate oxidative stress, thereby enhancing crop yield stability under climate stress (Smith & Read, 2008).

Integrating PGPR and endophytes with genetic and genome-editing strategies offers a synergistic approach to sustainable agriculture, reducing dependence on chemical inputs while strengthening crop adaptability.

Table 2. Biotechnological approaches for enhancing climate resilience in crops

Strategy	Mechanism	Example	Outcome
Genetic Engineering	Overexpression of stress-responsive genes	DREB1A in rice	Improved drought & cold tolerance
CRISPR/Cas Editing	Knockout of negative regulators	OsRR22 in rice	Enhanced salt resistance
PGPR Application	ACC deaminase activity, antioxidant induction	Bacillus subtilis in wheat	Increased drought resilience
Endophytes/AMF	Nutrient uptake, metabolite synthesis	AMF in maize	Higher yield under stress

4. Food Security and Agricultural Sustainability

4.1 Rising Global Demand and Yield Gaps

The continuous increase in the global population has placed significant pressure on agricultural systems to meet the growing demand for food. As illustrated in Figure 3A, the world population has risen from around 3 billion in 1960 to more than 7 billion in 2010, with projections estimating nearly 9 billion by 2050. This unprecedented rise in population is directly linked to the need for increased agricultural production and sustainable food supply chains (Tilman *et al.,* 2011; Godfray *et al.,* 2010).

Food supply trends also reveal regional disparities in dietary energy availability (Figure 3B). While Europe and North America maintain consistently high per capita caloric intake (around 3,000–3,500 kcal/person/day), regions such as Africa and Asia remain significantly lower, averaging between 2,000–2,500 kcal/person/day. These differences highlight not only geographical inequalities but also the pressing challenge of achieving global food security (FAO, 2017; Alexandratos & Bruinsma, 2012).

Despite technological progress and improved agronomic practices, yield gaps persist in many staple crops. Data on yield evolution (Figure 3C) shows that maize has achieved the most notable yield increase since the 1960s, surpassing 5 t/ha, while crops like barley, rice, and wheat show moderate but steady improvements. In contrast, potatoes, even when scaled up tenfold for comparison, display minimal gains. These yield disparities reflect both genetic and environmental constraints as well as differences in agricultural investment across regions (Ray *et al.,* 2013; Mueller *et al.,* 2012).

Furthermore, the global food energy supply remains dominated by a small number of crops (Figure 3D). Rice (23%) and wheat (22%) contribute nearly half of the caloric intake worldwide, followed by maize (6%), sugar (8%), and soybean oil (4%). Such heavy reliance on a few crops underscores the vulnerability of global food systems to climate change, pests, and diseases (Foley *et al.,* 2011). Expanding the crop base and closing regional yield gaps are therefore critical strategies to sustain food security in the coming decades. Figure 3. Global population growth, food supply, crop yield evolution, and major contributors to food energy supply. (A) World population (1960–2050); (B) Regional food supply in kcal/capita/day; (C) Yield evolution of major crops (1961–2013); (D) Major crops contributing to food energy supply. Adapted from FAO (2017).

Description:

A schematic comparison of rising food demand due to population growth and the stagnation of crop yields, highlighting the widening gap threatening food security.

4.2 Soil Degradation and Nutrient Depletion

Soil degradation is a pressing global issue that undermines agricultural productivity and long-term sustainability. An estimated one-third of the world's soils are moderately to severely degraded, directly impacting food production, livelihoods, and ecosystem health (Begum, 2024; IPCC, 2019). For instance, in Sub-Saharan Africa, soil erosion can reach up to 100 tonnes per hectare annually, reducing crop yields by 30% to 50% in the most severely affected regions (Heinrich-Böll-Stiftung, 2024).

Beyond physical erosion, nutrient depletion poses an equally serious threat. Tan, Lal, and Wiebe (2005) estimated substantial global deficiencies in nitrogen, phosphorus, and potassium—averaging 18.7 kg N, 5.1 kg P, and 38.8 kg K per hectare annually across 59% to 90% of harvested areas—resulting in over 1,100 teragrams of potential annual production loss. This nutrient exhaustion, especially widespread in low-income regions, severely impairs soil fertility and crop yield (Tan & Lal, 2005).

Soil compaction, acidification, and salinization further erode soil health. These stressors can reduce crop yields by 20% to 55% (Gomiero, 2016), threatening both productivity and ecosystem resilience. Degraded soils also deplete plant-accessible micronutrients such as zinc, copper, and manganese—linked to malnutrition and elevated child mortality, particularly in vulnerable populations (Khurana *et al.,* 2021).

Ultimately, soil degradation and nutrient depletion interact in a feedback loop that erodes productivity, exacerbates food insecurity, and escalates environmental and socio-economic vulnerabilities. Urgent soil restoration strategies—like conservation tillage, organic amendments, and nutrient management—are essential to halt and reverse this decline.

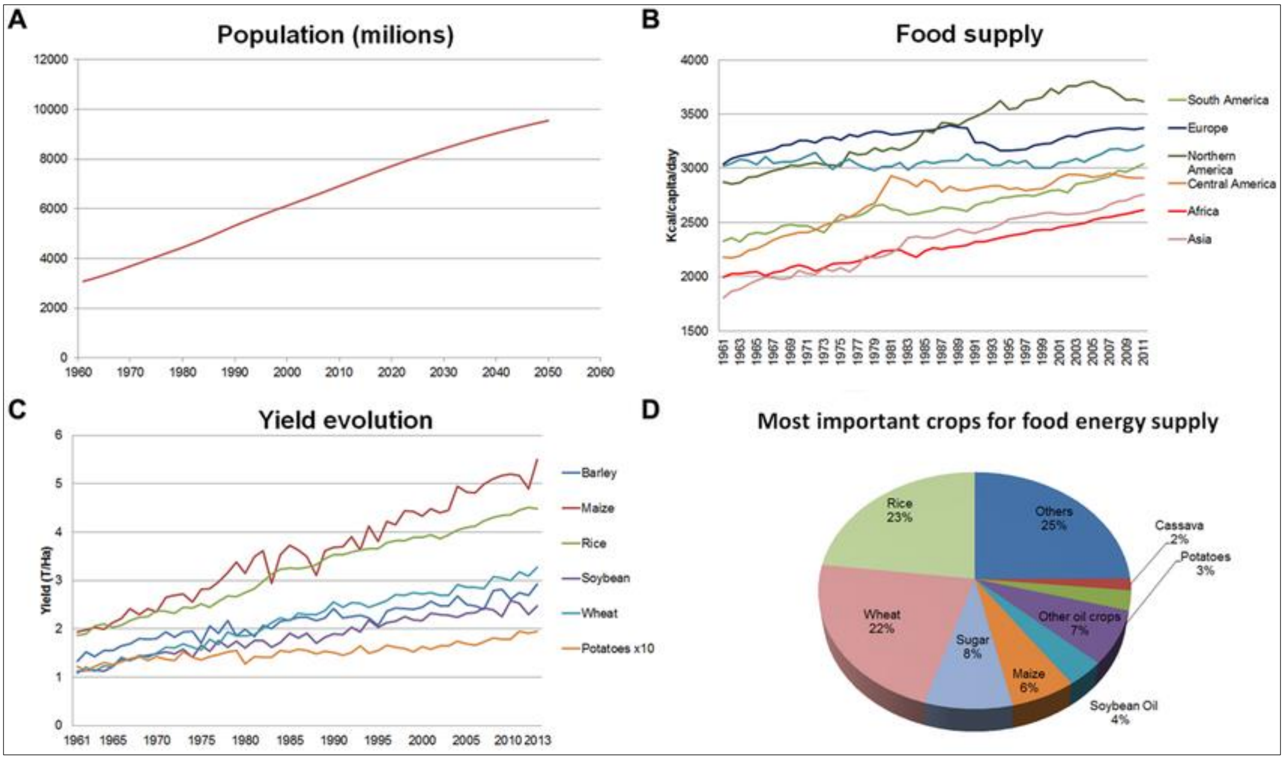

Figure 3: Global Food Demand Growth Versus Yield Gaps

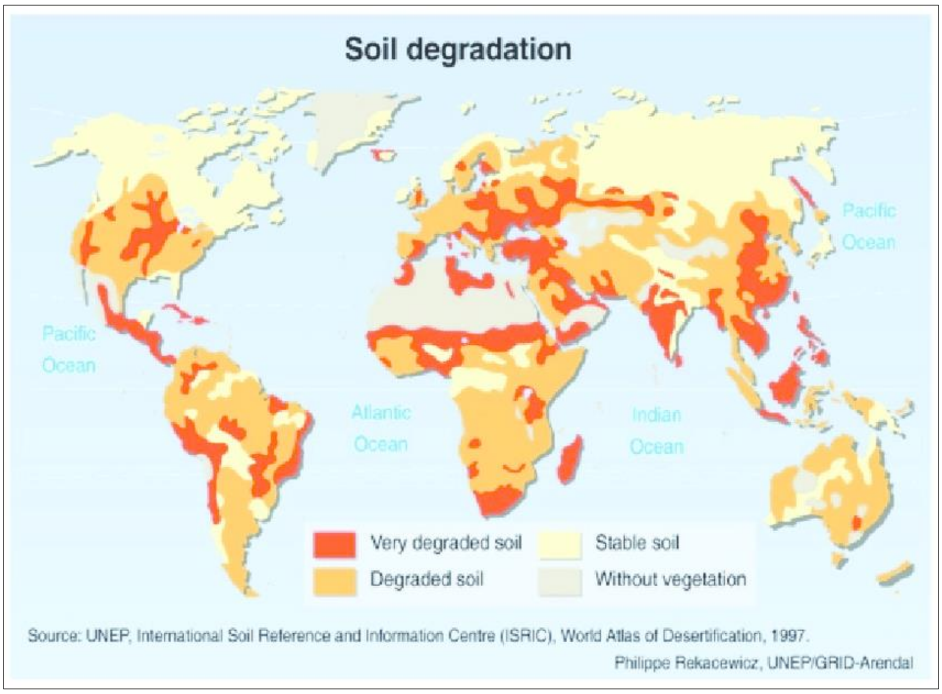

Figure 4: Global Soil Degradation Hotspots Map

This figure illustrates worldwide regions experiencing moderate to severe soil degradation, particularly due to erosion, nutrient loss, and fertility decline. Highlighted areas—such as parts of Africa, South Asia, Latin America, and Australia—correspond to zones of substantial productivity loss, underscoring the global scale of soil threats.

4.3 Pest and Disease Pressure on Major Crops

Pests and diseases remain a leading cause of crop losses worldwide, with substantial implications for food security and agricultural sustainability. On a global scale, annual yield losses due to pests range from 10% to 40% for key staple crops such as wheat, rice, maize, soybean, and potato (Savary *et al.,* 2019; Esker *et al.,* 2019). These losses translate into billions of dollars in economic damage, especially in developing regions. Estimates suggest that plant diseases alone incur $220 billion in economic cost each year, while invasive insects account for an additional $70 billion (FAO, 2020).

An expert-based assessment further quantifies crop-specific losses: rice suffers around 30% losses, while wheat, maize, potato, and soybean experience losses of approximately 21.5%, 22.5%, 17.2%, and 21.4%, respectively (Savary *et al.,* 2019). These figures highlight the varied vulnerability among different crops and the disproportionate impact on populations relying heavily on these staples.

Moreover, pests and diseases often interact with climate change to exacerbate stress. Changes in temperature, humidity, and rainfall patterns can disrupt pest life cycles, expand pathogen ranges, and intensify outbreaks—leading to increased frequency and severity of pest-driven damage (Kaushik *et al.,* 2023).

Table 3. Estimated Global Yield Losses from Pests and Pathogens by Crop

Crop	Estimated Global Loss (%)	Notes
Wheat	21.5	Crop severely impacted by rusts, blight, and fungi
Rice	30.0	Highest losses among staple crops globally
Maize	22.5	Affected by pests and fungal diseases
Potato	17.2	Lower percentage, but still significant
Soybean	21.4	Substantial pathogen and pest pressure

5. Plant Biotechnology in Enhancing Crop Productivity

5.1 Transgenic Crops for Nutritional Enhancement (Biofortification)

The global challenge of ensuring food and nutritional security in the face of population growth, climate change, and resource constraints has intensified the need for innovative agricultural solutions. One of the most promising approaches in this context is biofortification through transgenic crops, which involves genetic modification aimed at enhancing the nutritional composition of staple foods. Unlike conventional fortification, which requires post-harvest nutrient addition, biofortification integrates nutritional improvement into the crop itself, ensuring that nutrient-rich food is available directly at harvest and accessible to populations dependent on staple diets (Mayer *et al.,* 2008).

The most widely cited success story of biofortification through transgenics is Golden Rice, engineered to produce β-carotene, a precursor of vitamin A, in the endosperm of rice grains (Paine *et al.,* 2005). Vitamin A deficiency remains a serious public health concern in many developing countries, leading to preventable blindness and increased child mortality. Golden Rice demonstrates the potential of biotechnology in directly addressing such deficiencies by targeting the food staples consumed most frequently by affected populations. Beyond Golden Rice, several other transgenic crops have been developed to enhance micronutrients such as iron, zinc, and folate. For example, genetically engineered rice and maize varieties enriched with iron and zinc aim to reduce widespread anemia and stunting caused by mineral deficiencies (Bouis & Saltzman, 2017).

Another major advancement is the development of transgenic cassava with enhanced levels of pro-vitamin A, iron, and protein. This is particularly significant because cassava is a staple for millions of people in Africa and South America but is nutritionally poor in its conventional form (Wohlgenannt *et al.,* 2021). Similarly, transgenic bananas enriched with provitamin A are being promoted to address malnutrition in regions where bananas are a major dietary component (Paul *et al.,* 2017). Such biofortified crops not only improve health outcomes but also reduce dependency on supplements and industrial fortification programs, making them cost-effective and sustainable in the long run.

Critics of transgenic biofortification have raised concerns regarding biosafety, ecological risks, and ethical implications. However, numerous studies have demonstrated that genetically engineered biofortified crops are as safe as their conventional counterparts for both human consumption and the environment (Naqvi *et al.,* 2009). Moreover, regulatory frameworks and rigorous risk assessments have been established in many countries to ensure biosafety compliance before the commercial release of such crops. Despite initial resistance, there is growing recognition of biofortification as a powerful tool to combat "hidden hunger"—micronutrient deficiencies that affect over two billion people worldwide (WHO, 2020).

The broader implications of transgenic biofortification extend beyond individual health to societal and economic benefits. By reducing disease burdens related to malnutrition, such as impaired cognitive development, reduced immunity, and increased maternal mortality, biofortified crops contribute significantly to public health improvements and economic productivity. Furthermore, biofortification aligns with global sustainability goals, particularly those related to ending hunger (SDG 2) and improving health and well-being (SDG 3).

In conclusion, transgenic crops for nutritional enhancement represent a crucial innovation in agricultural biotechnology, addressing both food and nutritional security challenges. While continued research, regulatory oversight, and public engagement are necessary to ensure widespread adoption, biofortified transgenic crops offer a sustainable and scalable solution to global malnutrition.

5.3 Tissue Culture and Somaclonal Variation for Crop Improvement

Plant tissue culture is a fundamental biotechnological tool that has revolutionized modern agriculture by providing reliable methods for the rapid multiplication of elite genotypes, the conservation of endangered germplasm, and the improvement of crop productivity. The technique relies on the totipotency of plant cells, which enables single cells, tissues, or organs to regenerate into whole plants under controlled in vitro conditions. This property has been extensively harnessed to produce disease-free planting material, improve resistance to abiotic and biotic stresses, and support large-scale production of high-value crops (George *et al.,* 2008). In the context of global food demand, tissue culture offers a sustainable approach to enhancing crop productivity by ensuring uniformity, reducing input costs, and facilitating the introduction of genetic variation through somaclonal variation.

One of the most important contributions of tissue culture to agriculture is micropropagation, which enables the rapid production of genetically identical, pathogen-free plantlets. This approach has been particularly effective for vegetatively propagated crops such as banana, potato, cassava, sugarcane, and yam, which are prone to viral and bacterial infections. For instance, large-scale micropropagation of banana has significantly reduced yield losses caused by Banana Bunchy Top Virus and Fusarium wilt in many tropical countries (Vuylsteke, 1989). Similarly, tissue culture-based seed potato production has been widely adopted to overcome the limitations of conventional seed multiplication, ensuring higher yields and quality (Naik & Karihaloo, 2007). Such examples highlight the direct role of tissue culture in improving the availability of clean planting material, which is a key determinant of crop productivity.

Beyond clonal propagation, tissue culture also serves as a source of genetic variability through somaclonal variation. Somaclonal variation refers to the heritable phenotypic and genotypic changes observed among plants regenerated from in vitro cultures, arising due to chromosomal rearrangements, mutations, or epigenetic modifications induced under culture conditions (Larkin & Scowcroft, 1981). Although initially considered an undesirable byproduct, somaclonal variation is now recognized as a valuable resource for plant breeding. It provides an additional pool of variability for selecting traits such as disease resistance, salt tolerance, herbicide resistance, and enhanced yield potential. For example, somaclonal variants of sugarcane have been developed with improved resistance to red rot disease and better sucrose content, leading to increased productivity (Rao *et al.,* 1995). Similarly, rice somaclones exhibiting tolerance to salinity and drought stress have been successfully used to complement traditional breeding programs (Jain, 2001).

Tissue culture techniques such as anther culture, protoplast fusion, and somatic embryogenesis have also been widely employed for crop improvement. Another culture facilitates the production of haploids and doubled haploids, enabling rapid development of homozygous lines for breeding purposes. This accelerates the selection of desirable traits and shortens breeding cycles in cereals like rice, wheat, and maize (Maluszynski *et al.,* 2003). Protoplast fusion allows for the creation of somatic hybrids between sexually incompatible species, thereby expanding the gene pool for crop improvement. Somatic embryogenesis, on the other hand, provides an efficient system for large-scale propagation and genetic transformation, particularly in crops such as coffee, oil palm, and conifers (Guerra *et al.,* 2016).

In addition to direct crop improvement, tissue culture plays a crucial role in germplasm conservation and genetic resource management. Cryopreservation and slow-growth storage techniques allow the long-term preservation of valuable genetic material, which is vital for maintaining biodiversity and ensuring future breeding opportunities (Engelmann, 2011). Furthermore, tissue culture-based techniques facilitate the introduction of transgenes and genome-editing tools, making them integral to advanced molecular breeding strategies.

5.4 Molecular Breeding and Marker-Assisted Selection

Molecular breeding, particularly marker-assisted selection (MAS), has emerged as a revolutionary approach for accelerating crop improvement programs. Unlike traditional breeding methods, which rely on phenotypic selection and can be time-consuming and environmentally influenced, molecular breeding employs DNA markers closely linked with desirable traits, enabling precise and early selection of superior genotypes. This approach reduces the breeding cycle duration, enhances selection accuracy, and improves the efficiency of crop improvement (Collard & Mackill, 2008).

One of the primary applications of MAS is in improving resistance to biotic and abiotic stresses. For instance, in rice, molecular markers have been effectively utilized for introgressing genes conferring resistance to bacterial blight, blast, and sheath blight (Ashkani *et al.,* 2015). Similarly, in wheat, MAS has been successfully applied to incorporate rust resistance genes, safeguarding yield stability against devastating fungal pathogens (Randhawa *et al.,* 2019). Drought and salinity tolerance are also being targeted through MAS by identifying quantitative trait loci (QTLs) linked to stress-responsive traits and transferring them into elite cultivars. This is particularly crucial in the face of climate change, where resilient crops are essential for food security.

In addition to stress tolerance, MAS has played a pivotal role in enhancing yield-related traits. The identification of QTLs associated with yield components, such as grain size, weight, and tillering capacity, has facilitated targeted breeding strategies. For example, QTLs like *qSW5* and *GS3* in rice have been linked to grain size and shape, and their utilization through MAS has contributed to the development of high-yielding varieties (Huang *et al.,* 2013). In maize, MAS has been employed to improve traits like drought tolerance and kernel quality, significantly contributing to yield stability under diverse agroecological conditions (Xu *et al.,* 2017).

MAS is also extensively used in quality trait improvement. Traits such as grain protein content, oil composition in oilseeds, and β-carotene accumulation in crops like maize and cassava have been enhanced using marker-based selection. For instance, the development of *Quality Protein Maize (QPM)* varieties was facilitated by molecular markers linked to the opaque-2 gene, resulting in higher lysine and tryptophan levels and addressing protein malnutrition in developing countries (Babu *et al.,* 2005). Similarly, in barley, markers linked to malting quality traits have been utilized in breeding programs, ensuring improved industrial value (Schmalenbach *et al.,* 2009).

Recent advances in molecular breeding include genomic selection (GS), which builds on MAS but uses genome-wide markers to predict the breeding value of genotypes. Unlike MAS, which targets specific QTLs, GS considers the cumulative effect of thousands of loci across the genome, providing a more accurate prediction of complex quantitative traits (Crossa *et al.,* 2017). This method has been widely adopted in maize, wheat, and rice improvement programs, significantly enhancing the rate of genetic gain per breeding cycle. Coupling GS with high-throughput genotyping technologies and bioinformatics tools has further streamlined the breeding pipeline.

The integration of MAS with other biotechnological tools, such as transgenics, genome editing, and doubled haploid technology, has amplified its potential. For instance, combining MAS with CRISPR-Cas9-mediated editing allows precise trait introgression and accelerates cultivar development. This integrative approach ensures that crop breeding programs can effectively address the challenges of increasing food demand, climate change, and sustainability.

6. Medicinal Plants: Biodiversity Loss and Conservation Needs

6.1 Overharvesting and Habitat Fragmentation

Overharvesting has emerged as one of the most critical threats to medicinal plant biodiversity. The rising demand for herbal medicines and plant-derived pharmaceuticals has led to unsustainable collection practices, especially in developing countries where traditional medicine remains the primary healthcare source for nearly 80% of the population (Sharma *et al.,* 2019). Many collectors harvest entire plants rather than parts, leading to severe depletion of natural populations. For instance, species such as *Rauvolfia serpentina* and *Nardostachys jatamansi* are at risk due to excessive uprooting and destructive harvesting methods (Kala, 2018).

Habitat fragmentation exacerbates this problem by reducing the natural ecosystems that support these species. Expanding agriculture, deforestation, and urbanization have significantly reduced medicinal plant habitats, resulting in smaller, isolated populations that are vulnerable to genetic erosion (Hamilton, 2020). Such fragmentation not only diminishes biodiversity but also weakens ecosystem services vital for the regeneration of medicinal species.

Table 4: Key Medicinal Plants Under Threat from Overharvesting and Habitat Loss

Medicinal Plant	Region Affected	Key Threat	Conservation Status (IUCN)
Rauvolfia serpentina	South Asia	Root overharvesting	Endangered
Nardostachys jatamansi	Himalayan region	Uprooting of rhizomes	Critically Endangered
Taxus wallichiana	Nepal, India, Bhutan	Bark extraction	Endangered
Panax ginseng	East Asia	Habitat loss, collection	Vulnerable

6.2 Threats to Endangered Medicinal Species

Endangered medicinal plant species are particularly vulnerable due to their high economic value and restricted ecological niches. According to the International Union for Conservation of Nature (IUCN), nearly 15,000 medicinal plant species are currently threatened with extinction (Schippmann *et al.,* 2019). Species such as *Aconitum heterophyllum* and *Podophyllum hexandrum* have been pushed toward extinction by both overharvesting and climate change, which alters their fragile alpine habitats.

The lack of proper cultivation practices further aggravates this threat. Since most medicinal plants are still sourced from the wild, demand-driven harvesting often exceeds natural regeneration rates. This imbalance leads to population decline and eventual genetic bottlenecks (Singh & Chandra, 2021). Additionally, invasive alien species such as *Lantana camara* outcompete native medicinal flora, further threatening their survival.

Conservation efforts such as in-situ protection (biosphere reserves, sacred groves) and ex-situ approaches (seed banks, botanical gardens, and tissue culture propagation) are critical for sustaining these endangered species (Bodeker *et al.,* 2020). However, gaps remain in funding, public awareness, and integration of indigenous knowledge into modern conservation programs.

6.3 Global Trade Pressures and Ethical Concerns

The global trade of medicinal plants, valued at over USD 120 billion annually, exerts immense pressure on natural resources (Chen *et al.,* 2020). Major markets in Europe, North America, and Asia import raw plant materials from biodiversity-rich but economically disadvantaged countries, often without ensuring sustainable harvesting or fair trade practices. This creates an imbalance where local communities face biodiversity depletion but receive minimal economic benefits.

Unsustainable trade practices also lead to illegal harvesting and smuggling of rare species, such as *Saussurea costus* and *Coptis teeta*, listed under CITES Appendix I (Convention on International Trade in Endangered Species) (Hamilton, 2020). Such exploitation raises ethical concerns regarding biopiracy, where indigenous knowledge about medicinal plants is commercialized without equitable benefit-sharing.

Addressing these challenges requires the enforcement of international treaties like the Nagoya Protocol, which emphasizes Access and Benefit Sharing (ABS) principles to ensure that local communities are compensated for their traditional knowledge (CBD, 2019). Additionally, promoting certified sustainable trade, community-based conservation enterprises, and biotechnology-based alternatives can reduce wild harvesting pressures while meeting global demand.

7. Biotechnological Interventions in Medicinal Plant Conservation

Biotechnological approaches have become indispensable in the conservation and sustainable utilization of medicinal plants. Among these, in vitro propagation has emerged as a critical tool due to its ability to produce genetically uniform and disease-free plantlets. Micropropagation techniques such as shoot tip culture, nodal explant culture, and somatic embryogenesis are widely applied to endangered and commercially important medicinal species. This not only ensures the rapid multiplication of elite genotypes but also reduces dependence on natural populations, thereby preventing overharvesting (Fay, 1992; Debnath *et al.,* 2018). For example, the large-scale conservation and production of *Withania somnifera* and *Rauvolfia serpentina* have been achieved through micropropagation techniques (Rout *et al.,* 2000). In addition, tissue culture protocols enable year-round production of medicinal plant material under controlled conditions, which is particularly valuable for species with low seed viability (Teixeira da Silva & Nhut, 2013).

Another important biotechnological intervention is metabolic engineering, which plays a vital role in enhancing the biosynthesis of valuable phytochemicals in medicinal plants. Through genetic transformation, overexpression of biosynthetic pathway genes, or the application of elicitors, plants can be modified to yield higher concentrations of secondary metabolites such as alkaloids, flavonoids, and terpenoids (Verpoorte *et al.,* 2002). For instance, the yield of artemisinin in *Artemisia annua* has been improved by introducing key biosynthetic genes and elicitor treatments (Ikram & Simonsen, 2017). Likewise, metabolic engineering strategies in *Catharanthus roseus* have enhanced the production of vincristine and vinblastine, two critical anticancer compounds (Zhou *et al.,* 2015). These approaches not only ensure a reliable supply of phytochemicals for pharmaceutical industries but also help minimize the exploitation of wild plant resources (Sivanandhan *et al.,* 2015).

Cryopreservation represents yet another crucial strategy for the long-term conservation of medicinal plant germplasm. By storing plant tissues such as shoot tips, seeds, and somatic embryos in liquid nitrogen at −196 °C, this method maintains genetic stability and viability for extended periods (Engelmann, 2011). Techniques such as vitrification, encapsulation-dehydration, and droplet freezing have been successfully applied in medicinal plants including *Panax ginseng* and *Allium sativum* (Benson, 2008). Cryopreservation is especially useful for species with recalcitrant seeds or vegetatively propagated plants that cannot be conserved through traditional seed banking methods (Reed, 2008). By safeguarding rare and endangered species against threats such as climate change, habitat loss, and overexploitation, cryopreservation provides an effective and long-term solution for medicinal plant conservation (Engelmann, 2014).

8. The Role of Plant-Microbiome Interactions

Plant-microbiome interactions play a crucial role in maintaining soil fertility, enhancing plant health, and promoting agricultural sustainability. In the rhizosphere, microbes such as mycorrhizal fungi and rhizobia improve nutrient availability by facilitating nitrogen fixation and phosphorus solubilization (Smith & Read, 2010). Mycorrhizal fungi, in particular, form mutualistic associations with plant roots that not only increase water and nutrient absorption but also enhance soil aggregation through the production of glomalin, thereby strengthening soil structure (Rillig *et al.,* 2019). Nitrogen-fixing bacteria like *Rhizobium* and *Azospirillum* further contribute to sustainable nutrient cycling, reducing dependence on synthetic fertilizers and improving soil health (Gopalakrishnan *et al.,* 2015). These symbiotic relationships are essential for maintaining microbial diversity, soil organic matter, and long-term fertility.

Recent advances in microbiome engineering have expanded the potential of beneficial microbes in improving plant tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity. Microorganisms such as *Bacillus subtilis* and *Pseudomonas fluorescens* enhance plant stress responses by producing growth-promoting phytohormones, including indole-3-acetic acid (IAA), gibberellins, and cytokinins, which support plant growth under adverse conditions (Singh *et al.,* 2019). Additionally, these microbes can trigger systemic tolerance by regulating antioxidant enzyme activity and activating stress-responsive genes (Vurukonda *et al.,* 2016). With the advent of synthetic biology, microbial strains are now being engineered for improved traits such as salt tolerance and detoxification of heavy metals, offering sustainable alternatives to chemical inputs in modern agriculture (Zhang *et al.,* 2021).

Another important application of plant-associated microbes lies in the use of biofertilizers and biocontrol agents to achieve sustainable farming practices. Biofertilizers, including phosphate-solubilizing bacteria (*Pseudomonas*, *Bacillus*) and nitrogen fixers (*Azotobacter*), reduce the reliance on chemical fertilizers while increasing crop productivity (Mahanty *et al.,* 2017). At the same time, biocontrol agents such as *Trichoderma* spp. and *Pseudomonas fluorescens* suppress soil-borne pathogens through mechanisms like competition, antibiosis, and induced systemic resistance, thereby reducing the need for chemical pesticides (Pérez-García *et al.,* 2011). Together, these microbial inoculants provide eco-friendly solutions that enhance soil fertility, strengthen crop resilience, lower input costs, and minimize environmental pollution. Integrating these plant-microbiome interactions into agricultural practices offers a sustainable pathway for improving both productivity and ecosystem health.

Table 5: Role of Beneficial Microbes in Plant-Microbiome Interactions

Microbial Group	Key Functions	Agricultural Benefits
Mycorrhizal fungi	Enhance nutrient uptake (P, N), improve water access	Improved soil structure and fertility
Rhizobia (*Rhizobium*, *Azospirillum*)	Nitrogen fixation	Reduced dependence on synthetic nitrogen fertilizers
Bacillus subtilis	Stress tolerance via phytohormone production	Increased resilience under drought and salinity stress
Pseudomonas fluorescens	Antibiosis, pathogen suppression	Biocontrol of soil-borne diseases
Trichoderma spp.	Mycoparasitism, systemic resistance induction	Protection against fungal pathogens
Phosphate-solubilizing bacteria	Solubilize insoluble P	Enhanced phosphorus availability and crop yield

9. Ethical, Regulatory, and Societal Dimensions

Ethical, regulatory, and societal considerations strongly shape how genetic technologies are developed, governed, and accepted by the public. Public perception and acceptance of genetically modified organisms (GMOs) and newer gene-editing tools remain mixed: familiarity and direct experience with gene editing are consistently associated with greater perceived safety and higher acceptance, while poor trust, negative framing, and labeling choices can perpetuate skepticism and reduce public willingness to accept bioengineered foods (McFadden *et al.,* 2024; Howell *et al.,* 2025). At the regulatory level, national frameworks have struggled to keep pace with rapid advances in genome-editing techniques, creating uneven global approaches to risk assessment, approvals, and labeling that in turn influence both market access and public confidence (Rozas *et al.,* 2022). Environmental and biosafety concerns—including gene flow to wild relatives, evolution of herbicide- or pest-resistant weeds, non-target effects on biodiversity, and the indirect ecological impacts of associated agronomic practices—remain important drivers of precautionary regulation and of public debate, even while reviews and regulatory bodies report that approved products undergo extensive risk assessment (Teferra, 2021; Rozas *et al.,* 2022). Intellectual property (IP) regimes and commercialization strategies add further ethical complexity: seed and trait patents can incentivize innovation but also concentrate control in a few firms and create perceived or real constraints on farmers' rights and access to germplasm, raising equity questions that regulators and stakeholders must address (Bekele-Alemu *et al.,* 2025). Closely related are societal and legal efforts to protect Indigenous and traditional knowledge: calls for protections that respect free, prior, and informed consent, community stewardship, and benefit-sharing have intensified in recent years, and national and multilateral fora (including work by WIPO and congressional analyses) are actively developing policy responses to ensure that commercialization and IP regimes do not misappropriate or marginalize Indigenous knowledge and resources (Blevins *et al.,* 2024). Taken together, these ethical, biosafety, and societal dimensions argue for integrated governance approaches that combine transparent, evidence-based risk assessment; inclusive, sustained engagement with diverse publics (especially Indigenous and local communities); adaptive regulation for new breeding techniques; and fair IP or benefit-sharing arrangements that balance innovation incentives with social justice and ecological stewardship (Patrick & Barton, 2024; Rozas *et al.,* 2022).

10. Future Directions and Conclusion

The future of plant biotechnology lies in adopting integrated approaches that combine molecular breeding, genetic engineering, and agroecological practices to enhance resilience against climate change and environmental stresses. The integration of biotechnology with precision agriculture and digital tools, such as AI-driven crop monitoring, offers great potential to optimize inputs and minimize environmental footprints (Batool *et al.,* 2022). Equally important is the incorporation of traditional ecological knowledge with advanced molecular methods, ensuring that resilient agroecosystems are developed while simultaneously preserving biodiversity (Sharma & Tripathi, 2020). Such holistic strategies provide sustainable and long-term solutions to the mounting challenges of global food security.

Emerging research frontiers in plant biotechnology are rapidly expanding, particularly with the advancement of CRISPR-Cas–based genome editing, synthetic biology, and multi-omics integration for trait improvement. CRISPR technology now allows precise editing of genes responsible for critical traits such as stress tolerance, nutrient efficiency, and yield enhancement (Adli, 2018; Zaman *et al.,* 2023). At the same time, synthetic biology has opened new avenues for designing plants capable of producing high-value metabolites and bio-based materials (Liu *et al.,* 2022). Furthermore, the integration of transcriptomics, proteomics, and metabolomics provides a systems-level understanding of plant responses to biotic and abiotic stresses, thereby enabling the development of more efficient and targeted crop improvement strategies (Zhu *et al.,* 2021).

Plant biotechnology is now positioned at the intersection of technological innovation and global sustainability goals. The fusion of genetic engineering, digital agriculture, and ecological practices holds the potential to transform food systems and revolutionize agricultural production. However, the success of these innovations requires more than scientific advancement alone. Equitable access to biotechnological innovations, clear regulatory frameworks, and attention to ethical concerns must remain central to future progress (Eckerstorfer *et al.,* 2019). The challenges of climate change, resource depletion, and global food demand necessitate collaborative efforts among scientists, policymakers, farmers, and local communities. Only through such inclusive and collective action can biotechnology contribute not only to productivity but also to environmental sustainability and societal well-being. Moving forward, it is imperative to accelerate research, strengthen international regulations, and enhance public trust to fully realize the transformative potential of plant biotechnological innovations.

REFERENCES

- Adli, M. (2018). The CRISPR tool kit for genome editing and beyond. *Nature Communications, 9*(1), 1911.
- Alexandratos, N., & Bruinsma, J. (2012). *World agriculture towards 2030/2050: The 2012 revision*. FAO.
- Ashkani, S., Rafii, M. Y., Shabanimofrad, M., Miah, G., Sahebi, M., Azizi, P., … Latif, M. A. (2015). Molecular breeding strategy and challenges towards improvement of blast disease resistance in rice crop. *Frontiers in Plant Science, 6,* 886.
- Babu, R., Nair, S. K., Prasanna, B. M., & Gupta, H. S. (2005). Integrating marker-assisted selection in crop breeding – Prospects and challenges. *Current Science, 88(4),* 607–616.
- Bailey-Serres, J., Lee, S. C., & Brinton, E. (2012). Waterproofing crops: Effective flooding survival strategies. *Plant Physiology, 160*(4), 1698–1709.
- Bashan, Y., De-Bashan, L. E., Prabhu, S. R., & Hernandez, J. P. (2014). Advances in plant growth-promoting bacterial inoculant technology: formulations and practical perspectives (1998–2013). *Plant and Soil, 378*(1), 1–33.
- Batool, T., Mirza, M. U., Naqvi, A. Z., & Zaman, W. (2022). Applications of artificial intelligence in agriculture: A review on crop monitoring and yield prediction. *Computers and Electronics in Agriculture, 198*, 107081.
- Begum, T. (2024). *Soil degradation: The problems and how to fix them.* Natural History Museum.
- Bekele-Alemu, A., Dessalegn-Hora, O., Safawo-Jarso, T., & Ligaba-Osena, A. (2025). Rethinking progress: harmonizing the discourse on genetically modified crops. *Frontiers in Plant Science, 16*, Article 1547928.

- Benson, E. E. (2008). Cryopreservation theory. In E. E. Benson (Ed.), *Plant conservation biotechnology* (pp. 83–95). CRC Press.
- Berendsen, R. L., Pieterse, C. M. J., & Bakker, P. A. H. M. (2012). The rhizosphere microbiome and plant health. *Trends in Plant Science, 17*(8), 478–486.
- Bhatnagar-Mathur, P., Vadez, V., & Sharma, K. K. (2008). Transgenic approaches for abiotic stress tolerance in plants: Retrospect and prospects. *Plant Cell Reports, 27*(3), 411–424.
- Bjorkman, A. D., Myers-Smith, I. H., Elmendorf, S. C., Normand, S., Rüger, N., Beck, P. S. A., Blach-Overgaard, A., Blok, D., Cornelissen, J. H. C., Forbes, B. C., Georges, D., Goetz, S. J., Guay, K. C., Henry, G. H. R., HilleRisLambers, J., Hollister, R. D., Karger, D. N., Kattge, J., Manning, P., … Vellend, M. (2018). Plant functional trait change across a warming tundra biome. *Nature, 562*(7725), 57–62.
- Blevins, E. G., Murray, M. J., & Ortiz, N. R. (2024). *Indigenous knowledge and data: Overview and issues for Congress* (CRS Report R48317). Congressional Research Service.
- Bodeker, G., Ong, C. K., Grundy, C., Burford, G., & Shein, K. (2020). *WHO global atlas of traditional, complementary and alternative medicine*. World Health Organization.
- Bouis, H. E., & Saltzman, A. (2017). Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. *Global Food Security, 12,* 49–58.
- CBD. (2019). *Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization*. Secretariat of the Convention on Biological Diversity.
- Chen, S., Yu, H., Luo, H., Wu, Q., Li, C., Steinmetz, A., & Chen, S. L. (2020). Conservation and sustainable use of medicinal plants: Problems, progress, and prospects. *Chinese Medicine, 15*(1), 1–13.
- Collard, B. C. Y., & Mackill, D. J. (2008). Marker-assisted selection: An approach for precision plant breeding in the twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1491),* 557–572.
- Compant, S., Samad, A., Faist, H., & Sessitsch, A. (2019). A review on the plant microbiome: Ecology, functions, and emerging trends in microbial application. *Journal of Advanced Research, 19,* 29–37.
- Crossa, J., Pérez-Rodríguez, P., Cuevas, J., Montesinos-López, O., Jarquín, D., de los Campos, G., … Dreisigacker, S. (2017). Genomic selection in plant breeding: Methods, models, and perspectives. *Trends in Plant Science, 22(11),* 961–975.
- Debnath, S. C., Teixeira da Silva, J. A., Da Silva, J. T., & Saxena, P. K. (2018). Biotechnology of medicinal plants: Recent advances and potential. *Plant Cell, Tissue and Organ Culture, 132*(1), 1–23.
- Eckerstorfer, M. F., Engelhard, M., Heissenberger, A., Simon, S., & Teichmann, H. (2019). Plants developed by new genetic modification techniques—Comparison of existing regulatory frameworks in the EU and non-EU countries. *Frontiers in Bioengineering and Biotechnology, 7*, 26.
- Engelmann, F. (2011). Use of biotechnologies for the conservation of plant biodiversity. *In Vitro Cellular & Developmental Biology – Plant, 47*(1), 5–16.

- Engelmann, F. (2011). Use of biotechnologies for the conservation of plant biodiversity. *In Vitro Cellular & Developmental Biology – Plant, 47*(1), 5–16.

- Engelmann, F. (2014). Cryopreservation of clonal crops: A review of key parameters. *Acta Horticulturae, 1039*, 31–39.
- Esker, P., Savary, S., & McRoberts, N. (2012). Crop loss analysis and global food supply: Focusing now on required harvests. *CAB Reviews*, 7(1), 1–14.
- FAO. (2017). *The future of food and agriculture – Trends and challenges*. Food and Agriculture Organization of the United Nations.
- FAO. (2020). Climate change fans spread of pests and threatens plants and crops, new FAO study highlights global risks. *FAO News Report*.
- Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., & Basra, S. M. A. (2012). Plant drought stress: Effects, mechanisms and management. *Agronomy for Sustainable Development, 29*(1), 185–212.
- Fay, M. F. (1992). Conservation of rare and endangered plants using in vitro methods. *In Vitro Cellular & Developmental Biology – Plant, 28*(1), 1–4.
- Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., ... & Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature, 478*(7369), 337–342.
- Food and Agriculture Organization of the United Nations. (2010). *Climate-smart agriculture: Policies, practices and financing for food security, adaptation and mitigation*. Rome, Italy: FAO.

- Food and Agriculture Organization of the United Nations. (2010). *Climate-smart agriculture: Policies, practices and financing for food security, adaptation and mitigation*. Rome, Italy: FAO.

- George, E. F., Hall, M. A., & De Klerk, G. J. (2008). *Plant propagation by tissue culture* (3rd ed.). Springer.
- Glick, B. R. (2014). Bacteria with ACC deaminase can promote plant growth and help feed the world. *Microbiological Research, 169*(1), 30–39.
- Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., ... & Toulmin, C. (2010). Food security: The challenge of feeding 9 billion people. *Science, 327*(5967), 812–818.

- Gomiero, T. (2016). Estimates of the level of soil degradation at a global level. In *Soil degradation, land scarcity and food security: Reviewing a complex challenge*. MDPI.
- Guerra, M. P., Handro, W., & Silveira, V. (2016). Somatic embryogenesis in woody species. In A. Mujib & J. Šamaj (Eds.), *Somatic embryogenesis in woody plants* (pp. 1–20). Springer.
- Hamilton, A. C. (2020). The global need for sustainable wild collection of medicinal plants. *Plant Genetic Resources, 18*(2), 121–128.
- Hasanuzzaman, M., Nahar, K., Alam, M. M., Roychowdhury, R., & Fujita, M. (2013). Physiological, biochemical, and molecular mechanisms of heat stress tolerance in plants. *International Journal of Molecular Sciences, 14*(5), 9643–9684.
- Heikonen, S., Heino, M., Jalava, M., Siebert, S., Viviroli, D., & Kummu, M. (2025). Climate change threatens crop diversity at low latitudes. *Nature Food, 6*(4), 331–342.
- Heikonen, S., Heino, M., Jalava, M., Siebert, S., Viviroli, D., & Kummu, M. (2025). Climate change threatens crop diversity at low latitudes. *Nature Food, 6*(4), 331–342.
- Heinrich-Böll-Stiftung. (2024). *Soil degradation leads to nutrient depletion and a decline in soil biodiversity* [Map visual].
- Howell, B. F., Newcomb, E. M., Loh, D. W., Jackson, A. R., Dunn, M. L., & Jefferies, L. K. (2025). Shaping consumer perceptions of genetically modified foods: The influence of engineering, science, and design signifiers in packaging disclosure statements. *Foods, 14*(6), 909.
- Hu, H., Dai, M., Yao, J., Xiao, B., Li, X., Zhang, Q., & Xiong, L. (2006). Overexpressing a NAM, ATAF, and CUC (NAC) transcription factor enhances drought resistance and salt tolerance in rice. *Proceedings of the National Academy of Sciences, 103*(35), 12987–12992.
- Huang, X., Kurata, N., Wei, X., Wang, Z. X., Wang, A., Zhao, Q., … Han, B. (2013). A map of rice genome variation reveals the origin of cultivated rice. *Nature, 490(7421),* 497–501.
- Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E. N., Fauset, S., Mukinzi, J. M., Sheil, D., Sonké, B., Sullivan, M. J. P., Taedoumg, H., Thomas, S. C., White, L. J. T., Abernethy, K. A., Adu-Bredu, S., Amani, C. A., … Zemagho, L. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature, 579*(7797), 80–87.
- Ikram, N. K. B. K., & Simonsen, H. T. (2017). A review of biotechnological artemisinin production in plants. *Frontiers in Plant Science, 8*, 1966.
- Intergovernmental Panel on Climate Change (IPCC). (2022). *Climate change 2022: Impacts, adaptation, and vulnerability*. Cambridge: Cambridge University Press.
- IPCC. (2019). Summary for policymakers. In *Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
- Jain, S. M. (2001). Tissue culture-derived variation in crop improvement. *Euphytica, 118*(2), 153–166.
- Kala, C. P. (2018). Medicinal plants conservation and enterprise development: Exploring the role of local communities in India. *Environmental Development, 27*, 9–20.
- Kasuga, M., Liu, Q., Miura, S., Yamaguchi-Shinozaki, K., & Shinozaki, K. (1999). Improving plant drought, salt, and freezing tolerance by gene transfer of a single stress-inducible transcription factor. *Nature Biotechnology, 17*(3), 287–291.
- Kaushik, B., Singh, K., Tiwari, D. K., & Singh, U. K. (2023). Impact of climate change on crop yield due to pests and crop diseases: Future projections. *Microscopy and Microanalysis, 29*(S1), 56–58.
- Khan, N., Bano, A., & Babar, M. A. (2020). Impacts of plant growth-promoting rhizobacteria and abiotic stress in crop plants. In M. A. Khan & P. Ahmad (Eds.), *Plant growth-promoting rhizobacteria for sustainable stress management* (pp. 1–21). Springer.
- Khan, N., Bano, A., & Rahman, M. A. (2020). Role of plant growth-promoting rhizobacteria and endophytes in drought tolerance of plants. *Plant Biology, 22*(3), 133–147.
- Khurana, S., et al. (2021). The global expansion of food production has increased rates of soil micronutrient mining that can lead to eventual declines in crop yields. *Frontiers in Sustainable Food Systems*.
- Larkin, P. J., & Scowcroft, W. R. (1981). Somaclonal variation—A novel source of variability from cell cultures for plant improvement. *Theoretical and Applied Genetics, 60*(4), 197–214.
- Li, J., Forghieri, G., Geelen, D., du Jardin, P., & Brown, P. H. (2025). The optimization of crop response to climatic stress through modulation of plant stress response mechanisms. *Plant Science Reviews, 15*(2), 210–225.
- Li, J., Sun, Y., Du, J., Zhao, Y., & Xia, L. (2020). Generation of targeted point mutations in rice by a modified CRISPR/Cas9 system. *Molecular Plant, 13*(5), 667–670.
- Liu, W., Yuan, J. S., & Stewart, C. N. (2022). Synthetic biology for plant metabolic engineering. *Plant Physiology, 188*(2), 835–847.
- Maluszynski, M., Kasha, K. J., Forster, B. P., & Szarejko, I. (2003). Doubled haploid production in crop plants. *Springer*.
- Mayer, J. E., Pfeiffer, W. H., & Beyer, P. (2008). Biofortified crops to alleviate micronutrient

malnutrition. *Current Opinion in Plant Biology, 11*(2), 166–170.

- McFadden, B. R., Rumble, J. N., Stofer, K. A., & Folta, K. M. (2024). U.S. public opinion about the safety of gene editing in the agriculture and medical fields and the amount of evidence needed to improve opinions. *Frontiers in Bioengineering and Biotechnology, 12*, Article 1340398.
- McKay, J. K. (2025). Climate change challenges and plant science solutions. *Annual Review of Plant Biology, 76*, 145–168.
- McKay, J. K. (2025). Climate change challenges and plant science solutions. *Annual Review of Plant Biology, 76*, 145–168.
- Mitter, B., Pfaffenbichler, N., & Sessitsch, A. (2016). Plant–microbe partnerships in 2020. *Microbial Biotechnology, 9*(5), 635–640.
- Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature, 490*(7419), 254–257.
- Müller, D. B., Vogel, C., Bai, Y., & Vorholt, J. A. (2016). The plant microbiota: systems-level insights and perspectives. *Annual Review of Genetics, 50,* 211–234.
- Muluneh, M. G. (2021). Impact of climate change on biodiversity and food security: A global perspective—a review article. *Agriculture & Food Security, 10*(36), 1–12.
- Munns, R., & Tester, M. (2008). Mechanisms of salinity tolerance. *Annual Review of Plant Biology, 59*, 651–681.
- Naik, P. S., & Karihaloo, J. L. (2007). Micropropagation for production of quality potato seed in Asia-Pacific. *Asia-Pacific Consortium on Agricultural Biotechnology*.
- Naqvi, S., Zhu, C., Farre, G., Ramessar, K., Bassie, L., Breitenbach, J., Perez-Conesa, D., Ros, G., Sandmann, G., & Christou, P. (2009). Transgenic multivitamin corn through biofortification of endosperm with three vitamins representing three distinct metabolic pathways. *Proceedings of the National Academy of Sciences, 106*(19), 7762–7767.
- Paine, J. A., Shipton, C. A., Chaggar, S., Howells, R. M., Kennedy, M. J., Vernon, G., Wright, S. Y., Hinchliffe, E., Adams, J. L., Silverstone, A. L., & Drake, R. (2005). Improving the nutritional value of Golden Rice through increased pro-vitamin A content. *Nature Biotechnology, 23*(4), 482–487.
- Patrick, S., & Barton, J. (2024). Mitigating risks from gene editing and synthetic biology: Global governance priorities. Carnegie Endowment for International Peace.
- Paul, J. Y., Harding, R., Tushemereirwe, W., Dale, J. L., & Khanna, H. (2017). Banana21: From gene discovery to deregulated golden bananas. *Frontiers in Plant Science, 8,* 1589.
- Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., … Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science, 355*(6332), eaai9214.
- Qiao, C., Wang, X., Shirvan, M. B., Dijkstra, F. A., et al. (2022). Effects of drought and plant composition on shoot biomass in legumes, grasses, and mixtures. *Plant and Soil*.
- Randhawa, M. S., Bariana, H. S., Mago, R., Bansal, U. K., & Hayden, M. J. (2019). Marker-assisted transfer of multiple rust resistance genes into an Australian wheat cultivar. *Theoretical and Applied Genetics, 132(3),* 633–647.
- Rao, G. P., Singh, S., Upadhyay, S. K., & Agrawal, A. (1995). Somaclonal variation in sugarcane for resistance to red rot disease. *Plant Cell Reports, 14*(5), 301–304.
- Ray, D. K., Mueller, N. D., West, P. C., & Foley, J. A. (2013). Yield trends are insufficient to double global crop production by 2050. *PLoS One, 8*(6), e66428.
- Reed, B. M. (2008). *Plant cryopreservation: A practical guide*. Springer.
- Rout, G. R., Samantaray, S., & Das, P. (2000). In vitro manipulation and propagation of medicinal plants. *Biotechnology Advances, 18*(2), 91–120.
- Rozas, P., Kessi-Pérez, E. I., & Martínez, C. (2022). Genetically modified organisms: Adapting regulatory frameworks for evolving genome editing technologies. *Biological Research, 55*, 31.
- Savary, S., et al. (2019). The global burden of pathogens and pests on major food crops. *Nature Ecology & Evolution, 3*, 430–439.
- Schippmann, U., Leaman, D. J., & Cunningham, A. B. (2019). Impact of cultivation and collection on the conservation of medicinal plants: Global trends and issues. *Biodiversity and Conservation, 28*(9), 2435–2452.
- Schmalenbach, I., Léon, J., & Pillen, K. (2009). Identification and verification of QTLs for agronomic traits using wild barley introgression lines. *Theoretical and Applied Genetics, 118(3),* 483–497.
- Sharma, A., Shanker, C., Tyagi, L. K., Singh, M., & Rao, C. V. (2019). Herbal medicine for market potential in India: An overview. *Academic Journal of Plant Sciences, 7*(1), 23–26.
- Sharma, R., & Tripathi, A. (2020). Traditional ecological knowledge and plant biotechnology: Synergies for sustainable agriculture. *Journal of Ethnobiology and Ethnomedicine, 16*(1), 56.
- Singh, R. K., Singh, P., Li, Y., & Song, Q. Q. (2020). Plant microbiome and nutrient cycling. *Microorganisms, 8*(9), 1316.
- Singh, R., & Chandra, S. (2021). Medicinal plant biodiversity and conservation strategies: A review.

Journal of Applied Research on Medicinal and Aromatic Plants, 20, 100273.

- Sivanandhan, G., Rajesh, M., Arun, M., Kasthurirengan, S., & Ganapathi, A. (2015). Elicitation of high-value phytochemicals in medicinal plants through metabolic engineering and tissue culture technology. *Applied Microbiology and Biotechnology, 99*(10), 4309–4321.
- Smith, S. E., & Read, D. J. (2008). *Mycorrhizal symbiosis* (3rd ed.). Academic Press.
- Smith, S. E., & Read, D. J. (2010). *Mycorrhizal symbiosis* (3rd ed.). Academic Press.
- Tan, Z. X., Lal, R., & Wiebe, K. D. (2005). Global soil nutrient depletion and yield reduction. *Journal of Sustainable Agriculture, 26*(1), 1–12.
- Teferra, T. F. (2021). Should we still worry about the safety of GMO foods? Why and why not? A review. *Food Science & Nutrition, 9*, 5324–5331.
- Teixeira da Silva, J. A., & Nhut, D. T. (2013). The role of tissue culture in plant conservation. *Biotechnology Advances, 31*(3), 341–350.
- Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences, 108*(50), 20260–20264.
- Verpoorte, R., Contin, A., & Memelink, J. (2002). Biotechnology for the production of plant secondary metabolites. *Phytochemistry Reviews, 1*(1), 13–25.
- Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil, 255*(2), 571–586.
- Vurukonda, S. S. K. P., Vardharajula, S., Shrivastava, M., & SkZ, A. (2016). Enhancement of drought stress tolerance in crops by plant growth-promoting rhizobacteria. *Microbiological Research, 184*, 13–24.
- Vuylsteke, D. (1989). Shoot-tip culture for the propagation, conservation, and exchange of Musa germplasm. *International Institute of Tropical Agriculture (IITA)*.
- Wang, W., Vinocur, B., Shoseyov, O., & Altman, A. (2004). Role of plant heat-shock proteins and molecular chaperones in the abiotic stress response. *Trends in Plant Science, 9*(5), 244–252.
- Wang, Y., Meng, Z., Liang, C., Meng, Z., Wang, Y., Sun, G., ... & Guo, S. (2020). Increased drought tolerance in transgenic rice plants overexpressing transcription factor OsNAC10. *Plant Molecular Biology, 104*(1–2), 67–79.
- Wohlgenannt, A. A., Johnson, N. M., Hummel, M., Mbanjo, E. G. N., & Tohme, J. (2021). Biofortification of cassava for improved nutritional quality. *Plant Biotechnology Journal, 19*(1), 5–15.
- World Bank. (2024). *Climate-smart agriculture: Building resilience in food systems*. Washington, DC: The World Bank.
- World Health Organization (WHO). (2020). *Micronutrient deficiencies*. WHO.
- Xu, Y., Liu, X., Fu, J., Wang, H., Wang, J., Huang, C., … Zhang, G. (2017). Enhancing genetic gain in the era of molecular breeding. *Journal of Experimental Botany, 68(11),* 2641–2666.
- Yamori, W., Hikosaka, K., & Way, D. A. (2014). Typical temperature responses of photosynthesis in C_3, C_4, and CAM plants. *Photosynthesis Research*, 119, 101–117.
- Zaman, W., Khan, W. Z., & Ullah, R. (2023). Advancing diagnostic medical physics: AI, MR-guided radiotherapy, and 3D printing in modern healthcare. *Dialogue Social Science Review, 12*(1), 45–58.
- Zhang, A., Liu, Y., Wang, F., Li, T., Chen, Z., Kong, D., ... & Chen, S. (2019). Enhanced salt tolerance in rice plants via CRISPR/Cas9-targeted mutagenesis of the OsRR22 gene. *Plant Biotechnology Journal, 17*(5), 1852–1854.
- Zhang, Y., Massel, K., Godwin, I. D., & Gao, C. (2018). Applications and potential of genome editing in crop improvement. *Genome Biology, 19*(1), 210.
- Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J. L., Elliott, J., Ewert, F., Janssens, I. A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., & Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences, 114*(35), 9326–9331.
- Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J. L., Elliott, J., Ewert, F., Janssens, I. A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., & Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences, 114*(35), 9326–9331.
- Zhou, M., Memelink, J., & Verpoorte, R. (2015). Metabolic engineering of plant secondary metabolites in *Catharanthus roseus*: Prospects for increased production of vincristine and vinblastine. *Plant Cell Reports, 34*(10), 1701–1713.
- Zhu, J., Li, Y., & Zhang, W. (2021). Multi-omics approaches for crop improvement under stress conditions: Current status and future prospects. *Plant Biotechnology Journal, 19*(12), 2289–2302