

INTEGRATED CROP MANAGEMENT AND BREEDING FOR IMPROVING YIELD STABILITY UNDER ABIOTIC STRESS: A REVIEW

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ABSTRACT

Abiotic stresses such as drought, heat, salinity, water logging, chilling, and nutrient imbalance limit crop productivity and yield stability throughout the world. The increasing severity and unpredictability of abiotic stresses due to climate change limit crop growth, reproduction, resource-use efficiency, and food production. Increasing crop productivity under such stresses needs an integrated approach consisting of stress-tolerant crop management along with the genetic improvement of stress-resistant crop varieties. Integrated crop management (ICM) involves efficient water and nutrient management, conservation agriculture, improved soil organic matter content, crop diversification, optimal timing of crop planting, precision farming, and biological intervention. Genetic improvement of crops complements ICM with the development of crop genotypes with enhanced root morphology, water use efficiency, heat stress tolerance, ion homeostasis, reproductive tolerance, and yield stability under environmental variability. Genetic improvement of crops involves conventional breeding, marker-assisted selection, genomic selection, QTL mapping, genome editing, and high-throughput phenotyping to provide new ways of stress tolerance improvement. The recent developments in genomics, phenomics, and artificial intelligence help in the discovery of useful alleles and the selection of stress-tolerant genotypes in targeted stress environments. This review discusses the physiological basis underlying the responses to abiotic stresses, assesses integrated agronomic/breeding approaches, and explores avenues for integrating management with genetic solutions. In this review, the systems approach is outlined, whereby resilient germplasm, site-specific crop management, climate-smart decision making, and participatory evaluations can be brought together to maintain crop productivity. The implementation of these approaches in an integrated manner will enhance the stability of crop yield and efficiency of resource use.

KEYWORDS: Abiotic stress, integrated crop management, drought resistance, heat stress, salinity resistance, genomic selection, yield stability

1. INTRODUCTION

The production of agricultural crops is faced with the problem of environment instability through irregular rainfalls, high temperatures, deteriorated soils, water scarcity, and increased occurrence of climatic extremes. The abiotic factors affect the physiological functions of plants such as photosynthesis, respiration, nutrient absorption, water relations, flowering, fertilization, and distribution of assimilates. The effects caused by the factors can be independent or concurrent, making the response hard to control and anticipate. For instance, drought and heat stress together affect the functioning of the plant photosynthesis and hasten reproductive damage more seriously than when acting individually (Sato et al., 2024).

Abiotic stresses do not only limit yield averages but also induce year-to-year variability, farm income instability, inefficiency in the use of agricultural inputs and increased likelihood of crop failure. Therefore, the stability of yield has become a goal of modern crop breeding along with yield potential, quality, profitability and efficiency in the use of resources. High yield of the genotype in favorable conditions does not guarantee high productivity of this cultivar

in the presence of drought, heat, salinity or inconsistent rainfall. For sustainable crop production, it is necessary to develop genotypes that are stable in performance under different growing conditions, (Witcombe et al., 2008). Integrated crop management (ICM) represents a way to diminish negative impact of environment through proper management of soil, water, nutrients, crops and biological resources. The use of such techniques as mulching, conservation tillage, balanced fertilization, irrigation, drainage, diversification of crops and timely planting decreases influence of stresses and increases availability of necessary resources. However, there are limits to what management techniques can do when the level of stress becomes higher than the adaptive capability of the crop or when farmers cannot use irrigation, inputs and weather forecast information, (Mickelbart, et al., 2015).

Improvement of stress adaptation via plant breeding provides an additional, quite effective way. Genetic improvement can contribute to better adaptation of crops in terms of growth, reproduction and yield formation under stressful conditions (Mao et al., 2023). Progress in molecular genetics and genomics contributed greatly to the ability to find the genome regions associated with stress, predict breeding values and speed up breeding process (Varshney et al., 2024). High-throughput phenotyping technology helps to assess complex physiological and morphological traits in large populations of crops bred during the process.

Nevertheless, crop management and genetic improvement are usually considered as two different disciplines (Gilliam, et al., 2017). This can reduce the efficiency of both approaches, as stress adaptation is determined by the interaction of crop genotype, environment and management (Rizwan, et al., 2025). For example, a drought-tolerant cultivar will not be able to manifest its properties under poor nutrient content in the soil, low seed establishment and bad planting time. The same way, good irrigation practice will be insufficient for overcoming heat-induced problems in reproduction of stress-sensitive genotype. The present review deals with the integration of crop management and breeding strategies for yield stability improvement under abiotic stresses, (Mickelbart, et al., 2015).

2. Abiotic Stresses and Their Influence on Crop Yield

2.1 Drought stress

Drought is defined as the lack of adequate water supply to satisfy the needs of the plant during one or more growth stages. The impact of the stress depends on the timing of drought, severity, duration, water-holding capacity of the soil, and developmental phase of the plant (Kumar, 2020). Water deficiency limits cell expansion, growth of leaf area, conductance of stomata, photosynthesis, and transport of nutrients. In some cases, drought may lead to accelerated senescence and biomass reduction, (Mir et al., 2012).

Reproductive phases are especially vulnerable for many crops. Water deficiency during flowering and grain filling can negatively affect pollen viability, fertilization, seed setting, grain weight, and total yield. For vegetable and horticultural crops, drought stress can cause reduced fruit size and poor marketability. The connection between drought exposure, plant characteristics, and crop production is rather complicated as the response to drought is dependent on the plant species, soil properties, atmospheric demands, and management (Vadez et al., 2024).

Adaptation to drought can be achieved through different mechanisms that include development of deep and well-spread roots, efficient utilization of water, osmotic adjustment, ability to maintain photosynthesis, and proper timing of development. Early maturity/drought escape is advantageous in locations with predictable terminal drought, while deep rooting and maintaining reproductive capability can be an advantage in areas where water scarcity occurs periodically, (Yadva et al., 2020).

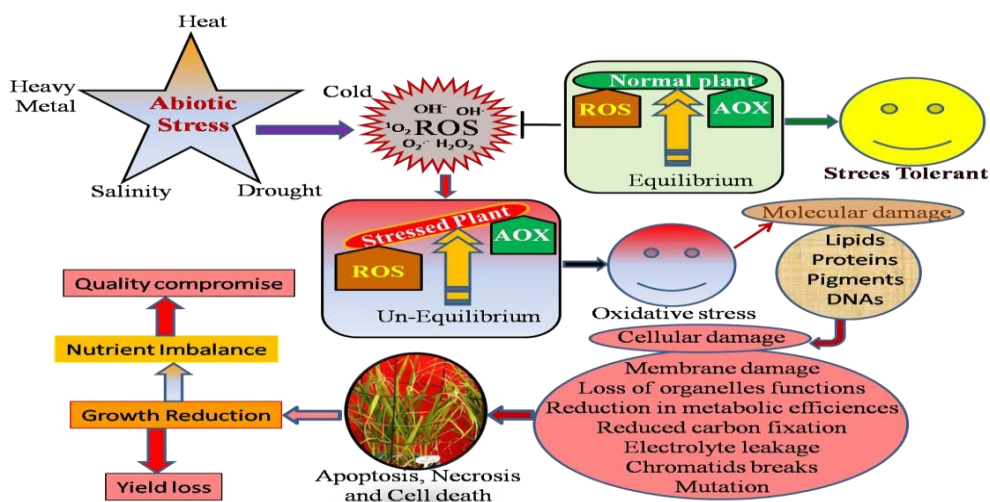


Figure 1. Impact of abiotic stress factors on plant growth, productivity, yield, and quality

Source, (Kumar, 2020).

2.2 Heat stress

Heat stress arises whenever temperatures surpass the optimal range for crop development. Elevated temperatures cause interference with membrane integrity, enzyme activity, photosynthesis process, pollen development, fertilization, and carbohydrate metabolism. Heat stress during the flowering period results in the reduction in pollen viability, stigma receptivity, fertilization capacity, and fruit or grain formation, (Kopecka et al., 2023).

Elevated night temperatures may lead to the loss in respiratory rate and decrease in dry matter accumulation. In crops like wheat, rice, maize, tomato, and chilli, heat stress results in poor reproductive efficiency, shortening of developmental time, and reduced marketable/economic yield, (Rajeswari et al., 2024).

Heat stress effects on crops are dependent on the timing and duration of heat stress, humidity, radiation, soil moisture, and genetic make-up. The tolerance level of crops to heat can be increased through proper scheduling of sowing times, selection of heat-resistant varieties, improved irrigation practices, and crop breeding for reproductive stress resistance. Nonetheless, it should be noted that the cooling ability of transpiration will be restricted in case of low soil moisture content (Sato et al., 2024).

2.3 Salinity and sodicity

Salinity limits the crop growth through osmotic pressure, ion toxicity, and imbalance in nutrient status. Too much concentration of sodium and chloride can limit potassium and calcium nutrition, damage cell membrane structure, inhibit leaf enlargement, and photosynthesis. Salinity at the time of germination and seedling establishment limits plant growth while its effects at the time of flowering and fruiting lower economic yield, (Lakshmanan, and Robinson, 2013).

Sodicity is another problem as too much exchangeable sodium limits soil structure, infiltration, and availability of air to the roots zone. Thus, both soil and crop management approaches are needed for salinity and sodicity problems, (Hussain et al., 2019).

Some management methods include irrigation water of proper quality, good drainage, leaching of salts whenever possible, proper fertilization, the use of organic materials, and cultivation of salt tolerant crop varieties. The breeding programs focus on sodium exclusion, potassium retention, plant tolerance, osmotic adjustment, and reproductive growth under salinity conditions, (Rathod, and Verma, 2023).

2.4 Waterlogging and flooding

Waterlogging arises due to an excess of water that saturates the soil within the root system and impedes oxygen diffusion and root respiration. It can negatively impact plant growth by impeding nutrient uptake, root growth, metabolism, and increase susceptibility to root diseases. Floods can physically harm plants, cause lodging, and kill standing crops, (Kumar et al., 2026).

The tolerance strategies include adventitious roots, aerenchyma formation, metabolism adaptation, and carbohydrate storage. However, different methods are important for different crops depending on the flooding regime, (Kumar, 2020).

Integrated management is achieved through planting on raised beds, surface and subsurface drainage, proper levelling of land, early sowing, and selecting tolerant varieties. The breeding programmes can be employed for submergence and waterlogging tolerant varieties in the flood-prone areas, (Kaur et al., 2020).

2.5 Cold, chilling, and frost stresses

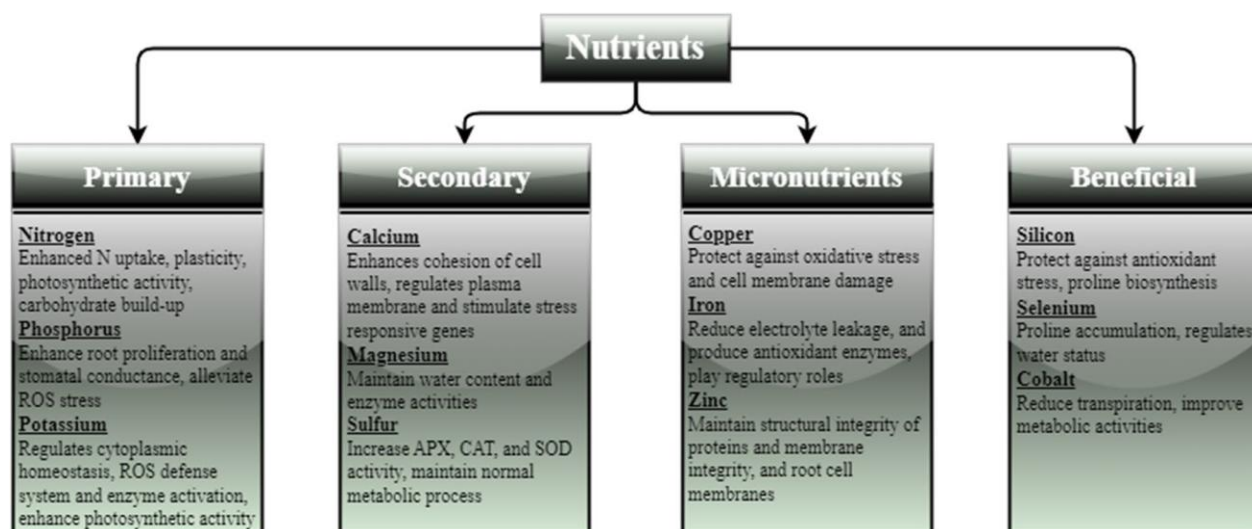
Temperatures influence germination, establishment of seedlings, membrane functions, enzyme activities, and reproductive processes. Chilling injuries are caused by temperatures below freezing point, while frost may result in direct tissue damage owing to ice formation. Delays in crop emergence, poor growth, flower abortion, and degradation of quality may be experienced, (Yadav et al., 2020).

2.6 Nutrient Imbalance and Other Abiotic Constraints

Deficiency or toxicity of nutrients can significantly lower crop yields, especially when soil is degraded, acidic, alkaline, or saline. Nitrogen, phosphorus, potassium, zinc, iron, and other elements may limit plant growth, photosynthesis, flowering, and seed production. Over-application of fertilizers can elevate salinity, nutrient depletion, and contamination of the environment, (Kumar et al., 2022).

Methods for coping with these stresses include growing cold resistant varieties, changing planting time, adopting protected cropping when economical, proper soil moisture and nutrients management. Breeding programs can be directed at membrane stability, cold hardiness, reproductive tolerance, and ability to survive low temperatures, (Minhas et al., 2017).

Soil acidity, alkalinity, toxic metals, and gaseous air pollutants like ozone are some of the other abiotic stresses. They can sometimes act in combination with drought and heat stress. It means that soil analysis, proper fertilization, suitable modifications to the soil, and cultivation of tolerant varieties should be key parts of a resilient strategy, (Oshunsanya, et al., 2019).

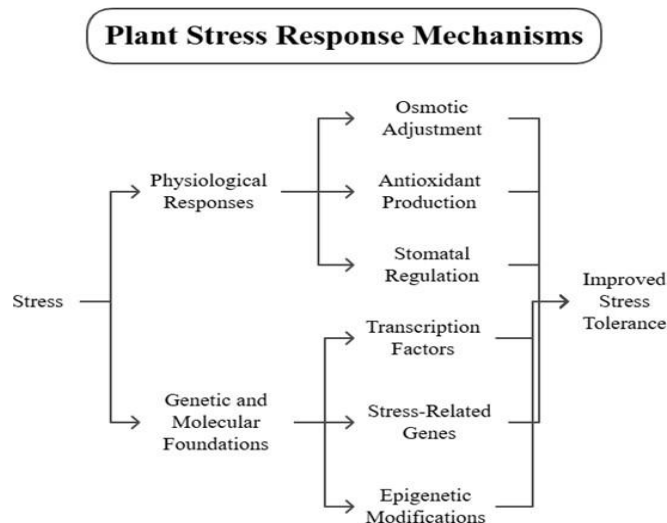


(Source, Hafeez et al., 2023)

Fig. 2 Mechanism of nutrients in alleviating abiotic stresses

3. Physiological and Genetic Mechanisms of Tolerance to Abiotic Stress

Abiotic stress tolerance in crop plants is governed by a complex interaction of physiological, biochemical, molecular, and genetic mechanisms that enable plants to survive and maintain productivity under unfavourable environmental conditions. Drought, heat, salinity, waterlogging, chilling, frost, and nutrient imbalances affect plant growth through changes in water relations, photosynthesis, membrane stability, nutrient acquisition, and reproductive development. The degree of tolerance depends on the genetic constitution of the crop, the intensity and duration of stress, the developmental stage at which stress occurs, and the prevailing environmental conditions. Understanding these mechanisms is essential for developing stress-resilient cultivars and integrating genetic improvement with appropriate crop-management practices (Cattivelli et al., 2008; Mickelbart et al., 2015).



(Source, Khalid, et al., 2024)

Figure 3. Mechanisms of plant stress responses: integrating physiological adaptations, genetic regulation, and molecular pathways for enhanced stress tolerance.

3.1 Root architecture and water uptake

Roots affect the capacity of plants to acquire water and nutrients from the soil during stress conditions. The depth of roots, branching, root length density, the angle of roots, and the distribution of the actively growing roots define the efficiency of use of available soil resources by crops (Kaur, et al., 2026). The deep rooting genotype can be beneficial in terminal drought conditions when water is available in lower soil horizons, whereas the broad distribution of roots may be beneficial under sporadic rains or unevenly distributed nutrients, (Khan et al., 2016).

Nevertheless, there is no universal root system that would be perfect in any environment. Roots require carbon to grow, and their overgrowth might result in the decreased allocation of biomass into economic organs.

3.2 Water-use efficiency and photosynthetic maintenance

Water-use efficiency refers to the biomass or economic yield achieved for the water utilized or applied. This can be enhanced in plants by stomatal control, leaf area management, reduction in non-productive water loss, and continual carbon fixation. Water productivity at the field level, on the other hand, depends on water management, rainwater harvesting, soil water evaporation, and conversion of biomass into economic output, (Rao, and Chaitanya, 2016).

Low transpiration cannot always be encouraged through selection alone as this will result in reduced carbon fixation and yield capacity due to limited stomatal movement. Therefore, selection needs to be done for productive water use instead of only for high water-use efficiency, (Negin, and Moshelion, 2016).

3.3 Osmotic adjustment and cell protection

Under drought and salt stress conditions, there may occur accumulation of compatible solutes such as proline, soluble sugars, and glycine betaine. They are part of osmotic adjustment, cell protection and water status maintenance. Antioxidant enzymes and non-enzymatic antioxidants can regulate reactive oxygen species formation as a result of stress, (Srenivasulu et al., 2007).

Heat shock proteins and other molecular chaperons protect cellular proteins from stress injury. Transcription factors and stress signaling pathways control gene expression related to water status, ion transport, defense and recovery, (Saleem et al., 2024).

Despite their potential in plant breeding and crop improvement, their presence does not necessarily mean better yield results. Physiological and molecular markers should be confirmed by real yield data, (Marco et al., 2015).

3.4 Reproductive resilience and assimilate partitioning

Stability of the crop yield is highly dependent on the capacity of crops to sustain flowering, pollination, fruit and grain formation, fruit and grain development, and grain filling in the face of stress (Dietz, et al., 2021). The important factors include the viability of pollen, synchronization of flowering, stable fruit set, sustenance of photosynthesis, carbohydrate reserves in the stems, and efficient mobilization of assimilates.

In cereals, these mechanisms determine the grain number and grain weight. In vegetable crops, they affect flower retention, fruit set, fruit size, and marketable yield. Therefore, in breeding programs, reproductive resilience to stress should be considered rather than just vegetative growth or survival.

3.5 Genetic control of stress tolerance

Tolerance to abiotic stresses is usually determined by many genes having small to moderate effect, together with major-effect loci for specific traits. The gene expression and the performance of traits are highly affected by the environment, developmental stage, and the interaction among the stress factors (Wang, et al., 2003). Thus, the selection of stress-stable genotypes becomes more difficult compared to some other traits.

Quantitative trait loci mapping, genome-wide association studies, genomic selection, and functional genomics help identify useful genetic variation. Their value is greatest when genomic information is combined with high-quality phenotypic data and representative multi-environment testing (Varshney et al., 2024).

Table 1. Key physiological and genetic mechanisms of plant adaptation to abiotic stress

Mechanism	Description	References
Physiological responses	Plants adapt to stress by accumulating osmolytes like proline to maintain cell turgor during drought.	(Ashraf & Foolad, 2007)
	Stomatal regulation helps reduce water loss under drought conditions.	(Zhang and Sonnewald, 2017)
	Under salt stress, plants sequester sodium ions in vacuoles to protect cellular functions.	(Munns & Tester, 2008)
Genetic responses	Stress-responsive genes, such as DREB and NAC, activate defense pathways.	(Yamaguchi-Shinozaki & Shinozaki, 2006)
	Overexpression of the DREB1A gene has been shown to improve drought tolerance in crops like Arabidopsis.	(Li <i>et al.</i> , 2018)
	Epigenetic modifications, such as DNA methylation, regulate gene expression during stress.	(Chinnusamy & Zhu, 2009; Kozai <i>et al.</i> , 2015)

(Source, Khalid, et al., 2024)

Table 2. Major physiological and genetic mechanisms of abiotic stress tolerance in crop plants

Mechanism	Major processes or traits	Potential breeding application
Root architecture	Root depth, branching, root length density	Improved water and nutrient acquisition
Osmotic adjustment	Proline, soluble sugars, glycine betaine	Maintenance of cellular water balance
Photosynthetic regulation	Stomatal control, chlorophyll stability, carbon assimilation	Improved productivity under drought and heat
Antioxidant defence	SOD, CAT, APX and non-enzymatic antioxidants	Reduced oxidative damage
Reproductive resilience	Pollen viability, flowering synchrony, stable fruit or grain set	Improved yield under reproductive-stage stress
Ion homeostasis	Sodium exclusion, potassium retention, vacuolar compartmentalization	Improved salinity tolerance
Hypoxia adaptation	Aerenchyma, adventitious roots, metabolic adjustment	Improved waterlogging tolerance
Molecular protection	HSPs, LEA proteins, dehydrins	Cellular protection during heat and dehydration
Stress signaling	ABA, calcium signalling, DREB/CBF, NAC and bZIP pathways	Regulation of stress-responsive gene expression
Genomic adaptation	QTLs, marker-assisted selection, genomic selection	Accelerated development of resilient cultivars

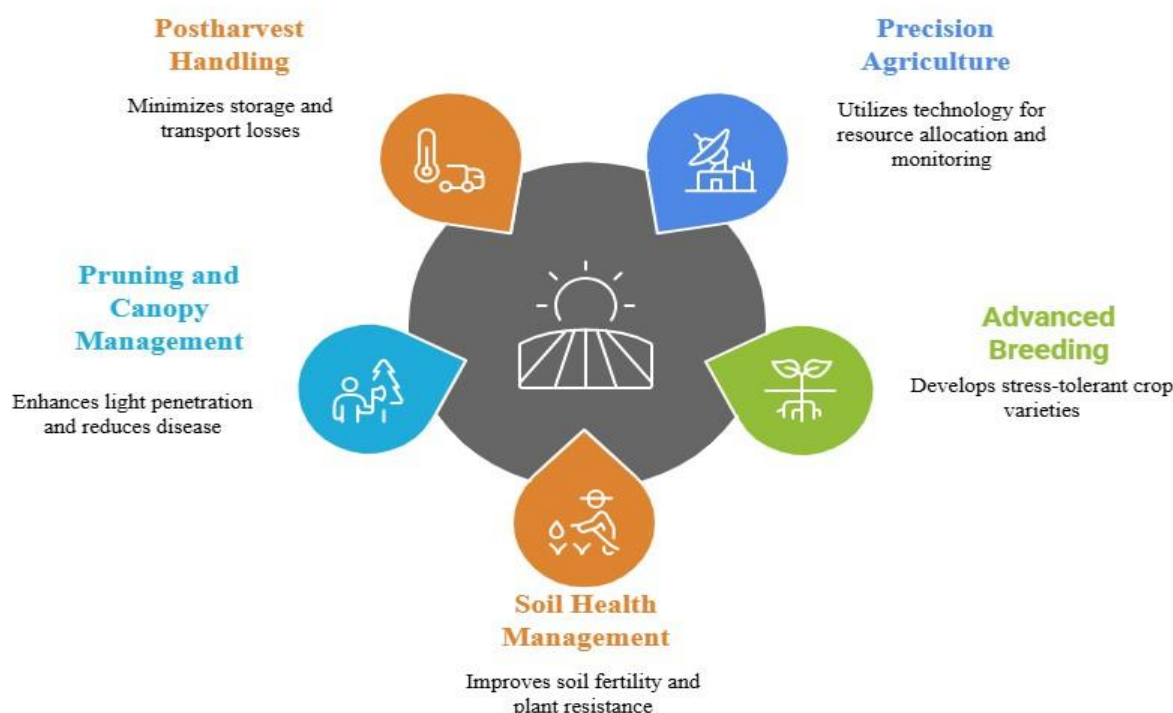
Source: Compiled and synthesized from (Cattivelli et al. 2008), (Lynch, 2007), (Gill and Tuteja 2010), and (Mickelbart et al. 2015).

4. Integrated Crop Management Techniques for Mitigating Stress

Integrated crop management involves the application of agronomic, soil, water, biological, and technological management approaches for improving the performance of the crop in varying environmental conditions. The major aim of integrated crop management is the mitigation of stress, improved efficiency of resource utilization and expression of the crop's genetic potential, (Khalid, et al., 2024).

Integrated crop management (ICM) combines soil, water, nutrient, crop, and biological management practices to reduce the adverse effects of abiotic stresses and improve crop productivity. The major techniques used to mitigate different stresses are summarized in Table 1.

Strategies for Enhancing Crop Resilience



(Source, Khalid, et al., 2024)

Figure-4: Strategy enhancing crop resilience

4.1 Soil moisture conservation and conservation agriculture

The maintenance of soil moisture is vital in the process of crop production in regions where rainfed or drought is common. Methods such as mulching, conservation of crop residues, minimum tillage, cover crops, contour farming, and rainwater harvesting will assist in improving infiltration rates and decreasing evaporation rates. It also helps in soil structure protection, soil erosion prevention, and soil organic matter accumulation, (Rana et al., 2025).

Conservation agriculture is suitable in cases where there are crop residues and appropriate equipment. However, the effectiveness of conservation agriculture varies according to the type of soil, distribution of rains, presence of crop residues, weeds, and crop rotations. Sometimes, conservation agriculture creates management problems in the case where crop residues interfere with livestock feeding requirements, (Xing, and Wang, 2024).

4.2 Efficient irrigation and water management

Efficient irrigation is one important intervention for alleviating water stress and increasing water productivity. Drip irrigation provides water near the root zone, while sprinkler irrigation distributes water above the canopy and soil surface (Khalid, et al., 2024). Irrigation scheduling using soil moisture, growth stage, evapotranspiration, and weather forecasting will increase water productivity, (Hashemi et al., 2024).

Deficit irrigation involves limiting the supply of water at less vulnerable growth stages and may increase water productivity if properly done. But severe water shortage during flowering, fertilization, or fruit formation stages will decrease yield. So, deficit irrigation must be planned with respect to plant sensitivity, (Passioura, 2006).

Rainwater harvesting, farm ponds, ground water recharge, and irrigation can be used to cover short dry spells in rain-fed farming. In saline soils, irrigation must also take into account drainage and irrigation water quality.

4.3 Balanced Nutrient Management and Soil Health

Nutrient management affects roots, canopies, photosynthesis, stress tolerance, and reproduction. Integrated nutrient management involves the use of mineral fertilizers, farmyard manure, compost, crop residues, green manures, and appropriate biofertilizers.

The nutrient nitrogen is responsible for enhancing the area of the leaves and photosynthetic ability while phosphorus provides help in the process of energy transfer and root development. Potassium plays an important role in maintaining osmoregulation and stomata. However, high levels of nitrogen lead to excessive vegetative growth, high water requirement, and delay in the maturity of some crops. Therefore, proper balance of nutrients should match the crop demand and environment in which the crops will be grown, (Shah and Wu, 2019).

Soil testing, site specific nutrient recommendation, splitting of the fertilizer applications, fertigation, and proper use of micronutrients can help minimize the losses of nutrients and maximize fertilizer efficiency (Biswas, et al., 2024). In acidic or alkaline soils, proper soil amendments should be used to increase nutrient availability. Gypsum could be helpful in sodic soils, but in saline soils proper drainage and leaching along with soil amendments are necessary.

4.4 Crop diversification, crop rotation, and modification of planting times

Crop diversification and crop rotation can lower production risks through the distribution of environmental effects among crops that vary in terms of their development phases, rooting characteristics, and stress responses. Leguminous crop rotations may enhance nitrogen availability in addition to soil quality, and cover crops may lower soil erosion, (Koli et al., 2025).

Intercropping and mixing crops could provide complementary use of resources in case of proper combinations. However, the competition of crops for light, water, and nutrients may lower the performance of components of intercrops. It is very important to choose compatible crops along with appropriate geometry of planting, (Hedayetullah, et al., 2025).

Timing of planting may allow plants to avoid periods of high temperatures and drought during critical growth stages. Short period varieties may avoid terminal drought, and change of sowing times may lower the exposure to heat during reproduction stage. All these practices need to be decided in consideration of local climate and soil conditions, and seasonal forecast.

4.5 Biological interventions and plant growth regulators

Useful microorganisms, such as selected types of Rhizobium, Azospirillum, phosphate-solubilizing bacteria, and endomycorrhizae, may help in acquiring nutrients, developing roots, and coping with stress. Some beneficial plant growth promoting microorganisms may affect the levels of phytohormones, antioxidant activity, and plant-soil interaction, (Ansabayeva, et al., 2025).

The effectiveness will depend on microorganism strains, crops, soil conditions, inoculant quality, as well as their compatibility with fertilization and pest control measures. Biological products need to be tested in the local field conditions and should supplement, but not substitute the necessary nutrients and water.

Plant growth regulators and biostimulants may have an effect on rooting, stomata function, antioxidant activity, flowering, and stress resistance. However, such an effect is dose- and environment-specific. Recommendations should be based on reproducible data, registration, and economic advantage, (Ratnakumar, et al., 2016).

Table 3. Effects of Exogenous Phytohormones on Plant Growth and Development under Abiotic Stress Conditions

Phytohormone	Plant species	Stress condition	Reported effect	Reference
Salicylic acid (SA)	<i>Torreya grandis</i>	Oxidative and salinity stress	Improves chlorophyll content and supports photosynthetic activity.	(Li et al. 2014)
Salicylic acid (SA)	<i>Solanum lycopersicum</i>	Salinity stress	Modulates the expression of glutathione S-transferase genes, including <i>SIGSTT2</i> , <i>SIGSTT3</i> , and <i>SIGSTT4</i> , potentially contributing to antioxidant defence.	(Csiszár et al. 2014)
Salicylic acid (SA)	<i>Triticum aestivum</i>	Heat stress	Modulates stress responses and may influence ethylene production and associated physiological processes.	(Khan et al. 2014)
Salicylic acid (SA)	<i>Hordeum vulgare</i>	Drought stress	Improves plant dry matter accumulation, stomatal conductance, and CO ₂ assimilation under suitable treatment conditions.	(Habibi 2012)
Jasmonates (JA)	<i>Oryza sativa</i>	Drought stress	May help maintain photosystem II activity and photosynthetic performance under water deficit.	(Sheteiwiy et al. 2018)
Jasmonates (JA)	<i>Triticum aestivum</i>	Drought stress	Promotes shoot growth, carbohydrate accumulation, and seed germination under appropriate application conditions.	(Ilyas et al. 2017)
Jasmonates (JA)	<i>Thymus vulgaris</i>	Drought stress	Enhances antioxidant activity, contributing to protection against oxidative damage.	(Sheteiwiy et al. 2018)
Auxin	<i>Triticum aestivum</i>	Heat stress	Exogenous auxin application increased grain number and yield by approximately 6–8% in a responsive wheat cultivar under field conditions.	(Abeysingha et al. 2021)
Auxin	<i>Oryza sativa</i>	Heat stress	Application of 1-naphthaleneacetic acid (NAA) can improve spikelet fertility by supporting reproductive development and fertilization.	(Zhang et al. 2018a, b)
Absciscic acid (ABA)	<i>Zea mays</i>	Drought and oxidative stress	Regulates antioxidant enzyme activity and stress-responsive gene expression, including <i>ASR1</i> , thereby contributing to stress acclimation.	(Yao et al. 2019)
Absciscic acid (ABA)	<i>Oryza sativa</i>	Salinity stress	Helps maintain ionic homeostasis, including the K ⁺ /Na ⁺ balance, and reduces the adverse effects of excessive ion accumulation.	(Gurmani et al. 2013)
Absciscic acid (ABA)	Bermuda grass	Cold stress	Modulates cold-responsive genes, including <i>LEA</i> , <i>CBF</i> , and <i>ABF1</i> , and may help preserve membrane integrity, chlorophyll content, and photosystem II function.	(Huang et al. 2017)
Cytokinins	<i>Solanum melongena</i>	Salt stress	Influences proline accumulation and stress-related physiological responses.	(Wu et al. 2013)
Cytokinins	Waxy corn (<i>Zea mays</i>)	Waterlogging	Reduces reactive oxygen species (ROS) accumulation and enhances antioxidant enzyme activities, including those of monodehydroascorbate reductase, dehydroascorbate reductase, glutathione reductase, and ascorbate peroxidase.	(Wang et al. 2021a, b, c)
Ethylene precursor	Grapevine (<i>Vitis</i> spp.)	Cold stress	Promotes cold tolerance and is associated with increased expression of the ethylene-responsive transcription factor gene <i>VaERF057</i> and other stress-responsive genes.	(Sun et al. 2016)

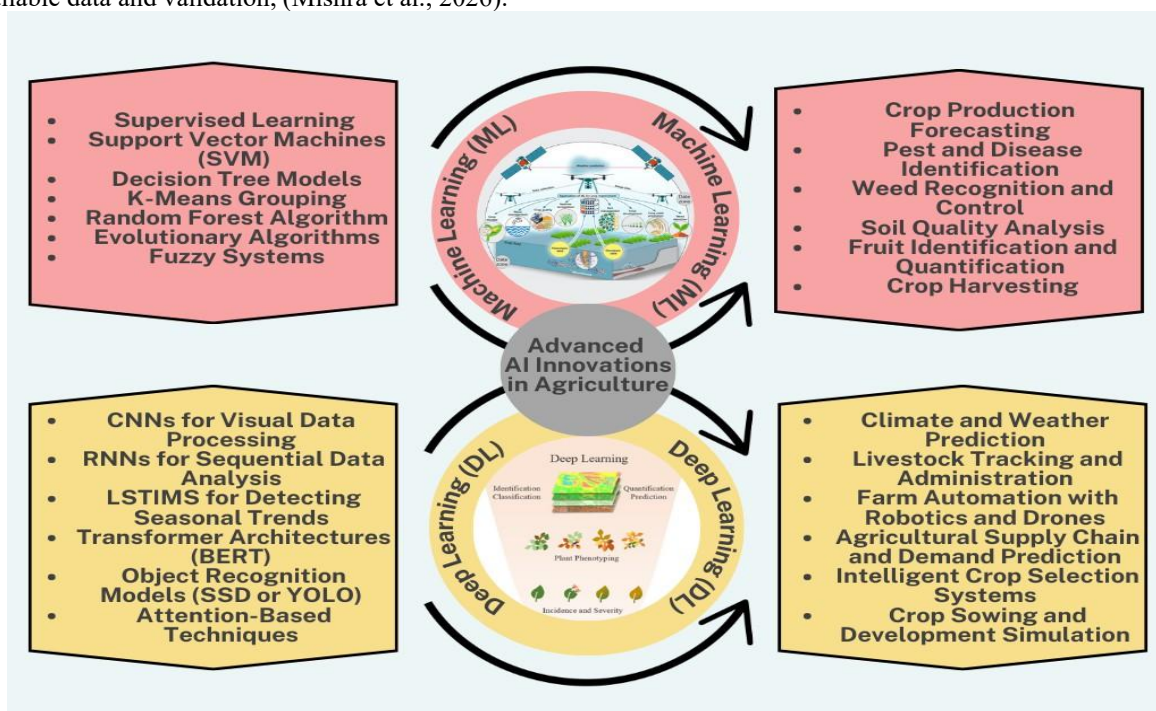
(Source, Hafeez et al., 2023)

4.6 Precision agriculture and climate-based decision making

The technology of precision agriculture uses soil sensors, weather stations, satellite remote sensing, drones, GIS, and decision-making aids for crop condition monitoring and management. Vegetation indices, canopy temperature, soil moisture, and crop growth modeling can be used to determine emerging stresses and to adjust irrigation or fertilization schedules, (Singh et al., 2026).

Remote sensing technology can be used for determination of variability in crop vigor and stress. Together with field monitoring technology, it will provide an opportunity to conduct specific interventions and to evaluate performance of various cultivars under different conditions, (Vardhan, et al., 2025).

Artificial intelligence and machine learning could integrate information about weather, soil, management, genomics, and phenotypes for prediction and decision-making purposes. The accuracy of these methods relies on the quality of available data and validation, (Mishra et al., 2026).



(Source, Khalid, et al., 2024)

Figure-5: Precision agriculture and climate-based decision making

Table 4. Integrated crop management techniques for mitigating abiotic stress in crop plants

Abiotic stress	Integrated crop management techniques	Mechanism of stress mitigation	Expected benefits
Drought stress	Mulching, crop-residue retention, rainwater harvesting, conservation tillage, drip irrigation and moisture-based irrigation scheduling	Conserves soil moisture, improves infiltration, and reduces unproductive water loss	Improved water-use efficiency, crop growth and yield stability
Heat stress	Adjustment of sowing dates, appropriate irrigation, canopy management, and suitable planting density	Reduces exposure to extreme temperatures and supports plant water status	Improved pollen viability, flowering, fruit set and grain filling
Salinity stress	Suitable-quality irrigation water, adequate drainage, salt leaching where feasible, soil amendments where indicated, and balanced fertilization	Reduces salt accumulation and improves root-zone conditions and nutrient balance	Better seedling establishment, root function and crop productivity
Waterlogging	Surface and subsurface drainage, raised beds, proper land levelling and timely planting	Improves root-zone aeration and reduces prolonged soil saturation	Improved root growth, crop establishment and survival
Cold and frost stress	Suitable planting dates, protected cultivation where feasible, windbreaks where appropriate, and	Reduces exposure to damaging temperatures	Reduced chilling and frost injury and

	maintenance of adequate crop nutrition	and supports plant recovery	improved crop establishment
Nutrient deficiency	Soil testing, balanced fertilization, split nutrient application, fertigation and suitable organic amendments	Improves nutrient availability and synchronizes nutrient supply with crop demand	Enhanced growth, nutrient-use efficiency and yield
Soil acidity and alkalinity	Soil testing, appropriate liming for acidic soils, gypsum for suitable sodic soils, and organic matter management	Improves soil chemical conditions and nutrient availability	Improved root development and nutrient uptake
Combined drought and heat stress	Moisture conservation, climate-informed planting, efficient irrigation, balanced nutrition and stress-adapted cultivars	Reduces water deficit while limiting exposure during sensitive growth stages	Lower yield losses and improved climate resilience
Combined salinity and drought stress	Improved irrigation scheduling, drainage, suitable water quality, mulching and salt-tolerant cultivars	Reduces water deficit and manages salt concentration in the root zone	Improved crop establishment and productivity under combined stress
General environmental stress	Crop rotation, diversification, intercropping where suitable, cover crops, integrated nutrient management and precision agriculture	Improves resource-use efficiency, soil health and adaptation to environmental variability	More stable production and sustainable resource management

Source: Compiled and synthesized from (Passioura et al., 2006), (Cattivelli et al. 2008), and (Mickelbart et al. 2015).

5. Breeding Approaches for Enhancing Yield Stability

5.1 Traditional breeding and selection under stress

Traditional breeding is still crucial for the creation of cultivars resistant to abiotic stresses. It includes parent selection, crossing, selection of superior offspring, and their assessment through generations and environments. The genetic diversity within landraces, traditional varieties, elite breeding materials, and crop wild relatives serves as an excellent base for improvement, (Hafeez et al., 2023).

Selection under stressful environment conditions may reveal superior genotypes in a given environmental situation. However, breeding must take into account the yield ability of crops under favourable conditions to prevent the selection of cultivars that only tolerate stresses but do not have sufficient yield ability under better conditions.

Thus, the selection under stress and favourable environments is also important. The multi-location trials will reveal consistent genotypes within the target environment, allowing the distinction between broadly adapted and environment-specific stress-tolerant cultivars, (Ammar et al., 2024).

5.2 Marker-Assisted Selection and Quantitative Trait Loci Mapping

Marker-assisted selection involves the use of DNA markers linked to the desirable alleles or QTLs for the purpose of breeding. This method is quite efficient in cases when the effect of target loci is sufficiently strong and consistent and the markers are still predictive in the particular genetic context, (Noor et al., 2025).

QTL mapping and genome-wide association studies help find the genomic regions linked to drought resistance, heat stress adaptation, salt tolerance, and other traits. Marker-assisted backcrossing allows validating and introducing the desired alleles into the elite cultivars while preserving most of the genetic background of the recipient parent, (Parihar and Shiwani, 2022).

Nevertheless, many stress-tolerant traits are polygenic, and the influence of environmental factors is quite significant. Thus, a marker that helps predict tolerance in one population or environment does not work equally efficiently in another one. Therefore, marker-assisted selection must be complemented by genetic validation and phenotypic selection.

5.3 Genomic Selection

Genomic selection involves the use of markers across the whole genome in estimating breeding values of candidate genotypes. It is especially useful in predicting the breeding values of genotypes of complex traits, such as those that are affected by many loci, e.g. yield in drought and heat stress environments, (Crossa et al., 2017).

The training populations are phenotyped and genotyped, after which models are fitted to predict the performance of the related candidates. This technique may lead to shorter breeding cycles, allowing for early selection of superior genotypes without phenotyping all candidates in all environments, (Tyagi et al., 2024).

The accuracy of prediction in genomic selection depends on various factors, such as training population size, genetic similarity between the training and validation populations, number of markers used, heritability of the trait, representation of the environmental conditions, among others.

5.4 Genomics, genome editing, and molecular techniques

Techniques such as genomic sequencing, transcriptomics, proteomics, metabolomics, and epigenomics are contributing to an enhanced knowledge about the response of plants to environmental stress conditions. Molecular techniques enable to detect candidate genes, regulatory pathways, metabolites, and pathways related to stress adaptation, (Sun et al., 2024).

Genome editing techniques, such as those based on CRISPR, offer the possibility to edit genes or regulatory regions responsible for stress adaptation. Genome editing targets can include genes controlling stomata regulation, ion transport, flower timing, root development, or thermotolerance at the reproductive stage, (Ahmar et al., 2020).

However, the effect of modification of a certain gene may be dependent on the genetic background and the environmental conditions. Adaptation to stress conditions is often linked to costs associated with resource retention, growth, and productivity (Raza et al., 2025). Gene editing materials should therefore go through molecular characterization, agronomic testing, and food and environmental safety evaluation in case it applies, according to the appropriate regulatory regime, (Ravikiran et al., 2025).

Table 5. Abiotic Stress Mitigation in Plants through CRISPR–Cas9-Mediated Genome Editing

Plant species	Abiotic stress	Target gene	Gene function	Reference
<i>Arabidopsis thaliana</i>	Cold	<i>CBF</i> genes	Encode C-repeat/dehydration-responsive element-binding transcription factors involved in cold-responsive gene regulation.	(Zhao et al. 2016a, b)
<i>Arabidopsis thaliana</i>	Drought/salinity	<i>AtA1TR</i> family	Encode ABA-induced transcriptional repressors involved in abscisic acid (ABA)-mediated stress responses.	(Chen et al. 2021a, b)
<i>Arabidopsis thaliana</i>	Drought	<i>AtOST2</i>	Encodes a plasma-membrane H ⁺ -ATPase involved in guard-cell regulation and stomatal opening.	(Osakabe et al. 2016)
<i>Arabidopsis thaliana</i>	Drought	<i>AREB1</i>	Encodes an ABA-responsive element-binding transcription factor that regulates ABA-dependent stress-response genes.	(Roca Paixão et al. 2019)
<i>Arabidopsis thaliana</i>	Salinity	<i>ACQOS</i> (verify gene symbol)	Reported as a protein associated with immune-receptor-like domains; the gene designation and functional annotation require verification.	(Kim et al. 2021)
<i>Zea mays</i>	Drought	<i>ARGOS8</i>	Negative regulator of ethylene responses; genome editing of its regulatory region can modify expression and improve grain yield under flowering-stage drought stress.	(Shi et al. 2017)
<i>Oryza sativa</i>	Cold	<i>OsPRP1</i>	Encodes a proline-rich protein associated with stress responses.	(Nawaz et al. 2019)
<i>Oryza sativa</i>	Cold	<i>OsMYB30</i>	Encodes an MYB transcription factor involved in stress-responsive gene regulation.	(Zeng et al. 2020)
<i>Oryza sativa</i>	Cold	<i>OsAnn5</i>	Encodes annexin 5, a calcium-associated protein involved in cellular stress responses.	(Que et al. 2020)
<i>Oryza sativa</i>	Cold	<i>OsAnn3</i>	Encodes annexin 3, which is associated with calcium signalling and stress responses.	(Shen et al. 2017)
<i>Oryza sativa</i>	Heat	<i>OsHSA1</i>	Encodes a fructokinase-like protein implicated in heat-stress responses.	(Qiu et al. 2018)
<i>Oryza sativa</i>	Heat	<i>OsNAC006</i>	Encodes a NAC-family transcription factor involved in stress-responsive transcriptional regulation.	(Wang et al. 2020a, b)

<i>Oryza sativa</i>	Drought	<i>OsERA1</i>	Participates in ABA signalling and the regulation of plant responses to water deficit.	(Ogata et al. 2020)
<i>Oryza sativa</i>	Drought	<i>OsSRL1/OsSRL2</i> (verify designation)	Associated with leaf rolling and plant water-status regulation.	(Liao et al. 2019)
<i>Oryza sativa</i>	Salinity	<i>OsRR22</i>	Encodes a B-type response regulator involved in cytokinin signalling; CRISPR–Cas9-mediated mutagenesis improved salinity tolerance at the seedling stage.	(Zhang et al. 2019)
<i>Oryza sativa</i>	Salinity	<i>OsVDE</i>	Encodes violaxanthin de-epoxidase, a key enzyme in the xanthophyll cycle and photoprotection.	(Wang et al. 2021a, 2022, 2021b)
<i>Oryza sativa</i>	Drought/salinity	<i>OsDST</i>	Encodes a zinc-finger transcription factor associated with stomatal regulation and drought/salinity responses.	(Santosh Kumar et al. 2020)
<i>Oryza sativa</i>	Salinity	<i>OsNAC041</i>	Encodes a NAC-family transcription factor involved in stress-response regulation.	(Bo et al. 2019)
<i>Solanum tuberosum</i>	Salinity	<i>Coilin</i>	Encodes a protein associated with Cajal bodies and nuclear RNA-processing functions; its direct contribution to salinity tolerance requires confirmation.	(Makhotenko et al. 2019)
<i>Solanum lycopersicum</i>	Heat/oxidative stress	<i>SlMAPK3</i>	Encodes a mitogen-activated protein kinase involved in signalling pathways that regulate heat-stress responses.	(Yu et al. 2019)
<i>Solanum lycopersicum</i>	Heat	<i>SlBZR1</i>	Encodes a transcription factor involved in brassinosteroid signalling and stress-related growth regulation.	(Yin et al. 2018)
<i>Solanum lycopersicum</i>	Fruit parthenocarpy (not an abiotic stress)	<i>SlIAA9</i>	Encodes an auxin-response repressor involved in fruit development and the regulation of parthenocarpy.	(Ueta et al. 2017)
<i>Solanum lycopersicum</i>	Heat/fruit development	<i>SlAGL6</i>	Encodes a MADS-box transcription factor involved in floral and fruit development; the direct heat-tolerance association requires verification.	(Klap et al. 2017)
<i>Solanum lycopersicum</i>	Drought	<i>SlLBD40</i>	Encodes a lateral organ boundaries domain transcription factor associated with plant development and stress responses.	(Liu et al. 2020)
<i>Solanum lycopersicum</i>	Drought	<i>SlARF4</i>	Encodes an auxin response factor involved in growth regulation and stress-associated responses.	(Chen et al. 2021a, b)
<i>Solanum lycopersicum</i>	Drought	<i>SINPR1</i>	Encodes a regulator of salicylic-acid-mediated defence signalling; its role in drought tolerance requires confirmation from the cited study.	(Li et al. 2019)
<i>Solanum lycopersicum</i>	Salinity	<i>SlHyPRP1</i>	Encodes a hybrid proline-rich protein associated with cell-wall functions and stress responses.	(Tran et al. 2021)

<i>Solanum lycopersicum</i>	Salinity	<i>SLARF4</i>	Encodes an auxin response factor implicated in development and stress-related responses.	(Bouzroud et al. 2020)
<i>Glycine max</i>	Salinity	<i>GmAIR</i>	Encodes an ABA-induced transcriptional repressor associated with ABA-mediated stress-response pathways.	(Wang et al. 2021a, b, c)
<i>Triticum aestivum</i>	Salinity	<i>TaHAG1</i>	Encodes a histone acetyltransferase involved in chromatin regulation and reactive oxygen species-associated salt-stress responses; its function was examined using CRISPR-mediated knockout and other genetic approaches.	(Zheng et al. 2021)

(Source, Hafeez et al., 2023)

5.5 High throughput phenotyping and physiological selection

High throughput phenotyping enables fast and accurate assessment of plant traits via the use of various imaging techniques, drones, thermal cameras, spectral sensors, and other automatic systems. Such technologies could help assess canopy temperature, vegetation indices, plant height, biomass, chlorophyll state, and reactions to water deficiency, (Reynolds et al., 2009).

Physiological traits such as canopy temperature, stomata conductance, chlorophyll fluorescence, root system architecture, and water-use efficiency could assist in identifying stress-adaptive genotypes. Nevertheless, these traits should not be viewed as substitutes for yield evaluations regardless of crop species, type of stress, growth stage, and the correlation with economic productivity, (Reynolds, and Langridge, 2016).

Modern developments in the field of phenotyping are increasingly incorporating data from the sensors with machine learning algorithms to enhance trait estimation and facilitate selection under changing conditions.

Table 6. Breeding approaches for improving crop yield stability under abiotic stress

Breeding approach	Major techniques	Application in yield stability	Limitations
Conventional breeding	Hybridization, pedigree selection, backcrossing and recurrent selection	Combines high yield potential with stress-adaptive traits	Time-consuming for complex traits
Germplasm evaluation	Screening landraces, traditional varieties, elite lines and crop wild relatives	Identifies useful genetic variability for stress tolerance	Useful sources may have poor agronomic characteristics
Physiological breeding	Selection for root traits, canopy temperature, water-use efficiency and reproductive resilience	Identifies genotypes that maintain productivity under stress	Requires reliable phenotyping and field validation
Marker-assisted selection (MAS)	DNA markers linked to major genes or QTLs	Facilitates selection for validated stress-tolerance loci	Less effective when tolerance is controlled by many small-effect genes
Marker-assisted backcrossing	Introgression of desirable alleles into elite cultivars	Improves stress tolerance while retaining desirable characteristics of the recipient variety	Requires validated markers and suitable donor parents
QTL mapping and GWAS	Identification of genomic regions associated with stress-related traits	Supports the discovery of useful genetic regions for breeding	Associations may vary across populations and environments
Genomic selection (GS)	Genome-wide markers and genomic estimated breeding values	Improves selection for complex traits, including stress yield and stability	Depends on training populations and prediction accuracy
Gene pyramiding	Combining multiple favourable genes or alleles	May improve tolerance to multiple stress mechanisms	Interactions among genes may affect performance

Mutation breeding	Induced mutations followed by screening and selection	Generates novel genetic variation for crop improvement	Desirable mutations are unpredictable and require extensive screening
Genetic engineering and genome editing	Transgenic approaches and CRISPR-based targeted modification	Enables investigation or modification of genes involved in stress responses	Requires validation, regulatory compliance and assessment of unintended effects
Speed breeding	Controlled environments and accelerated generation turnover	Shortens breeding cycles and enables faster advancement of generations	Requires suitable infrastructure and does not replace field testing
Multi-environment selection	Trials across locations, seasons and stress intensities	Identifies genotypes with broad or specific adaptation and stable yield	Requires representative environments and careful statistical analysis

Source: Synthesized from (Mickelbart et al. 2015), (Doggalli et al. 2024), (Ravikiran et al., 2025), (Raza et al., 2025), and recent reviews of genomics-assisted breeding.

6. Integration of Crop Management and Breeding

The biggest gains will be achieved if stress-adaptive genotypes are combined with management practices intended for the same target environment. Management minimizes avoidable stress, whereas breeding enhances plant adaptation under adverse conditions.

6.1 Genotype by environment by management interactions

Performance of crops is affected by the interactions among the genotype, environment, and management which are often termed as genotype by environment by management interactions. The rationale behind these interactions lies in the fact that cultivars have their unique responses when grown under different production systems, (Beres et al., 2020). For instance, the drought-resistant cultivars may respond well in deep soils with availability of subsoil water but have no advantages in shallow and compaction-prone soils. Likewise, a heat-tolerant cultivar would receive benefit in a production system characterized by the timely irrigation, balanced nutrient management, and appropriate planting dates to avoid extreme temperature stress at the reproductive stage, (Cooper et al., 2022).

It is necessary to test the performance of breeding programs through cultivars under representative management strategies rather than only testing them under ideal experimental conditions. The treatment management should take into account the resource and constraint availability of production system under consideration.

6.2 Complementary practices and traits integration

The approach needs to be directed towards synergy of complementary means and not mere aggregation of measures lacking any convincing rationale. Deep rooting, for example, can help access sub-soil moisture, while crop residues minimize evaporation, and timely irrigation maximizes utilization of the available moisture. These three measures together may be more effective than any of them separately.

In the same way, heat-resistant reproductive characters can be coupled with proper sowing times and soil moisture management for preventing failure to flower. Salt-resistant plant varieties can be linked with soil drainage and water management for reducing salt concentrations and maintaining root activity.

Table 7. Integration of crop management and breeding strategies under major abiotic stresses

Abiotic stress	Priority crop-management practices	Important breeding targets	Expected contribution
Drought	Mulching, rainwater harvesting, efficient irrigation, residue retention	Root architecture, reproductive resilience, water-use efficiency	Improved yield under water deficit
Heat	Adjustment of sowing dates, irrigation where appropriate, canopy management	Pollen viability, heat-stable photosynthesis, reproductive tolerance	Better flowering, fruit set, and grain filling
Salinity	Drainage, suitable irrigation water, salt leaching where feasible, soil amendments where indicated	Ion exclusion, potassium retention, tissue tolerance	Improved growth and productivity on saline soils
Waterlogging	Surface drainage, raised beds, appropriate land levelling	Root aeration, adventitious rooting, submergence tolerance where relevant	Better crop establishment and survival
Cold and frost	Suitable planting time, protected cultivation where feasible	Cold acclimation, membrane stability, reproductive tolerance	Reduced chilling and frost damage

Nutrient imbalance	Soil testing, balanced fertilization, organic amendments where suitable	Nutrient-use efficiency, root plasticity, tolerance to soil constraints	Improved nutrient acquisition and yield stability
Combined stresses	Integrated soil, water, and nutrient management	Multi-stress adaptation and stable reproductive performance	Reduced risk of severe yield losses

6.3 Breeding for specific and broad adaptation

Specific adaptation involves developing cultivars suited to a defined stress environment, such as recurrent terminal drought, saline soils, or regions with high temperatures during flowering. Broad adaptation aims to achieve satisfactory performance across a wider range of environments. The choice depends on the predictability of stress, the extent of environmental variation, market requirements, and the availability of suitable management practices. Where stress conditions are relatively predictable, specifically adapted cultivars may be advantageous. Where farmers face variable rainfall and temperature, broadly adapted cultivars with reliable performance may provide greater risk protection, (Chapman et al., 2012).

Breeding programmes should evaluate both yield potential and stability. High average yield is desirable, but a cultivar with consistently acceptable performance may be more valuable to risk-averse farmers than one with very high yield in favourable years and severe losses in adverse years.

7. Assessing Stability of Yield and Tolerance to Stress

Stability of yield is defined as the degree of consistency of crop yield in different environments, seasons, or years. Yield stability is associated with but not the same as the tolerance of a certain stress. The yield may be stable under drought condition but varies largely among environments. In contrast, yield stability may mean stable but moderate yield rather than high yield in any of the environments, (Cattivelli, et al., 2008).

7.1 Tests in multiple environments

Tests in multiple locations and multiple seasons are necessary in assessing the performance of the candidates under realistic situations. The trials should involve stress environment and favorable environment for comparison. Researchers should describe the levels of stress, time of stress, soil, and agronomic practice, if possible.

The use of mixed effects models in quantifying genotype performance can incorporate the effect of environment variations. The analysis of genotype-by-environment interaction could identify stable genotypes and whether different breeding recommendation is needed for different environments, (Jasemi et al., 2025).

7.2 Stability statistics and selection indices

Several statistical approaches can support the assessment of yield stability. Regression-based methods, variance components, AMMI (additive main effects and multiplicative interaction), and GGE biplot analysis are frequently used to examine genotype $\times$ environment interactions.

A combined selection index may incorporate mean yield, stress yield, yield reduction, stability, and economic quality. The weighting of these traits should reflect breeding objectives and farmer priorities.

The correct formula for calculating relative yield reduction under stress is:

$$\text{Yield reduction} = \frac{Y_p - Y_s}{Y_p} \times 100$$

The correct formula for calculating relative yield reduction under stress is:

Where:

(Y_p) = Yield under non-stress (favourable) conditions.

(Y_s) = Yield under stress conditions.

Example: If the yield under non-stress conditions is 40 t/ha and the yield under stress conditions is 28 t/ha:

$$\text{Yield reduction} = \frac{40 - 28}{40} \times 100 = 30\%$$

A lower value indicates a smaller proportional yield loss under stress. However, this parameter should be evaluated alongside absolute yield under stress and yield potential when comparing genotypes.

7.3 Farm-level validation

Performance in research plots does not always translate directly into farm-level benefits. Differences in soil fertility, seed quality, irrigation access, labour availability, and farmers' management decisions can affect cultivar performance. Participatory varietal selection and on-farm demonstrations can help identify cultivars and management combinations that perform well under local constraints. Economic evaluation should consider input costs, yield variability, marketable quality, and the probability of crop failure rather than relying solely on maximum experimental yield.

8. Crop-Specific Applications

8.1 Cereals

In rice, drought and salinity tolerance can be combined with appropriate water management, balanced fertilization, and improved planting schedules. Under flooding or submergence, suitable varieties and water-management strategies can reduce crop losses. In wheat, heat-adaptive flowering and grain filling, timely sowing, conservation practices, and improved nitrogen management are important for maintaining productivity, (Fischer, and Maurer, 1978).

In maize, drought and heat stress can affect flowering synchrony, pollen production, kernel set, and grain filling. Breeding for stress tolerance should therefore be combined with soil moisture conservation, appropriate plant density, and site-specific nutrient management. Research on drought- and heat-tolerant maize demonstrates the value of combining stress screening, breeding, and multi-location evaluation (Badu-Apraku et al., 2023).

8.2 Grain legumes

Chickpea, pigeonpea, lentil, and other grain legumes may be constrained by drought, heat, and salinity stress in various cropping situations. Adaptations may consist of early or well-timed maturity, better rooting, reproductive stability, and efficient resource acquisition, (Sultana, et al., 2013).

Integrated approaches may comprise moisture conservation, appropriate rotations, rhizobial inoculation, proper phosphorus nutrition, and proper planting times. The breeding programme should focus on stable seed yield, reproductive robustness, and adaptation to the intended production situation.

8.3 Vegetables and horticultural crops

Vegetable crops are especially sensitive to environmental stresses during flowering, fruit set, and development of marketable plant parts (Rouphael, et al., 2018). In tomatoes, heat stress may cause reduced pollination and fruit set, whereas drought may constrain fruit size and lead to uneven fruit development. In chillies, water and heat stress may interfere with flowering, fruit retention and fruit quality. In cabbages and other cole crops, high temperature may affect head formation and their marketability.

Protected cropping, mulching, drip irrigation, fertigation, management of shading where appropriate, and stress tolerant cultivars can minimize the above effects. Protected cropping, however, requires careful management of ventilation, temperature, humidity, and costs involved. Stress tolerance breeding should take into account not only yield but also marketable yield, quality and uniformity.

8.4 Root and Tuber Crops

Potato and sweet potato are subject to temperature, drought, and variable water availability. High temperatures in potatoes may affect tuber initiation and formation, whereas drought conditions are known to result in reduced tuber size and yield. Sweet potato varieties may vary significantly in drought tolerance; however, performance is conditional on soil type and stress occurrence.

Timing of planting, ridge culture, moisture retention, proper fertilization, and choosing suitable varieties can stabilize yields. Breeding efforts need to focus on assessing root or tuber yield under stress and analyzing quality characteristics.

9. Challenges and Limitations of Current Research

In spite of advancements in agronomic practices and genetic selection, there are certain challenges that hinder the creation of sustainable production systems.

First, resistance to abiotic stresses is frequently a multigenic trait. The impact of each particular gene or physiological feature can be different for different crop species at different developmental stages and under different environmental conditions. Such complexity creates difficulties in transferring laboratory results to practice of agricultural production. Second, multiple stresses are not sufficiently taken into account in the majority of breeding and agronomic trials. For instance, crops are often exposed to heat and drought stresses together, salt and heat stresses, or waterlogging followed by drought.

Thirdly, phenotyping is still a big challenge. With high-throughput technology able to collect huge amounts of data, there is a need for field validation and standardization of measurement methods and procedures together with adequate data analysis to ensure that the measured trait predicts economic yield.

Fourthly, inadequate access to improved seeds, irrigation facilities, accurate weather information, financial services, and extension services might limit the ability of farmers to fully take advantage of new technologies. There might also be an issue with the use of residue in small-holder systems for conservation purposes and as livestock feed.

Fifthly, the economic and environmental implications of integrated approaches should be studied further. A technology that boosts the yield may not be economically viable because of excessive input costs or increased use of water and energy. Research should, therefore, include partial budget analysis, risk assessment, resource efficiency and sustainability indicators.

10. Future Prospects

Future work should take more steps than simply developing stress-resistant varieties or offering isolated management tips; rather, the goal is to develop integrated crop production systems tailored to each environment.

Genomic selection in combination with high-throughput phenotyping would enhance predictions of stress adaptive abilities. Multidisciplinary omics analysis might contribute to identification of genes and biological pathways of interest, while genome editing will allow testing and modification of specific stress response mechanisms. These advances should be linked to rigorous field experiments rather than used as alternatives to agronomic trials.

Environmentally conscious breeding could facilitate identification of target environments considering frequency, timing, and intensity of droughts, heatwaves, salinity and other stress factors. The environmental characterization would enable proper choice of parents, managed stress studies, and variety breeding for particular environments.

Moreover, digital agriculture might assist in integration by combining weather forecasts, soil moisture data, crop models, remote sensing and other information on the crops' characteristics. Decision support systems could propose proper varieties, planting dates, irrigation schedules and fertilization practices.

Lastly, it would be important to have stronger cooperation of molecular scientists, plant physiologists, agronomists, soil scientists, climatologists, extension agents and farmers in breeding programs.

It would also be useful to examine the impact of combinations of interventions for future research. Factorial field trials could be used to assess the effect of different combinations of management strategies for genotypes and stress environments to achieve maximum yield stability and profitability.

Participatory breeding and evaluation by farmers is equally essential. This is because farmers will be able to assist in identifying traits such as productivity, maturity period, marketability, storage quality, and adaptability to the local agricultural system. Access to quality seeds and extension services is crucial for translating scientific knowledge to practical use.

11. CONCLUSION

Improving stability of yield performance in the presence of abiotic stresses calls for the combination of crop management, plant breeding, and environment-specific decision-making. Drought, heat, salinity, waterlogging, cold, and nutrient imbalance impose stresses on the productivity of crops via various but often related physiological and developmental effects. There is no crop management technique or plant breeding approach capable of dealing with the entire list of such stresses effectively.

Integrated crop management minimizes unnecessary stresses due to effective water utilization, maintenance of soil moisture, balanced nutrition, improved soil condition, timely planting, crop diversification, and precision agriculture. Plant breeding makes up for the deficiencies of these measures via cultivation of plants with enhanced root systems, reproductive performance, water-utilization efficiency, ion balance, and ability to perform well in adverse conditions. Selection, marker-assisted breeding, genomic selection, high-throughput phenotyping, and genome editing offer alternative ways of improving crop varieties.

The success of all of these techniques relies on interactions among genotype, environment, and management measures. Hence, new plant cultivars need to be tested under field conditions and used together with crop management measures appropriate for specific soils, climates, and available resources. Multi-environment trials, appropriate stability analysis, economic assessment, and participatory evaluation are essential for identifying technologies that deliver reliable farm-level benefits.

Further advancements will require interdisciplinary research efforts, enhanced integration of genome and phenotype data, climate-smart breeding practices, and available extension facilities. Finally, a blend of stress-tolerant varieties and efficient crop management represents an achievable approach to developing sustainable agriculture in changing climatic environments.

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