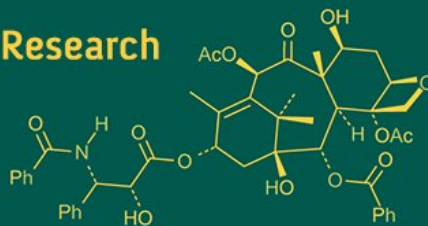


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Climate-resilient horticulture: Strategies to combat abiotic stress: A review

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Abstract

Horticultural crops are disproportionately vulnerable to climate variability, with abiotic stresses including drought, heat, cold, salinity, and waterlogging collectively responsible for more than 50% of global horticultural yield losses annually. As the frequency and intensity of extreme weather events accelerate under ongoing climate change, understanding and counteracting the multifaceted impacts of abiotic stress has become one of the foremost challenges in modern plant science. This review synthesizes current knowledge on the physiological, biochemical, and molecular mechanisms by which horticultural plants perceive and respond to abiotic stresses, with particular emphasis on reactive oxygen species (ROS) homeostasis, hormonal signaling networks, osmotic adjustment, and heat shock protein function. We critically evaluate a spectrum of climate-resilience strategies spanning traditional and molecular breeding, CRISPR-based genome editing, exogenous elicitor applications, grafting, biochar amendment, deficit irrigation, precision agriculture technologies, and microbial inoculants highlighting their efficacy, limitations, and integration potential. Integrated, multi-pronged approaches that combine genetic improvement with agronomic management and technological innovation offer the most promising pathway to sustainable, climate-resilient horticultural production. Future research must bridge the gap between laboratory discoveries and field-level implementation, prioritizing multi-stress tolerance and smallholder applicability.

Keywords: Abiotic stress, climate change, horticultural crops, drought tolerance, heat stress, salinity, reactive oxygen species, CRISPR, precision agriculture, stress priming

1. Introduction

Horticulture is the practice of growing fruits, vegetables, flowers, and herbs, all crops which make substantial contributions to human nutrition and biodiversity. Horticultural crops differ from cereals in being especially sensitive to changes in their environment, hence making them highly vulnerable to climate change. The world has experienced an increase in global temperatures of about 1.1°C relative to the pre-industrial period, with estimates projecting another rise of between 1.5 and 4.5°C by the end of the century (IPCC, 2021) [9]. These changes will be associated with increased cases of drought, extreme precipitation, heat waves, sea-level rise leading to increased soil salinity, and unexpected frosts all abiotic stresses for horticultural crops.

Abiotic stress refers to any non-biological factor within the environment that negatively influences plant growth, development, and productivity (Mittler, 2006) [4]. This may involve drought, extreme temperature, salinity, water logging, ultra violet radiation, heavy metal toxicity, and oxidative stress. According to Boyer (Boyer, 1982) [5], the environmental stresses cause about 30% loss of global crop production below their genetic capacity. Notably, according to recent reports, climate change-induced disasters have caused annual global crop production to be about 10% to 14% lower from 1964 to 2007 (Lesk *et al.*, 2016) [3]. The future outlook of this trend suggests even greater losses in upcoming years.

The horticultural crops are vulnerable to abiotic stress due to the impact of the stress on the quality of fruits and vegetables based on their appearance, flavor, aroma, nutrient content, and storage life. This is because, although environmental factors may influence crop yields of cereals significantly, they may affect other important quality characteristics of

of horticultural crops. Heat stress during the anthesis stage in tomatoes can result in complete failure of fruit formation (Bita & Gerats, 2013) [7]. Similarly, chilling of the mangoes, bananas, and cucumbers can lead to irreparable changes in fruit quality (Palta & Weiss, 1993) [28].

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Over the past two decades, numerous findings have advanced our knowledge about the underlying mechanisms of stress responses in plants, ranging from the identification of the signaling processes associated with ABA and non-ABA responses (Yamaguchi-Shinozaki & Shinozaki, 2006) [24], to the studies on the DREB/CBF family of transcription factors (Agarwal *et al.*, 2006) [65], ROS signaling pathways (Apel & Hirt, 2004) [35] and ion transport for salt tolerance (Munns & Tester, 2008) [14]. Moreover, significant achievements have been made in such domains as genomics, proteomics, metabolomics, and genome editing with CRISPR-Cas9, opening new opportunities for stressresilience improvements (Zhu, 2016; Varshney *et al.*, 2011) [16, 58].

In addition, the developments in agronomy, such as deficit irrigation, mulching, biochar treatment, precision farming, and PGPR, are valuable tools which have proved their effectiveness in practice in different agroecological environments (Farooq *et al.*, 2009) [49]. Finally,

osmoprotectant treatments, hormone, and signaling molecule application are effective low-cost strategies for temporary enhancement of tolerance (Choudhary *et al.*, 2012) [73].

Nonetheless, there are still considerable differences between what scientists have discovered in laboratories and how farmers use them in their fields. Tolerance to stress is a multi-gene trait that is situational and often comes at the expense of yield and product quality (Blum, 2005) [57]. In cases where plants experience several stresses at once, the resulting plant response will be entirely different from the response when a single stress factor is present (Zandalinas *et al.*, 2018; Hussain *et al.*, 2019) [2, 76]. This review will focus on the current state of knowledge regarding the science of abiotic stress in horticulture and critically assess the range of approaches currently being developed and implemented to create climate-resilient varieties.

2. Scope and Methodology

The key terms used for the literature search include ‘abiotic stress horticulture climate change vegetable crops’, ‘drought tolerance fruit crops’, ‘heat stress tomato’, ‘salinity tolerance horticultural plants’, ‘ROS signaling plants’, ‘DREB transcription factors’, ‘grafting stress tolerance’, ‘deficit irrigation’, and ‘CRISPR plant stress’. Only those papers that were related to: (i) the mechanism of abiotic stress response in horticultural plants, (ii) an assessment of breeding/biotechnology strategies for stress tolerance improvement, and (iii) agronomical management practices have been selected for analysis.

3. Types of Abiotic Stress in Horticultural Crops

Horticultural crops face a diverse array of abiotic stresses that vary in nature, duration, intensity, and combination (Table 1). Each stress type elicits distinct physiological responses while sharing common downstream signaling elements including calcium second messengers, MAPK cascades, and ROS networks (Cramer *et al.*, 2011) [6]. Understanding the specificity and overlap of these responses is crucial for designing broad-spectrum tolerance strategies.

Table 1 Major abiotic stresses affecting horticultural crops: primary targets, physiological consequences, and estimated yield losses.

Abiotic Stress	Primary Affected Crops	Key Physiological Effects	Estimated Yield Loss (%)	
Drought	Wheat, Maize, Rice, Tomato	Stomatal closure, reduced photosynthesis, osmotic imbalance	20-50	Boyer (Boyer, 1982); Mittler (Mittler, 2006); Fahad <i>et al.</i> (Fahad <i>et al.</i> , 2017); IPCC (IPCC, 2021); FAO (FAO, 2020) [5, 6, 1].
Heat Stress	Tomato, Pepper, Cucumber, Strawberry	Protein denaturation, pollen sterility, membrane damage	15-70	
Cold/Chilling	Banana, Mango, Citrus, Cucumber	Membrane rigidity, ice crystal formation, metabolic disruption	10-60	
Salinity	Vegetable crops, Melon, Lettuce	Ion toxicity, osmotic stress, nutrient imbalance	25-50	
Waterlogging	Tomato, Pea, Bean, Maize	Hypoxia, root asphyxiation, ethylene accumulation	20-40	
Heavy Metals	Leafy vegetables, Root crops	ROS overproduction, enzyme inhibition, chlorosis	10-30	
UV Radiation	Lettuce, Spinach, Pepper	DNA damage, chlorophyll degradation, oxidative stress	5-25	

3.1 Heat Stress

Heat stress arises due to high temperatures beyond the critical limit for physiological activity, usually above 35°C for most horticultural plants (Bita & Gerats, 2013) [7]. Heat stress affects cellular processes by denaturing proteins, disrupting membrane fluidity, blocking PSII electron transport, and producing reactive oxygen species (ROS)

(Wahid *et al.*, 2007) [12]. Heat stress also affects reproductive structures by interfering with pollen tube formation, aborting ovules, and impairing fruit set. The tomato (*Solanum lycopersicum*) crop is highly sensitive to heat stress: temperatures above 22°C during the night and above 38°C during the day can inhibit fruit formation by more than 90% (Bita & Gerats, 2013;

Hasanuzzaman *et al.*, 2013)^[11]. Ethylene production triggered by heat increases fruit ripening and decreases their shelf life. Heat stress effects on the molecular level have been extensively studied by Wahid *et al.* (Wahid *et al.*, 2007).

3.2 Drought Stress

Drought is the most damaging abiotic factor for crop yield in the world, resulting in reductions between 20% and 50% for crop plants (Boyer, 1982; Farooq *et al.*, 2009)^[5, 49]. Water stress leads to stomata closure through ABA signaling, causing reduction in transpirational water loss while simultaneously reducing CO₂ absorption and photosynthetic rates (Chaves *et al.*, 2009; Schroeder *et al.*, 2001)^[18, 55]. Chronic drought stress leads to cellular dehydration, membrane injury, protein denaturation, and activation of proteases. The development of new root architecture, such as deep roots and higher density of root hairs, is an important strategy for avoiding drought conditions (Price *et al.*, 2002)^[53]. Fruit quality factors in horticulture crops are highly dependent on water management (Jaleel *et al.*, 2009)^[52].

3.3 Salinity Stress

Soil salinization, resulting from irrigation, sea-level rise, and inadequate drainage, currently impacts more than 900 million hectares worldwide and is on the increase at the rate of 1-2% per year (Munns & Tester, 2008)^[14]. Salinity causes harm to plants through osmotic stress, which leads to reduced water uptake and ionic toxicity caused by the build-up of Na⁺ and Cl⁻ ions (Munns & Tester, 2008)^[14]. For horticultural plants, excess of Na⁺ results in its accumulation in older leaves and consequently in chlorosis, necrosis, and faster senescence (Flowers & Colmer, 2008; Deinlein *et al.*, 2014)^[20, 30]. The main pathway responsible for Na⁺ extrusion is called SOS, and it consists of the three proteins SOS3- SOS2-SOS1 (Zhu, 2016)^[16]. Compartmentation of Na⁺ into vacuoles via NHX antiporters and restricted Na⁺ loading into the xylem via HKT transporters are additional critical mechanisms (Roy *et al.*, 2014)^[31].

3.4 Cold and Chilling Stress: Cold stress is characterized into chilling injury (0-15°C) and freezing injury (< 0°C), both having different mechanisms. Chilling injury causes damage to the tropical and subtropical horticultural crops like bananas, mangos, cucumbers, and citrus fruits through membrane phase transition into gel form, metabolic malfunction, and loss of ions (Chinnusamy *et al.*, 2007; Palta & Weiss, 1993)^[27, 28]. Freezing injury results due to the development of ice crystals inside the cell, leading to rupture of the cellular membrane. Cold acclimation is the process of gradual adaptation resulting due to exposure to non-freezing low temperatures and consists of induction of transcription factors, production of cryoprotectants, and membrane lipid modification (Thomashow, 1999; Chinnusamy *et al.*, 2007)^[26].

3.5 Waterlogging and Hypoxia

The lack of oxygen results in the change in the cellular metabolism, leading to fermentation of sugars. This causes the formation of harmful products such as ethanol and acetaldehyde (Mittler, 2006)^[4]. The formation of aerenchyma in the roots allows oxygen to move from shoots to roots. It is one of the tolerance mechanisms found in plants adapted to flooding conditions. Ethylene gas is synthesized in roots when flooded and triggers the formation of aerenchyma and adventitious roots (Cramer *et al.*, 2011)^[6]. Tomato, pea, and bean plants are extremely sensitive to waterlogging beyond 24-48 hours.

3.6 Heavy Metal and UV Stress

Metal toxicity (Cd, Pb, As, Hg) constitutes a growing abiotic stress in peri-urban horticulture caused by industry effluents, mining and use of sewage sludge (Ahmad *et al.*, 2010)^[37]. Metals interfere with enzymatic activity, impairing photosynthesis while producing reactive oxygen species through Fenton and Haber-Weiss reactions (Apel & Hirt, 2004)^[35]. Increased levels of UV-B as a result of the thinning of the ozone layer affect DNA synthesis and impair photosynthesis while deteriorating proteins in horticultural produce (Potters *et al.*, 2007)^[39]. On the other hand, moderate exposure to UV-B light may increase phenolic production for quality management.

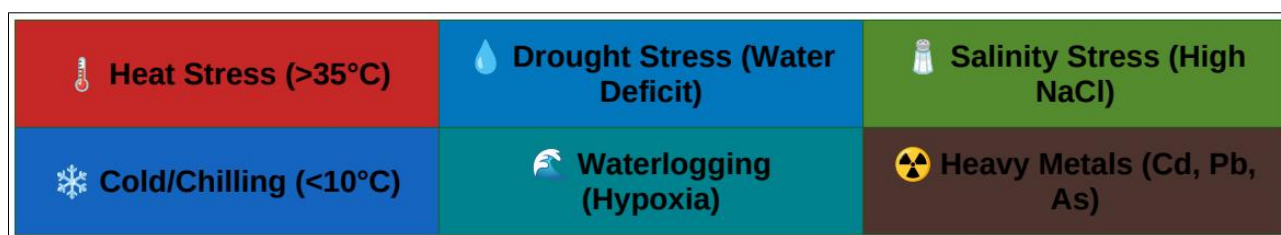


Fig 1: Abiotic stress categories (color-coded) showing six major stress types impacting horticultural crops globally. Each category triggers distinct yet overlapping physiological responses in plant systems (Mittler, 2006; Cramer *et al.*, 2011; IPCC, 2021).

4. Physiological and Biochemical Responses to Abiotic Stress

Plant responses to abiotic stress are orchestrated across multiple scales from subcellular biochemistry to whole-plant physiology in a hierarchically organized cascade (Figure 2).

Effective stress tolerance requires rapid perception, efficient signal amplification, coordinated gene expression reprogramming, and ultimately adaptive phenotypic adjustment (Zhu, 2016; Xiong *et al.*, 2002)^[16, 17].

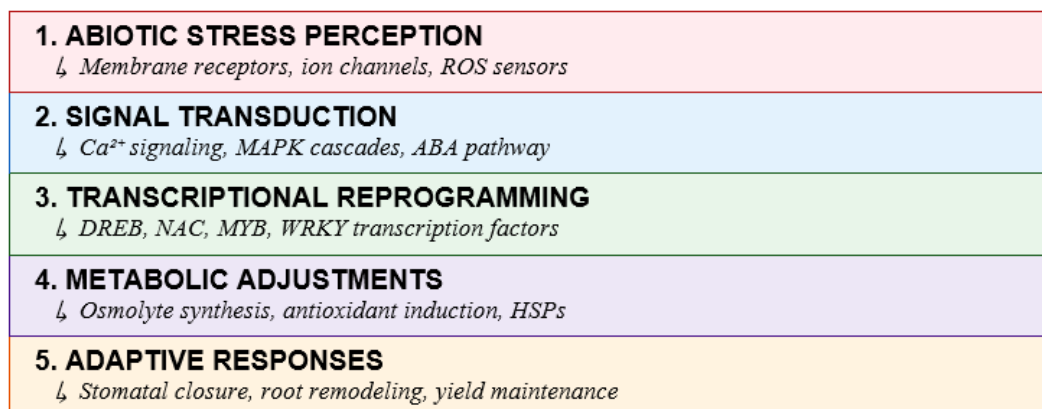


Fig 2: Stepwise representation of the abiotic stress response cascade from initial stress perception through signal transduction, transcriptional reprogramming, metabolic adjustment, and ultimate adaptive outcomes (Zhu, 2016; Xiong *et al.*, 2002; Yamaguchi-Shinozaki & Shinozaki, 2006; Apel & Hirt, 2004) ^[16, 17, 34, 35].

4.1 Reactive Oxygen Species and Antioxidant Defense

These include $O_2^{\bullet-}$, H_2O_2 , $OH^{\bullet}$, and $^1O_2$, which are produced as by-products of aerobic respiration and are highly over-produced under almost all abiotic stresses (Mittler *et al.*, 2004; Apel & Hirt, 2004) ^[34, 35]. Although excess ROS cause oxidative damage to the cellular constituents (lipids, proteins, and DNA), plants have a fine-tuned ROS signaling gene network and utilize H_2O_2 for local and long-distance communication in addition to being an ROS molecule (Mittler *et al.*, 2004; Miller *et al.*, 2008) ^[36].

Antioxidant enzyme system includes the following enzymatic components: SOD, CAT, APX, GR, MDHAR, DHAR, and peroxiredoxins, together with non-enzymatic antioxidants, which include ascorbic acid (vitamin C), glutathione, α -tocopherol, carotenoids, and flavonoids (Hasanuzzaman *et al.*, 2020; Ahmad *et al.*, 2010; Foyer & Noctor, 2009) ^[33, 37]. The ascorbate-glutathione cycle, functioning in chloroplasts, mitochondria, and peroxisomes, plays a crucial role in H_2O_2 scavenging (Foyer & Noctor, 2009) ^[38]. Increased activities of antioxidant enzymes are positively correlated with stress tolerance in horticultural species. Many studies have shown that increased antioxidant capacity confers better stress tolerance and stable production (Hasanuzzaman *et al.*, 2020; Ahmad *et al.*, 2010) ^[33, 37].

4.2 Osmotic Adjustment and Compatible Solutes

Osmotic adjustment refers to the active synthesis of compatible solutes within the cell cytoplasm to lower the water potential in the cells without toxicity. Osmotic adjustment is a vital stress tolerance mechanism (Serraj & Sinclair, 2002; Chen & Murata, 2002) ^[42, 43]. Compatible solutes include proline, glycine betaine, trehalose, polyols like mannitol and sorbitol, and sucrose (Bohnert & Jensen, 1996) ^[41]. Compatible solutes play several roles: They stabilize proteins and membranes, detoxify reactive oxygen species, maintain cytosolic pH balance, and act as reservoirs of reduced forms of carbon and nitrogen for use during recovery after stress (Chen & Murata, 2002; Bartels & Sunkar, 2005) ^[43, 44]. The accumulation of proline has been highly reported under drought and saline conditions in tomatoes, potatoes, and peppers. Its biosynthesis is controlled by the enzyme Δ^1 -pyrroline-5-carboxylate synthetase (P5CS) (Bartels & Sunkar, 2005) ^[44]. Overexpression of the gene encoding this enzyme, *codA* gene (encoding choline oxidase for glycine betaine), and

trehalose phosphate synthase (TPS) through transgenic technology.

4.3 Hormonal Signaling Networks

The key hormone for abiotic stress responses in plants, specifically for drought and salt, is abscisic acid (ABA). In response to the water-deficit conditions, there is a quick accumulation of ABA in the roots and leaves, resulting in stomata closure by controlling ion channels in the guard cells, as well as activation of a wide range of gene expressions through ABA Responsive Element Binding (AREB/ABF) transcription factors (Schroeder *et al.*, 2001) ^[55]. The molecular components of ABA signaling pathway include PYR/PYL receptors, PP2C repressor phosphatases, and SnRK2 kinases; these have already been thoroughly studied (Zhu, 2016) ^[16].

In addition to the role of ABA, salicylic acid (SA), jasmonic acid (JA), brassinosteroids (BRs), ethylene, and nitric oxide (NO) are also involved in stress signaling pathways, each displaying significant cross-talk (Choudhary *et al.*, 2012) ^[73]. SA priming is responsible for systemic acquired stress resistance, JA regulates wound and cold responses, BRs are involved in multiple stress resistance by enhancing BRI1-receptor signaling, while ethylene acts to induce flooding response and promote ripening during heat conditions (Choudhary *et al.*, 2012; Hussain *et al.*, 2019) ^[76].

4.4 Heat Shock Proteins and Molecular Chaperones

HSPs are chaperones that help protein folding, prevent aggregation of unfolded proteins, help in transport of newly synthesized polypeptide chains, and direct irreparably damaged proteins for proteolytic degradation (Hasanuzzaman *et al.*, 2013; Wahid *et al.*, 2007) ^[11, 12]. The classification of plant HSPs according to their molecular weights divides them into five types: HSP100/Clp B, HSP90, HSP70, HSP60/chaperonins, and small HSPs (s HSPs, 15-42 k Da) (Hasanuzzaman *et al.*, 2013) ^[11]. Among horticultural plants, s HSPs are abundant and have an important role in the protection of PSII and membrane-bound proteins from heat stress conditions (Wahid *et al.*, 2007) ^[12]. Expression of HSPs is controlled by heat shock factors (HSFs), mainly Hsf A1 isoforms, functioning as master controllers of heat stress responses in tomato (Bita & Gerats, 2013; Hasanuzzaman *et al.*, 2013) ^[7, 11]. Overexpression of HSPs constitutively in plants like tomato, pepper, and strawberry results in increased thermal tolerance.

Table 2: Key stress tolerance mechanisms in horticultural plants: categories, components, and representative species.

Mechanism	Category	Key Components	Example Species	References
Osmotic Adjustment	Biochemical	Proline, Glycine betaine, Trehalose, Mannitol	Tomato, Potato, Arabidopsis	Munns & Tester (Munns & Tester, 2008) ^[14] ; Mittler <i>et al.</i> (Mittler <i>et al.</i> , 2004) ^[4] ; Hasanuzzaman <i>et al.</i> (Hasanuzzaman <i>et al.</i> , 2020) ^[33] ; Chinnusamy <i>et al.</i> (Chinnusamy <i>et al.</i> , 2007) ^[27] ; Wahid <i>et al.</i> (Wahid <i>et al.</i> , 2007) ^[12] ; Zhu (Zhu, 2016) ^[16] .
Antioxidant Defense	Biochemical	SOD, CAT, APX, GR, Tocopherols, Ascorbate	Pepper, Cucumber, Spinach	
ABA Signaling	Hormonal	PYR/PYL receptors, PP2C, SnRK2, AREB/ABF	Arabidopsis, Rice, Maize	
Stomatal Regulation	Physiological	Guard cell K ⁺ channels, AQP, Calmodulin	Tomato, Grape, Bean	
Heat Shock Proteins	Molecular	HSP70, HSP90, HSP101, sHSPs	Tomato, Pepper, Melon	
Compatible Solute Synthesis	Biochemical	P5CS, BADH, TPS, MtD1	Potato, Banana, Strawberry	
Ion Exclusion/Compartmentation	Physiological	SOS pathway, NHX antiporters, HKT transporters	Halophytes, Tomato, Barley	
Root Architectural Modification	Morphological	Deeper roots, aerenchyma formation, root hair density	Maize, Rice, Wheat	
DREB/CBF Transcription Factors	Molecular	DREB1, DREB2, CBF1-3, RAP2.4	Arabidopsis, Tomato, Rice	

4.5 Membrane Integrity and Lipid Remodeling

Abiotic stress affects cell membranes, where both temperature extremes affect their permeability and fluidity. Heat stress makes membranes more fluid, causing electrolyte leakage and activation of heat stress genes by sending out thermo-signals through the cell membrane (Wahid *et al.*, 2007)^[12]. Cold temperature leads to reduced membrane fluidity, phase separation, and affects membrane permeability (Thomashow, 1999)^[26]. Plants compensate for the stress caused by high and low temperatures by changing the extent of unsaturation of their fatty acids. Unsaturation decreases under heat stress and increases during cold stress through the action of the enzymes of fatty acid desaturases (FADs) (Thomashow, 1999; Palta & Weiss, 1993)^[28]. Transgenic plants engineered to overexpress FAD7 and thus increase the content of UFAs showed increased chilling resistance and may be useful for improving cold-tolerant vegetables (Vinocur & Altman, 2005)^[29].

5. Molecular Mechanisms and Gene Regulatory Networks

5.1 DREB/CBF Transcription Factors

Dehydration-Responsive Element binding (DREB) proteins are unique transcription factors that belong to the AP2/ERF superfamily and are responsible for binding to DRE/CRT (dehydrationresponsive element/C-repeat) motifs in the promoters of stress-responsive genes (Agarwal *et al.*, 2006)^[65]. There are two main DREB sub-families - DREB1/CBF sub-family, which is up-regulated by cold stress and controls the expression of cold responsive (COR) genes, and DREB2 sub-family, which responds to drought and heat (Ito *et al.*, 2006; Agarwal *et al.*, 2006). The pioneering experiment carried out by Kasuga *et al.* (Kasuga *et al.*, 1999)^[62] showed that constitutive stress-induced expression of DREB1A in *Arabidopsis* dramatically improved the resistance of plants to drought, salt, and freezing, making them the major candidates for genetic engineering. In rice, overexpression of OsDREB1 led to increased cold and drought tolerance (Ito *et al.*, 2006)^[63], similarly to results obtained in tomato and potato (Agarwal *et al.*, 2006; Lata & Prasad, 2011)^[75].

5.2 NAC and MYB Transcription Factors

NAC transcription factors, including NAM, ATAF, and CUC, represent one of the largest plant-specific families containing more than 100 members in *Arabidopsis*, most of which are stress inducible (Puranik *et al.*, 2012)^[64]. The

stress-responsive NACs (SRNACs) play their roles in activation of downstream target genes responsible for osmotic regulation, antioxidants production, and senescence control (Puranik *et al.*, 2012). The function of MYB transcription factors is related to anthocyanins synthesis, cuticle formation, and stomatal closure, all of which can be associated with stress responses in horticultural plants (Agarwal & Jha, 2010)^[60].

5.3 Epigenetic Regulation of Stress Responses

Epigenetic processes such as DNA methylation, histone modification, and small RNA-mediated control are playing more and more important roles in the plant response to stress (Hirayama & Shinozaki, 2010). Chromatin modifications in the presence of stress factors that occur at certain loci can be maintained after mitosis or even in seeds during seed transfer across generations (transgenerational epigenetic memory), a process known as stress imprinting (Hirayama & Shinozaki, 2010)^[66]. Small RNA molecules, including mi RNAs and si RNAs, regulate gene expression post-transcriptionally by targeting transcription factors responsible for stress responses; for example, mi R169 controls NF-YA transcription factors, and its activity declines during drought to allow better stress gene expression (Hirayama & Shinozaki, 2010)^[64].

5.4 MicroRNA Regulation

Micro RNAs (mi RNAs) are natural noncoding RNAs of 20-24 nucleotides, which function as mediators of post-transcriptional gene silencing by virtue of their ability to bind to complementary regions on target m RNAs (Nakashima *et al.*, 2009)^[59]. Many mi RNAs have been identified to exhibit differential expression in response to environmental stresses in horticultural crops. For example, mi R156 affects vegetative phase transition and stress tolerance by targeting SPL transcription factors; mi R159 inhibits MYB transcription factors that participate in ABA signaling pathways; and mi R398 targets Cu/Zn-SOD m RNA, whose expression is inhibited under oxidative stress conditions for higher SOD synthesis (Hirayama & Shinozaki, 2010)^[66].

Breeding and Biotechnology Strategies for Stress Tolerance

Breeding for stress tolerance has historically been challenged by the quantitative nature of tolerance traits,

genotype × environment interactions, and trade-offs with productivity. Modern molecular tools are increasingly being

integrated with conventional breeding to accelerate progress (Table 3).

Table 3 Breeding and biotechnological strategies for developing climate-resilient horticultural crops.

Strategy	Approach	Target Trait	Limitation	Key References
Conventional Breeding	Selection & hybridization	Yield stability, adaptability	Time-consuming, narrow gene pool	(Cattivelli <i>et al.</i> , 2008; Tester & Langridge, 2010; Collins <i>et al.</i> , 2008) ^[50, 69, 14]
Marker-Assisted Selection	Molecular markers (SSR, SNP)	QTL for stress tolerance	QTL × environment interactions	(Xu & Crouch, 2008; Araus & Cairns, 2014) ^[71, 72]
Transgenic Approaches	Gene transfer (Agrobacterium)	Specific stress pathways	Regulatory hurdles, consumer acceptance	(Kasuga <i>et al.</i> , 1999; Ito <i>et al.</i> , 2006; Garg <i>et al.</i> , 2002) ^[62, 67]
Genome Editing (CRISPR)	Targeted gene modification	Stress-responsive genes	Off-target effects, delivery challenges	(Zhu, 2016; Varshney <i>et al.</i> , 2011) ^[16, 58]
Speed Breeding	Controlled environment photoperiod	Rapid generation cycling	Limited to some species	(Tester & Langridge, 2010) ^[69]
Exogenous Elicitors	Priming (SA, JA, polyamines)	Broad stress tolerance	Dose and timing dependent	(Choudhary <i>et al.</i> , 2012) ^[73]
Microbial Inoculants	PGPR, mycorrhizae	Drought, salt tolerance	Soil-specific efficacy	(Hasanuzzaman <i>et al.</i> , 2020) ^[33]
Nano biotechnology	Nano-fertilizers, nano-sensors	Nutrient efficiency, monitoring	Ecotoxicological risks	(Varshney <i>et al.</i> , 2011) ^[58]

6.1 Conventional and Participatory Breeding

The conventional method of breeding including hybridization, selection, backcrossing, and polyploidization continues to serve as the base for crop improvement. Selection for stress-tolerance genes in large germplasm pools followed by introgression in elite germplasm through backcross breeding has led to the development of stress-resistant varieties of tomato, pepper, melon, and cucumber (Cattivelli *et al.*, 2008; Tester & Langridge, 2010) ^[69]. Participatory plant breeding where farmers select and evaluate has been found to be very effective in breeding for locally adapted stressresistant varieties in developing nations (Jain, 2010) ^[68]. The important problems associated with breeding for stress tolerance are its polygenic nature, genetic uniformity of elite breeding pools, and the lengthy breeding process involved (Cattivelli *et al.*, 2008) ^[50].

6.2 Marker-Assisted Selection (MAS)

With MAS technology, there is an indirect selection based on flanking DNA markers for selecting the target genes rather than dealing with the problem of phenotyping such stress tolerance traits in an environmental variable condition (Xu & Crouch, 2008) ^[71]. Some major QTLs that confer resistance against drought stress, salinity stress, and cold stress in tomatoes (fruit setting, ABA concentration), melons (accumulation of ions), and cucumbers (CI index) have been identified and marked by SSR or SNP molecular markers (Collins *et al.*, 2008; Xu & Crouch, 2008). With whole genome sequences available for tomatoes, peppers, cucumbers, watermelons, and strawberries, there is a rapid advancement in QTL-to-gene candidate identification and GWAS for various stresses (Collins *et al.*, 2008) ^[70]. Genomic Selection (GS) technology, where prediction of the breeding values is made with genomic information without QTL mapping, is becoming increasingly popular (Xu & Crouch, 2008).

6.3 Transgenic Approaches

This technique allows the transfer of selected genes imparting stress tolerance ability, which may be obtained from plants, bacteria, or even designed artificially (Vinocur & Altman, 2005; Wang *et al.*, 2003) ^[29]. Transgenic genes include transcription factors (DREB, NAC, MYB),

osmolyte synthesis enzymes (P5CS, codA, TPS), antioxidative enzymes (SOD, CAT, APX), ion transporters (NHX, SOS1), and chaperone proteins (HSP70, HSP101) (Vinocur & Altman, 2005; Kasuga *et al.*, 1999; Garg *et al.*, 2002) ^[62, 67]. It has been found that stacking more transgenes targeting various aspects of the stress pathway gives better results than individual transgene techniques (Wang *et al.*, 2003) ^[48]. But the regulatory mechanism for GM crops is still a problem in Europe and some developing nations (Varshney *et al.*, 2011) ^[58].

6.4 CRISPR-Cas9 Genome Editing

CRISPR-Cas9 technology has revolutionized the study of plant stress biology, allowing site-specific and efficient modification of the plant genome (Zhu, 2016) ^[16]. Some examples of CRISPR applications for the improvement of stress tolerance in horticultural crops include knockout of negative stress regulators (e.g., PP2C in ABA signaling), promoter engineering for enhanced stress inducibility, and base editing to incorporate beneficial mutations discovered via natural variation analysis (Zhu, 2016; Varshney *et al.*, 2011). CRISPR-edited crops without foreign DNA are likely to be regulated less strictly than transgenic plants in some countries, thus providing a more rapid method of implementation than genetic engineering (Varshney *et al.*, 2011) ^[58]. Some of the potential targets in horticultural crops are Sl ARF4 in tomatoes (drought), Cs SAMDC in cucumber (cold tolerance via polyamines), and Ca NPR1 in pepper (salinity) (Agarwal *et al.*, 2006; Hirayama & Shinozaki, 2010) ^[60, 65, 66].

6.5 Grafting as a Stress Tolerance Strategy

The process of grafting involves attaching a piece of shoot from a fruit-bearing species to a rootstock from another stress-resistance species and represents one of the most ancient and frequently used approaches to overcome abiotic stress in plants (Vinocur & Altman, 2005) ^[29].

Contemporary grafting operations rely on rootstocks that possess deep root networks (drought resistance), ability to exclude Na⁺ ions (salt resistance), and form aerenchymas (waterlogging resistance) (Roy *et al.*, 2014) ^[31]. Grafting tomato, cucumber, melon, and watermelon crops onto

vigorous rootstocks (hybrids between *Cucurbita maxima* and *C. moschata* for cucurbits and *S. torvum* and *S. sisymbriifolium* for tomatoes) has become an accepted practice within protected cultivation of valuable crops in the Mediterranean region, East Asia, and the Middle East countries (Roy *et al.*, 2014; Gollack *et al.*, 2014) ^[32].

7. Agronomic Management Strategies

7.1 Deficit Irrigation and Water Use Efficiency

Deficit irrigation (DI), which involves irrigating at less than complete evapotranspiration rates, is a key water management technique used in vegetable crop cultivation in areas where water is limiting (Condon *et al.*, 2004; Blum, 2005) ^[57]. The principle behind regulated deficit irrigation (RDI) and partial root zone drying (PRD) lies in the effect of root-to-shoot ABA signaling, which leads to partial stomatal closure, thus minimizing the amount of transpirational water loss while not lowering carbon assimilation or yield (Schroeder *et al.*, 2001; Condon *et al.*, 2004) ^[55]. For example, the use of RDI in tomatoes has been proven effective in maintaining crop yields, while lowering water consumption by 20-40%, improving quality parameters such as lycopene, sugars, and total soluble solids (Condon *et al.*, 2004) ^[56]. Other irrigation strategies include soil moisture monitoring sensors, ET weather models, and variable rate drip irrigation. drip irrigation enable fine-scale water management tailored to spatial heterogeneity within fields (Araus & Cairns, 2014) ^[72].

7.2 Biochar and Organic Amendments

Biochar, which is charcoal produced through the pyrolysis process of organic biomass under limited oxygen, improves the soil's water retention, cation exchange capacity, and microbial diversity while decreasing soil bulk density, qualities which are advantageous in situations of drought and salinity stress (Bartels & Sunkar, 2005) ^[44]. Meta-analysis shows that the use of biochar leads to an increase in crop yield by 10-15% during drought stress and a reduction in soil salinity among saline-infected soils by increasing Na⁺ leaching (Bartels & Sunkar, 2005). In horticulture, the combination of biochar and compost in soil management is associated with improved soil structure and microbial activity under heat and drought stress conditions (Farooq *et al.*, 2009) ^[49]. Organic mulching with straw, plastic films, or biodegradable materials can lower soil temperature fluctuation, moisture conservation, and weed suppression (Farooq *et al.*, 2009).

7.3 Exogenous Chemical Applications

The exogenous application of stress-alleviating compounds represents a flexible, rapid-response tool for horticultural stress management (Table 4). These compounds act through diverse mechanisms: hormonal priming (SA, JA, BRs, ABA), osmotic protection (glycine betaine, proline, trehalose), antioxidant supplementation (ascorbate, tocopherol), signaling modulation (NO, H₂O₂), and nutritional compensation (Zn, Si) (Choudhary *et al.*, 2012) ^[73].

Table 4 Exogenous chemical applications for abiotic stress alleviation in horticultural crops: compounds, mechanisms, and effective doses.

Compound	Stress Type	Application Mode	Effect on Plant	Dose (mg/L or mM)	Reference
Salicylic Acid (SA)	Drought, Heat, Cold	Foliar spray, seed priming	Activates PR proteins, antioxidants	0.5-2.0 mM	Choudhary <i>et al.</i> (Choudhary <i>et al.</i> , 2012) ^[73] ; Ahmad <i>et al.</i> (Ahmad <i>et al.</i> , 2010) ^[37] ; Chen & Murata (Chen & Murata, 2002) ^[43] ; Vinocur & Altman (Vinocur & Altman, 2005) ^[29] ; Hasanuzzaman <i>et al.</i> (Hasanuzzaman <i>et al.</i> , 2020) ^[33] ; Hussain <i>et al.</i> (Hussain <i>et al.</i> , 2019) ^[76] .
Jasmonic Acid (JA)	Drought, Salinity, Cold	Foliar, root drench	ROS scavenging, stomatal closure	0.1-1.0 mM	
Absciscic Acid (ABA)	Drought, Salinity	Foliar spray	Stomatal closure, osmolyte synthesis	10-100 µM	
Brassinosteroids (BRs)	Heat, Drought, Salt	Foliar spray	Enhanced photosynthesis, antioxidant defense	0.01-1.0 mg/L	
Glycine Betaine	Drought, Salinity, Cold	Foliar, seed soaking	Osmotic adjustment, membrane protection	5-50 mM	
Proline	Drought, Salinity, Heavy metals	Foliar spray	Osmotic protection, ROS scavenging	10-100 mM	
Silicon (Si)	Salinity, Heavy metals, Drought	Root application, foliar	Cell wall strengthening, ion exclusion	0.5-2.0 mM	
Nitric Oxide (NO)	Drought, Salt, Cold, Heat	Seed priming, foliar	ROS detoxification, signaling	0.1-1.0 mM SNP	
Hydrogen Peroxide (H ₂ O ₂)	Drought, Salt, Heat	Seed priming, foliar spray	Acclimation response activation	1-10 mM	
Melatonin	Drought, Salt, Cold, Heat	Seed soaking, foliar	Antioxidant, promotes root growth	0.1-100 µM	
Polyamines (PAs)	Drought, Salinity, Heat	Seed priming, foliar	Membrane stabilization, antioxidants	0.5-2.0 mM	
Zinc (Zn)	Drought, Heat	Foliar spray	Enzyme cofactor, membrane integrity	5-20 mg/L ZnSO ₄	

Seed priming with osmoprotectants, hormones, or mineral nutrients before sowing enhances germination uniformity, seedling establishment, and early stress response capacity (Vinocur & Altman, 2005; Farooq *et al.*, 2009) ^[29]. Hydro-priming, halopriming, osmopriming, and biopriming with PGPR are established commercial practices for vegetable seed treatment that can significantly improve performance under field stress conditions (Farooq *et al.*, 2009) ^[49]. The challenge with exogenous applications lies in translating

laboratory-scale efficacy to consistent field performance, accounting for variation in dose, timing, formulation, application method, and crop developmental stage (Choudhary *et al.*, 2012) ^[73].

7.4 Microbial Inoculants and Biostimulants

Plant Growth Promoting Rhizobacteria (PGPR) and Mycorrhizal Fungi have evolved mutualistic relationships with roots, which offer several advantages during abiotic

stress conditions (Hasanuzzaman *et al.*, 2020) [33]. The mechanisms involved in PGPR-induced stress tolerance include the secretion of ACC deaminase (stress ethylene reduction), synthesis of IAA and cytokinins (root morphology), phosphate mobilization (nutrient uptake), osmolyte synthesis, and Induced Systemic Tolerance (IST) through activation of antioxidant and stress-related signaling pathways (Hasanuzzaman *et al.*, 2020). Arbuscular mycorrhizal fungi (AMF) improve drought and salt stress resistance through increased effective root surface area, glomalin synthesis (soil aggregation), and regulation of ABA levels and antioxidants in plants (Hasanuzzaman *et al.*, 2020). Biostimulants based on various combinations of microorganisms have become commercially available for horticultural growers, even though quality control remains an issue (Hasanuzzaman *et al.*, 2020; Farooq *et al.*, 2009) [49].

7.5 Precision Agriculture and Digital Technologies

Advances in precision agriculture technology that include the use of remote sensing by UAVs and satellites, IoT-based sensor technology, machine learning-based crop modeling, and decision support systems are enhancing the ability to identify and mitigate abiotic stresses in real-time (Araus &

Cairns, 2014) [72]. Thermal imaging helps in identifying heat and drought stress via measurement of canopy temperature; hyperspectral imaging helps in measuring the level of chlorophyll, water content, and stress metabolites; and electric resistivity tomography can help in assessing soil moisture and salinity levels (Araus & Cairns, 2014). This is further enhanced when combined with climate prediction models and automated irrigation/fertigation systems to provide the necessary technology for horticultural production in climate variable regions (Araus & Cairns, 2014). In order for this technology to be adopted by smallholder farmers in climate vulnerable areas, precision agriculture must become accessible via the use of cheaper sensors and mobile technology (IPCC, 2021; Araus & Cairns, 2014).

Crop-Specific Resilience Strategies in Horticulture

While general principles of abiotic stress tolerance apply broadly, effective resilience strategies must be tailored to the biology, production system, and stress profile of individual horticultural crops. Table 5 summarizes climate-resilient cultivars and integrated strategies for ten major horticultural crops, illustrating the diversity of approaches and outcomes achieved.

Table 5 Climate-resilient cultivars and integrated management strategies for key horticultural crops.

Crop	Major Stress	Resistant Cultivar/Line	Strategy Used	Improvement	References
Tomato (<i>Solanum lycopersicum</i>)	Heat, Drought, Salinity	Heat Master, Solar Fire, AVTO9517	Breeding + HSPs overexpression	Improved fruit set at 38-40°C	Bita & Gerats (Bita & Gerats, 2013) [7]; Munns & Tester (Munns & Tester, 2008) [14]; Vinocur & Altman (Vinocur & Altman, 2005) [29]; Roy <i>et al.</i> (Roy <i>et al.</i> , 2014) [33]; Araus & Cairns (Araus & Cairns, 2014) [72].
Pepper (<i>Capsicum annuum</i>)	Heat, Drought	Camelot, Aristotle, Vidi	MAS + exogenous SA	50% higher pollen viability	
Cucumber (<i>Cucumis sativus</i>)	Chilling, Salinity	JIN YOU 35, Marketmore	Cold priming + grafting onto Figleaf gourd	Chilling tolerance <12°C	
Melon (<i>Cucumis melo</i>)	Salinity, Drought	Ananas, Galia, PMR 45	Grafting on salt-tolerant rootstock	Salt tolerance up to 6 dS/m	
Lettuce (<i>Lactuca sativa</i>)	Heat, Salinity	Muir, Big Boston, Valmaine	Somaclonal variation + SA priming	Reduced tip-burn incidence	
Strawberry (<i>Fragaria × ananassa</i>)	Drought, Heat, Cold	Albion, Festival, Chandler	Biochar amendment + antioxidants	20-30% yield stability	
Onion (<i>Allium cepa</i>)	Drought, Heat	Pusa Ratnar, N-53, NHRDF Red	Deficit irrigation + zinc foliar	WUE improved by 35%	
Broccoli (<i>Brassica oleracea</i> var. <i>italica</i>)	Heat, UV	Marathon, Green Magic, Fiesta	Antioxidant treatment + shading	Maintained bioactive compounds	
Potato (<i>Solanum tuberosum</i>)	Drought, Heat	Desiree, Unica, Jelly	Deficit irrigation + PGPR inoculation	15-20% tuber yield retention	
Banana (<i>Musa spp.</i>)	Chilling, Drought	Grand Nain, FHIA-01, Williams	Tissue culture + Si supplementation	Reduced chilling injury index	

Tomato, as the world's most important vegetable crop, has received the most intensive research attention for abiotic stress improvement. The characterization of heat-tolerant varieties such as 'Heat Master' and 'Solar Fire' has provided genetic resources for breeding programs, while transgenic and CRISPR approaches targeting HSPs, DREB factors, and ABA pathway components continue to advance (Bita & Gerats, 2013; Kasuga *et al.*, 1999) [7, 62]. In cucumber, grafting onto Cucurbita rootstocks remains the dominant commercial strategy for chilling tolerance management in heated greenhouse production (Roy *et al.*, 2014) [31]. In potato, integrated approaches combining deficit irrigation with PGPR inoculation and resistant cultivars have demonstrated yield stability under moderate drought stress while reducing water inputs by 30% (Farooq *et al.*, 2009) [49].

Combined and Multiple Stress Scenarios

As a consequence of climate change, there will be frequent encounters of horticultural crops with multiple or sequential abiotic stresses, especially drought and heat stress that trigger plant responses very different from, and even more deleterious compared to those induced by the two individual stresses (Zandalinas *et al.*, 2018; Mittler, 2006) [2, 4]. The limitations of using a single stress for studying the plant responses to stresses were pointed out by Mittler (Mittler, 2006) [4]. Zandalinas *et al.* (Zandalinas *et al.*, 2018) [2] showed that the response of the plants to the combined drought and heat stress conditions is characterized by novel patterns of transcriptome expression including coactivation of the two pathways, ABA-dependent and ABA-independent.

According to Hussain *et al.* (Hussain *et al.*, 2019) [76], under combined conditions of drought and heat stress, the maize suffers larger decrease in photosynthesis rate, antioxidants activities and production as well as reduced yield due to interactions of membrane stability and reactive oxygen species balance. Combined salinity and heat stress affects both ABA signaling in stomata closure and HSPs induction in tomatoes resulting in a decrease in their photosynthesis and fruit quality. Drought and UV-B combination results in premature senescence in lettuce and increased anthocyanins production simultaneously (Potters *et al.*, 2007) [39].

Developing tolerance to stress combinations requires identification of genes and pathways that confer broad-spectrum protection. Several transcription factors including WRKY, NAC, and HSF family members have been shown to regulate responses to multiple stresses simultaneously (Puranik *et al.*, 2012; Hirayama & Shinozaki, 2010) [64, 66]. CRISPR-based approaches targeting key regulatory nodes of multi-stress signaling networks, and stacking tolerance transgenes addressing multiple stress types, represent promising strategies for developing truly climate-resilient horticultural cultivars (Zhu, 2016; Varshney *et al.*, 2011) [16, 58].

10. Emerging Technologies and Future Directions

10.1 Nanobiotechnology

The nanoparticles of silicon, zinc, titanium dioxide, and carbon nanotubes have shown stress alleviation capacity in agricultural crops under nano-concentration levels (Varshney *et al.*, 2011) [58]. The modes of action involved include increased antioxidant enzyme activities, ion homeostasis, stimulation of root growth, and gene delivery for genetic modification. Agrochemicals delivered in nanoencapsulation form exhibit greater efficiency and sustained release of stress alleviation chemicals, thereby decreasing the environmental load and increasing plant uptake. However, the potential ecotoxicity issues of nanoparticle effects on soil microbiology, fauna, and food safety need detailed evaluation before their application (Varshney *et al.*, 2011).

10.2 Artificial Intelligence and Genomic Big Data

Machine learning models are being used to analyze the relationship between genomic, phenomic, environmental, and management factors to predict the stress resistance phenotype using only genotype data, which would greatly enhance the speed of selection in breeding programs (Araus & Cairns, 2014) [72]. Deep learning models can be used for image processing to conduct high-throughput and non-destructive analysis of plant stress responses in large-scale field trials (Araus & Cairns, 2014). Multi-omics datasets, including genomics, transcriptomics, proteomics, and metabolomics, analyzed using network biology tools have provided insights into critical regulatory nodes in stress response networks, which are important targets for genetic manipulation (Cramer *et al.*, 2011; Hirayama & Shinozaki, 2010) [6, 66].

10.3 Speed Breeding and Accelerated Generation Cycling

The speed breeding technologies that employ long day lengths (22 hours) through intense LED light can be used to cut down the generation period of several horticultural crops from 3-4 months to 6-8 weeks, resulting in 4-6 cycles per year (Tester & Langridge, 2010) [69]. If coupled with

genomics-based selection and double haploids breeding methods, speed breeding can drastically shorten the process from gene discovery to cultivar development, allowing breeding programs to respond quickly to the fast rate of climate change (Tester & Langridge, 2010).

10.4 Plant Microbiome Engineering

The plant microbiome, which includes phyllosphere, rhizosphere, and endophytic microbial populations, has a significant and widely acknowledged impact on plant stress tolerance (Hasanuzzaman *et al.*, 2020) [33]. Modification of the plant microbiome by selective inoculation of beneficial microbial communities, alteration of root exudates to attract certain microbes, and precise microbiome transfer is a unique strategy for dealing with stress that does not depend on host genetic makeup (Hasanuzzaman *et al.*, 2020). Synthetic microbial communities (SynComs) tailored with synergistic stress-protection activities have the potential to be a promising area in horticulture biostimulant innovation (Hasanuzzaman *et al.*, 2020).

11. Constraints, Challenges, and Knowledge Gaps

Notwithstanding significant scientific advances, there are still several key limitations on the applicability of abiotic stress biology research in improving practical horticultural traits. One key limitation is related to the complexity of genetic mechanisms underlying stress tolerance and involving many QTLs, modifier genes, and epigenetic mechanisms (Cattivelli *et al.*, 2008; Collins *et al.*, 2008) [50, 70]. Due to its complicated nature, it may be challenging to achieve genetic engineering of stress tolerance while avoiding adverse pleiotropic effects on crop yields, quality, or phenological phase shifts (Blum, 2005) [57].

Another key issue is the discrepancy between laboratory conditions of experiments and field practices (Araus & Cairns, 2014) [72]. Genetic mechanisms of stress tolerance discovered in growth chamber or greenhouse conditions where plants face homogenous and single-stress environments rarely prove to be effective when transferred to actual, more complex growing conditions where plants have to cope with multiple stresses simultaneously (Mittler, 2006; Hussain *et al.*, 2019) [4, 76]. Effective methods of field-based high-throughput phenotyping are essential to address this problem (Araus & Cairns, 2014) [72].

Third, regulation policies regarding the use of GM crops are quite varied worldwide, limiting the economic viability of transgenic solutions in many regions (Varshney *et al.*, 2011) [58]. Science communication strategies and transparent regulatory policies are needed to positively influence consumer attitudes toward new technologies in plant cultivation, such as GM and CRISPRengineered plants (Tester & Langridge, 2010) [69]. The issues related to intellectual property concerning genomics technology and stress resistance genes may hinder the application of genetic innovations in public crop breeding programs (Varshney *et al.*, 2011) [58].

Fourth, regional and local climate change predictions for the next decades are marked by significant uncertainties, hindering the development of breeding targets that account for future stress tolerance requirements (IPCC, 2021) [9]. Breeding strategies need to take into consideration not only one possible scenario for the future climate but multiple scenarios, thus employing modular tolerance stacking

technologies (IPCC, 2021; Cattivelli *et al.*, 2008) ^[50]. The rise of unprecedented stress combinations, which could not have occurred under historical environmental conditions, complicates the prediction of stress tolerance efficiency (Zandalinas *et al.*, 2018; Hussain *et al.*, 2019) ^[2, 76].

12. Conclusion

The existence of abiotic stress remains a significant risk factor for the sustainability of global horticulture in the face of intensifying climate change. This review attempts to collate current knowledge on the field within molecular biology, physiology, genetics, agronomy, and technological innovations to provide an overview of the problem and existing tools of defense. Several important conclusions can be drawn from the analysis.

The molecular mechanisms of abiotic stress resistance in plants are inherently multi-tiered, relying on responses at molecular, cellular, organ, and whole plant levels. ROS balance, ABA signaling, osmoprotectant metabolism, HSP-dependent protein stability, and ion homeostasis are recurring themes that tie across different types of stresses. The most crucial knowledge gap is the elucidation of how such mechanisms are integrated and modulated under multi-stress conditions.

A single approach will not suffice for achieving climate-resilient horticulture. Some of the most effective strategies involve: (i) genetic enhancement using conventional breeding programs and modern molecular tools such as CRISPR/Cas9 technology, marker-assisted selection (MAS), and genomic selection; (ii) exploiting favorable grafting pairings; (iii) the selective application of stressmitigating chemicals; (iv) using microbial biostimulants for promoting soil and root health; (v) optimizing irrigation and fertilization using precision agriculture techniques; and (vi) using digital agriculture for detecting stressors in real-time and adaptive crop management.

Some of the key research directions for the future should be: (1) elucidation of stress tolerance mechanisms in wild relatives of crop plants and rare, but valuable, horticultural species with evolved tolerance to harsh environmental conditions; (2) studies on the functional genomics of combined stresses in priority horticultural crops; (3) development of low-cost, high-throughput field-based phenotyping systems to screen for stress tolerance in crops; (4) testing of integrated management strategy packages under farm-level field trials in climate-sensitive agricultural areas; and (5) creation of regulatory frameworks for new horticultural biotechnologies that accelerate their deployment to farmers.

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