

Review Article

Stressors in Agriculture: Challenges and Implications for Sustainable Crop Production

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Abstract

Modern agriculture faces a growing array of stressors, abiotic, biotic, climate-induced, socio-economic, and technological, that collectively threaten global crop productivity and food security. This review systematically classifies these stressors, providing a structured framework to understand their individual and combined impacts on agricultural systems. The paper explores how stressors such as drought, salinity, heat, pests, and diseases are intensifying under the influence of climate change and globalisation, with particular focus on the emergence of invasive species and rapidly evolving pathogens. Biotechnological interventions are reviewed as key mitigation strategies, including transgenic crops, genome editing tools like CRISPR, and microbiome engineering approaches. Additionally, the review discusses the use of precision agriculture technologies and early warning systems for proactive stress management. The paper further identifies emerging research gaps, especially in the understanding of multi-stress interactions at physiological and molecular levels, and the need for locally adapted, scalable solutions. Emphasis is placed on the integration of genetic, ecological, and technological approaches supported by policy frameworks, institutional infrastructure, and capacity building. The review concludes that an interdisciplinary and inclusive approach is essential for the development of climate-resilient agricultural systems capable of sustaining productivity under increasing environmental uncertainties.

Keywords

Agricultural Stressors, Crop Productivity, Sustainable Agriculture, Sustainable Crop Production, Multi-Stress Tolerance, Climate-Resilient Crops

1. Introduction

Agricultural systems are being increasingly pressured by a widespread and connected range of stressors, which can adversely affect crop production, the livelihood of farmers, and global food security. Agricultural stressors include a range of abiotic (water stress, salinity, extreme temperature) and biotic (insect pests, plant pathogens, parasitic weeds) challenges that can be compounded by climate variability, inequality, and

technological disparities [1]. The pressure to intensify agricultural production without environmental costs, coupled with risks in stressor scale, severity, frequency and adaptation, has led to growing complexity in agroecosystems and the decline of sustainable food production [2]. Agricultural biotechnology offers new options to develop resiliency to challenges posed by a changing environment, including developments in

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CRISPR-Cas genome editing, transgenic resistance, and plant-microbiome engineering [3]. Nevertheless, stressors are dynamic, and particularly for the established presence-importation of invasive pests and rapid evolution of plant pathogen virulence, new approaches integrating genetic, ecological and institutional responses will need to be adaptive across spatial and temporal scales [4]. This review provides an extensive classification of the agricultural stressors, implements an assessment of their cumulative and cooperative effects on crop production, and identifies recent innovations for stress mitigation. The review will also reflect on sustained research needs, emphasising understanding of multi-stress interactions, while advancing place and context-based strategies.

2. Classification of Agricultural Stressors

Agricultural systems experience a wide range of stressors that can be categorised in an array of ways, including abiotic, biotic, climate-related, socio-economic and technological stressors. These stressors frequently use synergies, making the resulting issues compound. These stressors often influence crop health, yields and long-term sustainability.

2.1. Abiotic Stressors

Abiotic stresses are among the most important environmental limitations on agriculture on a global scale, especially as climate conditions change. Abiotic stresses include all of the non-living aspects of habitat (i.e., drought, salinity, heat, cold, flooding, and soil degradation). Collectively, abiotic stresses can impact one or more aspects of plant physiology, development, and yield, and are often the cause of severe economic costs and impacts to food security [5, 6]. Increasing frequency of climate extremes (as evidenced by social media) and evidence for all of these abiotic stresses drive the need for adaptation that is resilient.

2.1.1. Drought Stress

Drought stress is one of the most critical abiotic constraints to agriculture globally influencing around 40% of cultivated land and some of the greatest losses occur in primary cereals including: rice, wheat, and maize [1]; when using rainfall-fed agriculture, which accounts for over 60% of the global food supply, the impact is particularly acute [7]. Drought affects the productivity of crops by affecting leaf water potential, which causes stomata closure, limits carbon assimilation, and leads to oxidative stress due to reactive oxygen species [8]. Drought stress also restricts root growth and nutrient uptake, limiting plant growth and development.

In response to avoid plant mortality from water deficit, plants initiate various morpho-physiological and molecular processes, including decreased leaf area, increased root-to-shoot ratios, osmotic adjustment with solutes like

proline, and ABA-regulated stress signalling [9]. The DREB transcription factor has been overexpressed to tolerate drought, and some ABA-related genes, such as OsPYL have been edited with gene technology [10]. Marker-assisted selection and genomic selection have catalysed the implementation of critical drought-tolerance QTLs in rice for increased yield stability during water limitations.

2.1.2. Salinity Stress

Salinity stress limits crop productivity, with significant impacts in arid and semi-arid regions that rely on irrigation. Soil salinisation affects more than 20% of irrigated land globally (about a third of global food production), which is made worse by climate change, sea level rise, and poor irrigation practice [11]. Salinity causes osmotic stress by reducing soil water potential, resulting in ionic stress as ions of sodium (Na^+) and chloride (Cl^-) can reach toxic levels that also impede potassium uptake and result in oxidative stress through reactive oxygen species [5]. Plants can adapt to salt stress by Na^+ exclusion or sequestering to vacuoles by utilising ion transporters (for example, NHX1), producing osmoprotectants like proline to increase osmosolic equilibrium, or by producing antioxidant enzymes. There are several important genes involved in salinity tolerance, including SOS1 , HKT1 , as well as transcription factors such as DREB2A and NAC . Transgenic and genome editing efforts have included overexpressing AtNHX1 and OsHKT1 and CRISPR knock-out of OsRR22 to enhance salt tolerance in rice and wheat [12]. Marker-assisted selection and use of the Saltol QTL has also increased salinity tolerance at the seedling stage of rice varieties in South Asia [13].

2.1.3. Heat Stress

Heat stress is an important abiotic factor limiting crop productivity, especially in the many tropical and subtropical growing regions of the world. Heat stress is most impactful during the sensitive inputs for flowering and grain filling, causing pollen sterility, decreased seed set, and loss of yield of up to 50% of mature grain in major cereals such as wheat and rice [14]. The impacts of heat stress are further complicated by the increase in global temperatures and the increased frequency of heat waves predicted due to climate change [6]. Heat stress also disrupts cellular functions related to membrane stability, denatures proteins, and generates excessive amounts of reactive oxygen species (ROS) during heat stress [15]. Plants have evolved mechanisms to mitigate heat stress effects by producing heat shock proteins (HSPs), other heat stress transcription factors (HSFs), and hormones such as ABA and ethylene that signal responses to heat stress. The use of novel technologies such as CRISPR to improve antioxidant responses (e.g. SlMAPK3), and QTL introgression studies such as qHTSF4.1 for heat tolerance in rice and wheat, further highlight the advances researchers are making to address heat stress in planting systems [16, 17].

2.1.4. Cold Stress

Cold stress, which includes chilling (0–15 °C) and freezing (<0 °C), limits the productivity of thermophilic commodities like rice, maize, and soybean, especially in temperate and high-altitude areas. Climate change has compounded this issue by introducing unseasonal cold snaps to subtropical areas, affecting crop phenology and crop growth [18]. Cold stress inhibits seed germination, reduces photosynthetic efficiency, alters membrane fluidity, and causes oxidative stress by inducing excessive build-up of ROS [19]. Plants can adapt to these stresses by inducing cold-regulated (COR) genes, accumulating osmoprotectants (e.g., proline, trehalose), and activating antioxidant enzymes. Cold tolerance is regulated primarily through the CBF (C-repeat binding factor) transcriptional pathway [20]. The transgenics of east Arctic/Scandinavian breed rice cultivar (AtCBF1) and tomato throat breed, OsDREB1, enhance cold resistance [21]; CRISPR editing of OsMYB30 have provided even greater survival under low ambient temperatures [22]. Marker-assisted selection has also facilitated the introgression of cold tolerant QTL into elite cultivars (with qLTG3-1 first expressed in the tested strains, Fujino et al., manufactures before they can be released for farming use [23].

2.1.5. Flooding and Soil Degradation

Flooding can cause root hypoxia, wilting and greater exposure to root pathogens. Flood-tolerant varieties, such as rice varieties with the SUB1A gene, have greater survival due to regulated elongation and metabolic changes [24]. In contrast, soil degradation (e.g., erosion, loss of nutrient status, compaction) acts to limit agricultural productivity and long-term viability. Resilient or restorative practices such as zero tillage, organic amendments, and integrated nutrient management should be embraced [25].

2.2. Biotic Stressors

Biotic stressors, resulting from living organisms including pathogens (fungi, bacteria, viruses), insect pests, nematodes, and parasitic weeds, represent a continuing, multifaceted problem in sustainable crop production. The loss of yield attributable to these stressors is considerable, estimated globally at 20% to 40%, and they entail real challenges to food security and agricultural livelihoods. Unlike abiotic stressors, biotic stressors can be dynamic and rapidly adapt through evolutionary changes that circumvent plant resistance mechanisms [26]. These biotic stressors are compounded by global trade, changing land use dynamics, and climate change, which help invasive and novel pathogen races establish and spread in non-native environments. For example, higher temperatures and changing patterns of rainfall may allow pests like *Spodoptera frugiperda* (fall armyworm) and diseases like wheat blast and rusts to expand their geographic ranges into regions where they were previously non-existent [27].

2.2.1. Fungal Pathogens

Fungal diseases are one of the most damaging biotic stressors in agriculture, leading to substantial pre- and post-harvest losses and threatening global food security. They afflict virtually every important food and cash crop and produce symptoms including rusts, smuts, blights, mildews, wilts, and leaf spots. Climate change has intensified the threat posed by fungal pathogens by accelerating evolution, increasing their geographic spread, and allowing them to overcome genetic resistance. Rice blast, which is caused by *Magnaporthe oryzae*, is recognised as the most destructive rice disease anywhere in the world, causing enough yield loss to feed more than 60 million people per year. Wheat stem rust, particularly the Ug99 race of *Puccinia graminis* f. sp. *tritici*, which is highly virulent in Africa and is now spreading rapidly to Asia, will threaten world wheat production [27]. Fungal pathogens employ many different infection strategies. They can be classified as biotrophs, which include rusts and powdery mildews, as they derive nutrients from living cells. The other strategy is to kill host tissue, such as *Botrytis cinerea* (a necrotrophic pathogen), and the dead tissue will then be colonised. Fungal pathogens employ specialised infection structures, such as appressoria and haustoria, specifically to manipulate and invade a plant host. They also secrete effector proteins and cell wall-degrading enzymes into plant cells to suppress plant immune responses and enhance the process of infecting a plant host [28].

In response to the pathogen attack, plants initiate a multi-layered immune response. Pattern-triggered immunity (PTI) can be activated by the recognition of shared microbial patterns (such as chitin), while effector-triggered immunity (ETI) can be activated in response to specific pathogen effectors by using resistance (R) genes, evoking stronger responses such as a hypersensitive response (HR), reactive oxygen species (ROS) burst, or systemic acquired resistance (SAR) [26]. However, the adaptive nature of fungal pathogens necessitates the use of progressive biotechnological strategies. Gene pyramiding (e.g., Pi9, Pita, Pi54) and the transgenic expression of antifungal proteins (chitinases/defensins) has been used to enhance resistance in rice and wheat [29], while RNA interference (RNAi) and host induced gene silencing (HIGS) against the CYP51 gene in *Fusarium* has conferred resistance in barley [30]. The CRISPR-Cas9 editing of susceptibility genes (e.g., OsERF922 in rice) has improved resistance to certain fungal pathogens without negatively affecting agronomic yield benefits [31]. Furthermore, these new omics-based breeding and marker-assisted selection strategies are developing cultivars that will be durable and that have broad resistance. In light of climate change and unpredictable climate, sustainable plant protection from fungal diseases will require a systems approach (i.e. combining conventional plant breeding with molecular tools and real-time pathogen monitoring).

2.2.2. Bacterial Pathogens

Bacterial pathogens are a significant cause of global crop

loss, which negatively impacts plant health, productivity, and marketability in multiple species. Infections mostly occur through the natural plant openings, such as stomata and hydathodes, or wounds, so that bacteria can reproduce in the apoplast and interfere with plant metabolic and physiological processes. Some notable examples of bacterial diseases include bacterial blight of rice (*Xanthomonas oryzae* pv. *oryzae*), fire blight of apples and pears (*Erwinia amylovora*), and bacterial wilt of solanaceous plants, such as tomato (*Ralstonia solanacearum*) [32]. Bacterial pathogens impair vascular function and cause wilting, chlorosis, necrosis, and overall death of the plant. Interestingly, bacterial pathogens use a virulence effector that they deliver using a special type III secretion system (T3SS), which allows them to insert effector proteins directly into host cells. Typically, these effector proteins suppress host immunity by targeting fundamental regulators of both defence and metabolism [33]. In response to this, plants have a two-faceted immune system. The first part is PAMP-triggered immunity (PTI), which marks the detection of conserved microbial patterns (e.g., flagellin) using pattern recognition receptors (PRRs). To evade or trigger PTI, bacteria use effectors to induce effector-triggered immunity (ETI) in plants. ETI is triggered through resistance (R) genes that usually encode NBS-LRR proteins that directly detect specific effectors, and induce powerful defence responses such as hypersensitive response (HR) and systemic acquired resistance (SAR) [26]. Biotechnological progress has included the ability to provide resistance against bacterial diseases. In rice, *Xanthomonas* species can turn on SWEET genes, which use TAL effectors to trigger efflux of sugars. By editing the promoter region of SWEET genes using CRISPR-Cas9, rice has durable and broad-spectrum resistance while maintaining yield. Marker-assisted selection (MAS) has aided the introgression of bacterial resistance genes such as Xa21, Xa23, and Xa27 in rice lines [3]. Current research looks at using RNA interference (RNAi) to silence bacterial virulence, alongside techniques to manipulate the plant-associated microbiome to induce systemic resistance. In general, the combination of genome editing, MAS and manipulating microbial associates provides exciting, sustainable pathways for managing bacterial disease in the face of increasing global climate stressors.

2.2.3. Viral Pathogens

Plant viruses are a pest that can greatly reduce global agricultural productivity, particularly in the tropics and subtropics, where insect vector populations comprising aphids, whiteflies, thrips, and leafhoppers are often abundant and difficult to control. Plant viruses are transmitted either mechanically or circulative by these vectors, making disease initiation rapid and advantageous for the virus. Control measures against viruses are notably futile because of their higher mutation rates, wide host ranges, and latent vectors within plants [34]. Three significant plant viruses of economic concern are the Tomato yellow leaf curl virus (TYLCV),

Cucumber mosaic virus (CMV), and Rice tungro virus complex. TYLCV is capable of causing severe stunting, yellowing, and leaf-curling symptoms on tomatoes. CMV is capable of affecting over 1,000 plant species and is capable of decreasing photosynthesis and fruit quality. Rice tungro virus complex consists of the synergistic infection of Rice tungro bacilliform virus (RTBV) and Rice tungro spherical virus (RTSV) and causes severe dwarfing of plants, decreases flowering, and grains are significantly impacted [35]. Upon entering the plant, viruses manipulate host cellular machinery (e.g., translation factors), movement proteins, and hormones to replicate and move systemically. This often results in chlorosis, leaf mosaic patterns, leaf deformation, and yield losses for farmers. Because viruses are obligate intracellular pathogen organisms, breeding to generate virus resistance is particularly difficult. Modern biotechnological innovations are already addressing plant viruses. RNA interference (RNAi) has been successfully used to silence RNA viruses such as CMV and TYLCV by targeting viral RNA via siRNA pathways. Virus-induced gene silencing (VIGS) is being used now for functional genomics and transient resistance. Recently, targeting RNA viruses with CRISPR-Cas13, which cleaves single-stranded RNA, has been promising for viruses such as Turnip mosaic virus (TuMV) and Potato virus Y (PVY) [36]. Further, editing host S-genes (such as eIF4E) related to susceptibility (and essential for translation of many viruses) has produced resistant cultivars in crops including tomato, melon, and cucumber [37].

While viral evolution presents continuous challenges, RNAi, Cas13, and S-gene editing could provide precise, durable, and possibly non-transgenic strategies. Their success in the future will likely hinge on effective delivery systems, vector management, and prevailing regulatory frameworks.

2.2.4. Insect Pests

Insect pests are probably the most widespread and damaging biotic stressors harming agriculture around the world. They cause both direct and indirect harm to crop plants. Direct harm manifests from feeding, chewing, sucking, or mining, which removes or reduces photosynthetic area, interrupts nutrient flow, creates stunting, chlorosis, and ultimately reduced yields. Indirectly, many insect vectors also transmit viral and bacterial pathogens that further exacerbate plant health issues. Key insect pests of concern include aphids, whiteflies, leaf-hoppers, stem borers, and the cotton bollworm (*Helicoverpa armigera*), affecting staples like rice, maize, cotton, and vegetables. Traditionally, chemical pesticides have been the main control method to manage insect pest populations, but excessive reliance has developed pest resistance, caused widespread ecotoxicity, affected beneficial organisms and humans, and resulted in a shift toward sustainable biotechnological solutions.

Several innovations are important, but one of the most successful developments has been Bt crops, genetically modified that can express *Bacillus thuringiensis* (Bt) toxins. These

Cry proteins specifically target pest larvae (*Lepidoptera*, *Coleoptera*) to use reduced amounts of insecticides and promote yield increases in cotton and maize, particularly in countries like India, China, and the U.S. [38, 39]. RNA interference (RNAi) represents a more targeted approach to insect pest management. Transgenic maize constitutively expressing double-stranded RNA (dsRNA) to V-ATPase in *Diabrotica virgifera virgifera* represents pest management with minimal non-target impacts [40]. CRISPR-Cas9 systems are being examined for engineering pest-resistant crops and for engineered changes to insect genomes; however, biosafety and ecological questions still exist. These genetic tools are increasingly being used within Integrated Pest Management (IPM) approaches to integrate other components like biocontrol agents and the processes of marker-assisted breeding and microbiome engineering. Altogether, Bt, RNAi and CRISPR technologies have begun an innovative and transformative trend towards more environmentally sustainable and synergistic crop protection approaches.

2.2.5. Nematodes

Plant-parasitic nematodes can be a major agricultural biotic stress that often goes overlooked by researchers and producers. Damage from nematodes is responsible for an estimated \$80 billion a year in yield loss worldwide. Plant-parasitic nematodes grow and live in microscopic roundworms and infect plant roots, affecting the plant's ability to uptake water and nutrients, change root architecture, and leave the plant susceptible to secondary infections from fungi and bacteria. Some important genera of plant-parasitic nematodes are root-knot nematodes (*Meloidogyne* spp.) that produce root galls, and cyst nematodes (*Heterodera* and *Globodera* spp.), that producing cysts that can endure for years and are important to cereals and legumes.

Nematode-infected roots are reduced in vascular development, stunted growth, chlorosis, and nutrient deficiency symptoms. Even more troubling, nematodes often facilitate disease complexes as they alter the pathogenesis of other pathogens synergistically, further complicating management [41]. Conventional control relies on resistance breeding, such as incorporating Mi-1 resistance in tomato; however, there are limitations, including virulence shifts, narrow-spectrum resistance, and nematode persistence in soil. To counteract the limitations of conventional nematode control methods, various biotechnological advancements are being utilised. Transgenic crops containing nematocidal proteins, such as cysteine proteinase inhibitors, lectins and *Bacillus thuringiensis* (Bt) crystal proteins, have been effective in reducing nematode penetration and reproduction [42]. In addition to transgenic nematode control methods, RNA interference (RNAi) is capable of allowing transgenic plants to silence important nematode effector genes, such as MiMsp40 in *Meloidogyne incognita*, significantly reducing gall formation and the nematode's ability to reproduce [43]. CRISPR-Cas genome editing offers a promising non-transgenic method that

can alter susceptibility genes in plants in a precise manner, ultimately resulting in durable nematode resistance. Lastly, omics technologies like transcriptomics and metabolomics will foster the identification of nematode-responsive pathways and enable the use of marker-assisted selection (MAS) in breeding resistant cultivars. The effective application of genetic resistance, RNAi, genome editing, and omics-guided breeding into an integrated approach for nematode management will be key to achieving sustainable and climate-resilient practices.

2.2.6. Parasitic Weeds

Parasitic weeds are highly destructive biotic stressors, particularly in low-input agricultural systems. The genera *Striga* (which includes witchweed) and *Orobanche* (which includes broomrape) are obligate parasites, meaning that they have to attach haustoria to host plant roots to extract water, nutrients, and photosynthates. As these haustoria negatively affect the host plant's resources, the root system of plants is not allowed to grow normally, leading to slower flowering and ultimately grain filling. As could be expected, the reduction of resources due to the parasitism of the host plants leads to consequential yield losses in crops such as cereals, legumes, and oilseeds [44]. For example, the *Striga hermonthica* species is known for being highly damaging to sorghum, millet, and maize. In sub-Saharan Africa and regions of Asia, when there are higher-than-normal drought conditions, the yield losses can be as high as 80%. The parasitism of *Orobanche* species negatively affects legumes (holy basil, garlic, onion), and vegetables (fava beans, chickpeas) and can be very damaging in the Mediterranean region and parts of Asia.

Controlling them is difficult because of their complex life cycles and covert means of infection, such as seed germination in response to plant hormones, strigolactones that are released by plant roots. While biotechnological approaches promise new solutions, for example, RNA interference (RNAi) has been used to silence host genes that contribute to strigolactone biosynthesis (e.g. CCD7, CCD8) and reduce *Striga* seed germination. Host-induced gene silencing (HIGS) targeting parasite-specific genes like SHHT1 has been demonstrated to restrict haustorium development. Moreover, perennial strategies such as transferring (introgressing) resistance QTLs from resistant (tolerant) genotypes such as sorghum (eg. N13 and Framida) and the application of transgenes that encode protease inhibitors or allelochemicals to deter attachment. As biotic and abiotic stressors continue to overlap, optimising breeding for crops with combined resistance to multiple stressors will be essential for maintaining yield under a changing climate [45].

2.3. Climate Change-Driven Stressors

Climate change introduces an array of environmental stressors that directly impact crop productivity, stability, and food security. Among the critical concerns associated with

climate change are climate extremes, uncharacteristic rainfall, elevated CO₂ concentrations, and an increase in the frequency of extreme weather events. All of these stresses interfere with plant growth and development, but also alter pest and disease dynamics. Meeting these challenges necessitates innovative biotechnological solutions that develop multiple, simultaneous stress-tolerant crops.

2.3.1. Temperature Extremes

The growing trend of extreme weather, like severe heat waves that last longer, together with unexpected cold and frost events all partly attributable to global warming, is something we will have to address moving forward. Extreme temperatures can have negative impacts on crops reproductive development, grain filling and enzyme activity, especially for climate-sensitive crops, such as wheat and rice [5]. In addition to breeding practices and approaches, genetic engineering and genome editing techniques (such as the overexpression of some HSF and DREB transcription factors) are being used to increase heat and cold tolerance in crops [46].

2.3.2. Erratic Rainfall

Uncertain and inconsistent rainfall patterns can disrupt regular planting and harvesting cycles, resulting in droughts or waterlogging. Stress conditions can inhibit seed germination, root elongation and nutrient uptake. Drought-tolerant varieties produced by marker-assisted selection, and transgenic methods (e.g., MON87460 maize) are providing new opportunities for superior yield performance under water-deficit conditions [47].

2.3.3. Elevated CO₂ Levels

Though measurable increases in CO₂ can enhance photosynthesis (especially for C₃ plants), there are always changes in the basic metabolism of the plant, and also in nutrient partitioning. Furthermore, CO₂ increases can influence pest management through increases in fecundity, or by altering views of host-pest interactions [48]. Multi-omics studies shed light on CO₂-mediated changes in plant blood metabolic pathways and their potential to provide support for breeding programs that achieve plant nutrient-use efficiency or resilience in pest-host interactions.

2.3.4. Increased Frequency of Natural Disasters (Droughts, Floods, Storms)

Extreme weather events are increasing in intensity and frequency, resulting in substantial yield losses and threats to world food security [1]. Risks to crops arise from both abiotic damage (e.g., lodging, submergence) and disease outbreaks post-disaster. The development of submergence-tolerant rice (e.g., Swarna-Sub1 via MAS) and CRISPR-based modification of genes upregulated during flooding events shows promise in reducing these risks.

2.4. Socio-Economic and Technological Stressors

In addition to environmental drivers, socio-economic and technological barriers are substantial obstacles to agricultural productivity and the adaptation of resilient farming systems. Challenges posed by land fragmentation, poor access to quality inputs, labour shortages, volatility in the marketing environment, and inadequate technology determination in rural areas adversely affect the smallholder farmer, particularly in low-income countries. Indeed, these stressors are frequently the barriers inhibiting the application of modern biotechnological solutions, and highlight the importance of inclusive policies, rural investment for innovation, as well as capacity development, to help mitigate the technology adoption gap.

2.4.1. Land Fragmentation

Rising fragmentation of agricultural land, particularly in the developing world, limits the potential for large-scale mechanisation and improved modern crop management practices. Fragmented holdings mean the use of inputs is far less efficient and productivity is lower [49]. Stress-resilient and input-efficient crop types, such as drought-tolerant maize or disease-resistant hybrids, are particularly important for smallholders farming fragmented market plots.

2.4.2. Lack of Access to Inputs (Seeds, Fertilisers, Irrigation, Credit)

Farmers in low-income regions often miss having timely access to improved seeds and fertilisers, irrigation facilities, and affordable credit, which hold back many low-income farmers from adopting productivity-increasing technologies. Developing low-input, climate-resilient crops, especially crops that require little fertiliser or are tolerant to water stress, can help close input gaps and reduce production costs.

2.4.3. Market Instability (Price Volatility and Trade Barriers)

Unstable markets, recurrent price crashes, and trade restrictions worldwide disturb the revenue and investment activities of farmers, discouraging them from adopting innovations [50]. Stable and high-yielding crops within biotech crops can diminish production risk and shelter farmers from price shocks by providing a reliable output.

2.4.4. Labour Shortages

The migration of people from rural areas to urban ones, and the ageing of the farming population, has created significant labour shortages in many of the world's rural regions. Labour-intensive practices are becoming increasingly unviable [51]. Biotech crops with traits such as herbicide tolerance and pest resistance reduce the need for weeding or spraying, which alleviates labour constraints.

2.4.5. Technological Gaps

Many low-income countries experience limited access to advanced tools like precision agriculture, AI-driven analytics, and biotechnology, due to barriers of infrastructure, education,

and economics [52]. Technology transfer, capacity building, and open-access biotechnologies (e.g., CRISPR-based tools with no IP barriers) are important to democratize access to innovation.

Table 1. Classification of Agricultural Stressors and Their Impacts.

Category	Source	Examples	Mechanisms of Impact	Consequences
Abiotic Stressors	Environmental conditions	Drought, salinity, heat, cold, flooding, soil erosion	Disrupt water/nutrient uptake, impair metabolism, damage tissues	Reduced yield, poor quality, stunted growth
Biotic Stressors	Living organisms	Insects, pathogens (fungi, bacteria, viruses), weeds	Tissue damage, toxin production, competition for resources	Crop loss, disease outbreaks, reduced competitiveness
Climate-Driven Stressors	Global climate change	Heatwaves, erratic rainfall, rising CO ₂ , natural disasters	Altered growth cycles, pest dynamics, weather extremes	Food insecurity, production instability, stress overlap
Socio-Economic & Technological Stressors	Human and policy-related factors, Lack or misuse of innovations	Land fragmentation, input scarcity, labor shortage, poor access to technology	Limited resource efficiency, slow adoption of innovations	Low productivity, vulnerability of smallholder farmers

3. Impact of Stressors on Crop Productivity and Food Security

Global food security is seriously threatened by climate-induced and socioeconomic stressors together because they lower crop yields, degrade nutritional quality, and threaten farmer livelihoods, especially in low-income and vulnerable areas. Drought, salinity, heat stress, and pest outbreaks can all drastically reduce crop output; if adaptive measures are not taken, estimates suggest that yield losses in staple crops might reach 20-50% by 2050 [45]. Abiotic stressors and elevated CO₂ in the atmosphere also degrade the nutritional value of grains like rice and wheat, lowering vital micronutrients like protein, iron, and zinc, which can have detrimental effects on human health [48]. Farmers are compelled to spend more on pesticides, fertilizers, and irrigation in response to these stressors, which raises production costs and lowers profitability. Furthermore, inadequate legislative frameworks, technology gaps, and restricted access to robust crop types present disproportionate difficulties for developing nations, exacerbating already-existing disparities in global food systems [53].

4. Emerging Threats: New Pest Species and Evolving Pathogen Strains

Large-scale monoculture methods and climate change are hastening the evolution of severe disease strains as well as the appearance and spread of new pest species. Insect pests and disease-causing organisms can proliferate and migrate into previously inappropriate places due to factors like rising global temperatures, changed precipitation patterns, and an increase in the frequency of extreme weather events. For example, formerly indigenous to the Americas, the fall armyworm (*Spodoptera frugiperda*) has spread quickly throughout Africa, Asia, and Australia, resulting in catastrophic crop losses in maize and other cereals [54]. In a similar vein, warmer temperatures are promoting faster pest reproduction cycles and increasing the rates at which viral pathogens, like *Bemisia tabaci*, transmitting Tomato Yellow Leaf Curl Virus (TYLCV), spread through vectors, expanding their host spectrum and geographic range. Additionally, monoculture farming methods decrease genetic variation, resulting in homogeneous environments that facilitate the evolution of pest and pathogen resistance to chemical treatments and plant defence mechanisms [55]. Through genomic plasticity, pathogens such as *Magnaporthe oryzae*, the cause of rice blast disease, have demonstrated the ability to quickly adapt and get past host resistance genes. These patterns highlight the pressing need for integrated approaches to managing

pests and diseases that include climate-resilient crops, biotechnology advancements, and agricultural system diversity in order to lower vulnerability to emerging biological threats.

5. Strategies for Managing Agricultural Stressors

An integrated approach that combines agronomic techniques, technology advancements, and supportive policies is necessary for the effective management of agricultural stressors. Crop rotation, conservation agriculture (e.g., low tillage, cover cropping), agroforestry, and integrated agricultural systems are examples of agronomic and ecological practices that increase soil fertility, decrease erosion, and strengthen resistance to climate-induced variability. In arid and semi-arid locations, water harvesting and micro-irrigation techniques are essential for maximising water utilisation and reducing the effects of drought. In terms of technology, crop varieties that are climate-resilient and have been created through genome editing, biotechnology, and conventional breeding provide resistance to a variety of stressors. Drones, AI-based decision-support systems, and remote sensors are examples of precision agriculture technologies that facilitate effective resource management and prompt stress detection. Genetically modified crops and CRISPR-edited cultivars are examples of biotechnological interventions that greatly reduce stress and stabilise yield in challenging circumstances [8]. Preparation for drought, insect outbreaks, and extreme weather events is improved by early warning systems that use climatic models and satellite-based remote sensing. Institutional and policy assistance are still essential: infrastructure improvements, insurance plans, and targeted subsidies lessen farmer vulnerability, while training programs and capacity-building projects equip smallholders with adaptable skills [53, 56]. Furthermore, in order to scale breakthroughs and guarantee fair access to technologies across regions, public-private collaborations are becoming more and more important.

6. Research Gaps and Future Directions

A systematic research strategy that closes important knowledge gaps and harmonises innovation with field-level realities is necessary to address the complex issues in agriculture brought on by climate change. A primary area of research is to gain a deeper understanding of the physiological and molecular mechanisms underlying multi-stress tolerance. According to Mittler and Blumwald (2010), the majority of crop improvement strategies currently in use focus on individual stresses, but climate-induced stress combinations, like drought combined with heat or salinity, call for coordinated responses that involve intricate gene networks and hormonal interaction [57]. Localised and context-specific solutions are also required because agro-ecological zones differ greatly in

terms of resource availability and stress profiles. This necessitates more funding for locally relevant technologies and community-based participatory [58]. Additionally, socioeconomic integration is crucial; in order to guarantee uptake, affordability, and cultural relevance, technological advancements must be co-developed with farmers [17]. Additionally, to give actionable insights with higher geographical and temporal resolution for stress prediction and mitigation planning, better climate modelling and forecasting systems are required [59]. Lastly, to convert research findings into workable policies that support resilience, especially for smallholders who are at risk, a more efficient policy-science interface needs to be developed. It will take interdisciplinary cooperation, inclusive policy frameworks, and consistent capacity-building investment to close this gap.

7. Conclusion

Sustainable crop production and global food security are at risk due to a confluence of environmental, biological, and socioeconomic stresses facing modern agriculture. In order to tackle these complex issues, a comprehensive, systems-based strategy that incorporates state-of-the-art scientific discoveries with customs, regional expertise, and socio-economic factors is needed. Coordinated efforts across disciplines connecting biotechnology, agroecology, data-driven technologies, and policy will be essential to the future of climate-resilient agriculture in order to promote adaptive capacity at all scales. A robust agricultural system that can endure future uncertainties and benefit people and the environment will need to promote democratic governance, ensure equal access to innovations, and fortify institutional support.

Abbreviations

ABA	Absciscic Acid
Bt	Bacillus thuringiensis
CMV	Cucumber Mosaic Virus
COR	Cold-Regulated (genes)
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
dsRNA	Double-Stranded RNA
DREB	Dehydration-Responsive Element-Binding Protein
ETI	Effector-Triggered Immunity
GS	Genomic Selection
GM	Genetically Modified
HIGS	Host-Induced Gene Silencing
HR	Hypersensitive Response
HSF	Heat Shock Factor
HSP	Heat Shock Protein
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Pest Management

MAS	Marker-Assisted Selection
NHX1	Na ⁺ /H ⁺ Exchanger 1
PAMP	Pathogen-Associated Molecular Pattern
PRR	Pattern Recognition Receptor
QTL	Quantitative Trait Loci
RNAi	RNA Interference
ROS	Reactive Oxygen Species
SAR	Systemic Acquired Resistance
SOS	Salt Overly Sensitive (gene family)
TAL	Transcription Activator-Like (effectors)
T3SS	Type III Secretion System
TYLCV	Tomato Yellow Leaf Curl Virus
VIGS	Virus-Induced Gene Silencing

Conflicts of Interest

The authors declare no conflicts of interest.

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