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REVIEW ARTICLE

Crops on the edge: Mechanisms and strategies for yield stability in challenging climates

Sheershika[1], G Prasanna[1*], Gopal Narkhede[1], Shourabh Joshi[2], Pusarla Susmitha[3], B Rama Devi[4], Aman Tutlani[5], Vivek Kumar Pathak[6], Tajamul Aziz Alaie[7], Vishal Kumar Gupta[8] & Subhashree Das[9*]

[1]Department of Genetics and Plant Breeding, SR University, Warangal 506 371, Telangana, India
[2]Department of Plant Biotechnology, College of Agriculture Nagaur, Agriculture University Jodhpur 341 001, Rajasthan, India
[3]Department of Seed Science and Technology, Vignan Institute of Agriculture and Technology, Vignan's Foundation for Science, Technology and Research, Guntur 522 213, Andhra Pradesh, India
[4]Department of Agronomy, Koneru Lakshmaiah college of Agriculture, KL university, Vadheswaram, Guntur 522 502, Andhra Pradesh, India
[5]Division of Genetics and Plant Breeding, Sher-e-Kashmir University of Agricultural Sciences and Technology (SKUAST–K), Wadura 193 201, Jammu and Kashmir, India
[6]Department of Agronomy, School of Agriculture, Graphic Era Hill University, Dehradun 248 002, Uttarakhand, India
[7]Department of Soil Science and Agricultural Chemistry, Shri Vishwakarma Skill University, Dudhola, Palwal 121 102, Haryana, India
[8]Department of Genetics and Plant Breeding, M S Swaminathan School of Agriculture (MSSSoA), Centurion University of Technologyand Management, Odisha, India
[9]All India Coordinated Research Project on Cotton, Odisha University of Agriculture & Technology (OUAT), Bhawanipatna 766 001, Odisha India

*Correspondence email - g.prasanna@sru.edu.in; subhashreedas@gmail.com

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Abstract

Climate change has emerged as a major constraint to global crop productivity by intensifying abiotic and biotic stresses such as drought, heat, flooding, nutrient limitations and pest disease pressures, thereby threatening yield stability across agro-ecosystems. The primary objective of this review is to critically synthesise contemporary genetic, genomic, physiological, biotechnological and agronomic strategies that enhance crop yield stability under challenging climatic conditions. The review systematically integrates evidence from recent advances in molecular breeding, marker-assisted and genomic selection (GS), genome editing technologies (particularly CRISPR/Cas systems) and functional genomics with plant physiological mechanisms including root system architecture, water-use efficiency (WUE), osmoprotectant accumulation and stress-adaptive morphological traits. Key findings indicate that yield stability is best achieved through multi-trait and multi-scale approaches that combine stress-tolerant genetics with optimised resource-use efficiency, resilient seed systems and climate-smart agronomic practices. The synthesis further highlights the role of pest and disease resistance, nutrient-use efficiency and flood-tolerance mechanisms as integral components of resilient cropping systems rather than isolated traits. In conclusion, the review demonstrates that integrated, systems-based strategies are essential for sustaining crop productivity under climate variability. Future perspectives emphasise the convergence of artificial intelligence-assisted breeding, microbiome engineering, speed breeding and supportive policy frameworks to accelerate the deployment of climate-resilient cultivars and ensure long-term food security in an era of increasing climatic uncertainty.

Keywords: CRISPR-Cas technology; genomic selection; molecular approaches; yield stability

Introduction

Agriculture is the backbone of the world economy and is increasingly vulnerable to climate change, which results in erratic rainfall, temperature extremes and other stresses that threaten crop productivity. Among these, the rise in atmospheric temperature due to anthropogenic activities significantly influences the functioning of agro-ecosystems (1). Climate change poses a serious and growing threat to global food security. Its major effects include an increased frequency and intensity of extreme climatic events such as heavy rainfall, prolonged dry spells, droughts, water shortages, land degradation and rising sea levels (2). These impacts can severely disrupt the global agricultural system, ultimately leading to food insecurity across all dimensions: availability, stability, access and utilisation.

Ensuring yield stability in challenging climates is a top priority for farmers and agricultural stakeholders facing increasing climate variability. Several effective strategies can help maintain stable crop yields under adverse conditions such as drought, heat, floods and unpredictable weather. Yield stability refers to the ability of a crop production system to deliver consistent outputs over time despite environmental stresses and fluctuations (3). It is crucial for meeting the demands of a growing population and ensuring the economic viability of farmers. Achieving yield stability requires a comprehensive understanding of the mechanisms that enable crops to withstand and adapt to climatic stresses, alongside the development and implementation of targeted agronomic and breeding strategies (4).

The mechanisms underlying yield stability primarily involve plant physiological and genetic adaptations that enhance resilience to both abiotic and biotic stresses. These adaptations include traits such as drought tolerance, heat resistance, efficient nutrient uptake and pest resistance. Physiological mechanisms, such as root architecture modifications, stomatal regulation, osmotic adjustment and antioxidant defense, enable crops to withstand environmental stress (5). Genetic diversity and breeding programs further support yield stability by developing and selecting crop varieties with improved stress tolerance and adaptive capacity (6). In addition to genetic and physiological approaches, strategic agronomic practices are crucial in safeguarding yield stability. Precision agriculture techniques, including optimised irrigation, soil health management and integrated pest management help mitigate the adverse impacts of climate variability (7).

Crop selection and diversification play a crucial role in building climate resilience in agriculture. Farmers can opt for drought-tolerant and heat-resistant crop varieties specifically bred to endure heat stress and water scarcity. Multi-cropping and intercropping, which involve growing multiple crops together, help reduce the risk of total crop failure and enhance overall productivity (8). Crop rotation is another vital practice that supports soil fertility and minimises pest and disease buildup. Maintaining soil health and conservation is equally important. Increasing soil organic matter using compost, manure and cover crops improves water retention and soil structure. Minimum tillage practices reduce soil disturbance, helping maintain soil structure and moisture while mulching aids in retaining soil moisture, stabilising soil temperature and preventing erosion (9). Effective water management further strengthens resilience by optimising water use through efficient irrigation systems like drip and sprinkler methods. Rainwater harvesting ensures water availability during dry spells, while proper drainage systems prevent waterlogging during heavy rainfall. Integrated pest and disease management (IPM) combines biological, cultural and chemical control measures to reduce pest outbreaks, while adjusting planting dates based on weather forecasts can help minimise exposure to extreme weather events (10). Climate-smart technologies also play a key role in supporting farmers. Weather forecasting tools provide real-time weather data for informed decision-making, crop insurance safeguards farmers against losses from extreme weather and precision agriculture leverages data and technology to optimise inputs like fertilisers, water and pesticides (11). Strengthening resilient seed systems is essential as well. Seed banks help preserve and distribute locally adapted seed varieties, while hybrid seeds offer higher yield potential and better stress tolerance. Lastly, empowering farmers through training and knowledge sharing enhances their capacity to adapt. Capacity-building programs educate farmers on climate-resilient practices and community networks encourage the exchange of experiences and strategies (12). Combining these approaches helps create long-term resilience, enabling farmers to adapt and mitigate the challenges posed by climate change.

The growing global population demands the development of resilient agricultural systems capable of withstanding the impacts of climate change. Droughts, heatwaves, flooding and soil degradation pose significant threats to crop yields, highlighting the need for adaptive strategies that enhance plant resilience and ensure yield stability. This paper reviews current knowledge on the mechanisms and strategies that support stable crop production under such challenging conditions (13). Achieving yield stability in the face of climate variability requires a multifaceted approach, combining plant physiological resilience, genetic advancements and innovative agronomic practices. Understanding and integrating these components is essential for promoting sustainable agricultural productivity and securing global food systems in an era of climate uncertainty.

Despite substantial advances in crop improvement research, existing literature largely addresses genetic, physiological, biotechnological and agronomic strategies for climate resilience in a fragmented manner, often focusing on individual stresses or isolated interventions. Many reviews emphasise either molecular breeding and genome editing or field-based management practices, with limited integration across biological scales and production systems. As a result, the mechanistic links between stress-responsive genes, plant physiological adaptations and practical agronomic outcomes influencing yield stability remain insufficiently synthesised. Furthermore, emerging tools such as genomic selection (GS), CRISPR/Cas-mediated editing and transcriptomic profiling are seldom discussed in conjunction with traits like root system architecture, nutrient-use efficiency and pest–disease dynamics under variable climates. The present review addresses this gap by providing a comprehensive, systems-level synthesis that bridges molecular and physiological mechanisms with climate-smart agronomic strategies, thereby offering a unified framework for enhancing crop yield stability under increasingly unpredictable climatic conditions.

The objectives of this review are to synthesise current genetic, genomic, physiological and agronomic strategies that enhance crop yield stability under climate stress. It aims to evaluate advances in molecular breeding, GS and genome-editing tools for developing climate-resilient crops. The review also examines key plant traits and stress-response mechanisms underpinning yield stability. Finally, it integrates these approaches to identify future directions for sustainable and climate-smart crop improvement.

Genetic and genomic approaches for yield stability

Climate change poses significant challenges to global agriculture, with increasing occurrences of drought, heat stress, flooding and other extreme weather events threatening crop productivity. Ensuring yield stability, which refers to maintaining consistent crop production despite environmental fluctuations, is vital for food security. Genetic and genomic approaches have emerged as critical tools for developing climate-resilient crops capable of withstanding both abiotic and biotic stresses, enhancing their adaptability and ensuring stable yields (14). The unpredictability of climatic conditions necessitates innovative agricultural solutions, making the development of climate-resilient crops more crucial than ever. Traditional breeding has long served as a fundamental approach to improving agricultural performance. By selecting and crossing crop varieties with desirable traits such as drought tolerance, early maturity and pest resistance, breeders have achieved gradual improvements in stress resilience. Marker-assisted selection (MAS) has refined this process by enabling the identification of genetic markers linked to stress tolerance, thus streamlining breeding efforts and accelerating the development of robust crop varieties (15).

Building on these traditional methods, molecular breeding and GS have introduced advanced techniques that further enhance breeding efficiency. The GS utilises genome-wide markers to predict the performance of breeding lines under stress conditions, allowing breeders to identify high-performing plants without the need for extensive field trials. This reduces both the time and resources required, expediting the development of climate-resilient crops. Genetic engineering technologies provide additional precision in crop improvement. The introduction of specific genes that confer tolerance to environmental stresses such as drought, heat and pests has shown promising results (16). Examples include crops engineered with heat shock proteins (HSPs), drought-responsive transcription factors and Bt genes for pest resistance. These genetic modifications contribute significantly to crop stability in adverse climatic conditions.

A breakthrough in crop improvement has been the advent of genome editing tools, particularly CRISPR-Cas9 (17). This technology allows precise modifications to plant DNA, enhancing stress tolerance traits without introducing foreign genetic material. Adjustments to genes regulating water use efficiency, root architecture and disease resistance exemplify the transformative potential of genome editing in developing resilient crops. Furthermore, research into functional genomics and stress signalling pathways has provided deeper insights into plant adaptation mechanisms. Understanding gene expression patterns and plant responses to stresses like drought, heat and flooding has enabled the development of crops capable of optimising water use, maintaining cellular stability and recovering from environmental shocks.

Harnessing genetic diversity also remains a vital strategy in enhancing crop resilience. Wild relatives and landraces (locally adapted traditional varieties) often harbour unique stress tolerance traits that are absent in modern cultivars. Integrating these genetic resources into breeding programs strengthens crop resilience and ensures the stability of future agricultural production. In conclusion, genetic and genomic approaches are indispensable in safeguarding agricultural productivity in the face of climate change (18). Marker-assisted selection (MAS), molecular breeding, genetic engineering and genome editing collectively drive the development of climate-resilient crops (19). Coupled with the exploration of genetic diversity and a deeper understanding of plant stress responses, these strategies play a pivotal role in securing yield stability and ensuring global food security (20).

Breeding strategies for yield stability

Drought and heat-tolerant varieties

Drought and heat tolerant crop varieties are essential for maintaining yield stability under climate change. Rising temperatures, erratic rainfall and prolonged droughts threaten global food security by reducing water availability, affecting germination, growth and yield. Heat stress accelerates respiration, disrupts photosynthesis and induces pollen sterility, ultimately lowering grain filling (21). To counter these challenges, developing climate-resilient crops through breeding strategies, genetic engineering and agronomic practices is crucial. Crops have evolved various mechanisms to withstand drought and heat stress. Morphological and physiological adaptations include deep root systems in crops like pearl millet and sorghum, which enable water access from deeper soil layers and reduced stomatal conductance in rice and wheat to limit water loss (22). The stay-green phenotype in sorghum maintains chlorophyll during drought, ensuring prolonged photosynthesis, while leaf rolling and a waxy cuticle in rice and maize reduce transpiration. Early maturing varieties, such as certain chickpeas, escape peak drought and heat periods. On a molecular level, HSPs prevent protein denaturation, while drought-responsive transcription factors (e.g., DREB, NAC and MYB) regulate stress responses. Reactive oxygen species (ROS) scavenging through antioxidant enzymes like superoxide dismutase (SOD) and catalase reduce oxidative damage and abscisic acid (ABA) signalling enhances stomatal closure to conserve water (23).

Breeding strategies play a crucial role in developing stress-resilient crops. Conventional approaches include selecting landraces and wild relatives with natural stress tolerance, such as *Oryza rufipogon* Griff. in rice, *Aegilops* species in wheat and *Zeadiplo perennis* in maize (24). Hybrid breeding has led to the development of heat-tolerant maize and sorghum varieties, while mutation breeding has produced drought-tolerant rice through gamma ray induced mutations. Marker-assisted selection (MAS) enables targeted breeding by identifying quantitative trait loci (QTLs) controlling traits like root architecture, stomatal conductance and osmotic balance, as seen with *qDTY1.1* and *qDTY3.1* QTLs in rice (25). Marker-assisted selection (MAS) has also been used to introduce traits such as flood tolerance via the Sub1 gene and salinity tolerance via Saltol in rice. Genomic selection (GS) leverages whole-genome sequencing to predict complex traits like drought and heat tolerance, significantly reducing breeding cycles. Programs like Drought Tolerant Maize for Africa (DTMA) have successfully implemented GS to enhance maize resilience (26).

Genetic engineering and genome editing offer additional solutions for developing stress-tolerant crops. Transgenic approaches include overexpressing drought-responsive genes like DREB in rice and wheat and HSPs to maintain cellular integrity under heat stress. C4 engineering in C3 crops, such as rice, enhances water-use efficiency (WUE) and heat tolerance. CRISPR-Cas9 has enabled precise gene editing, including modifying *OsNAC14* in rice to improve drought resilience and knocking out ABA-degrading genes to enhance water conservation (27). Gene editing can also target heat stress pathways, such as HSFA2 in wheat, to improve pollen viability under high temperatures (28). Agronomic and management strategies further support stress mitigation. Soil and water management practices like mulching and cover cropping reduce soil moisture loss, while drip irrigation optimises water use (29). Conservation tillage helps retain soil moisture and mitigates heat stress. Climate-smart agricultural practices, including integrated stress management that combines genetic and agronomic solutions, maximise resilience. Early warning systems utilising satellite data and AI help predict drought and heat waves, allowing proactive measures (30).

Despite these advances, breeding for stress resilience presents challenges. Genotype-by-environment (GxE) interactions complicate breeding for stable traits, while modern breeding has led to reduced genetic diversity. High costs associated with genomic tools such as GS and genome editing further hinder widespread adoption (31). Future directions include leveraging AI and big data in breeding to predict stress resilience using machine learning models, as well as applying synthetic biology to engineer new metabolic pathways for drought and heat resistance. Public-private partnerships are essential to deploying stress-resilient varieties on a large scale (32). In conclusion, climate change poses a serious threat to global food production, making the development of drought and heat tolerant crops a priority for sustainable agriculture. Integrating genomics, transgenics and agronomic management can significantly enhance yield stability under stress conditions (33). A combination of breeding, genetic engineering and management strategies will be key to ensuring global food security in the face of climate change. Breeding strategies and mechanisms for enhancing yield stability under drought and heat stress presented in Table 1. Fig. 1 illustrates key abiotic stress adaptation mechanisms in drought-resilient crop varieties, highlighting morphological, physiological and molecular responses that contribute to yield stability. The figure emphasises traits such as enhanced root system architecture, stomatal regulation, osmotic adjustment and stress-responsive gene activation that enable crops to maintain productivity under water-limited conditions.

Flooding and waterlogging tolerance

Flooding and waterlogging are major abiotic stresses that significantly reduce crop productivity, particularly in regions experiencing erratic rainfall and extreme weather events. Plants exposed to excessive water face multiple physiological and metabolic challenges, including oxygen deprivation (hypoxia/ anoxia), reduced nutrient uptake and increased susceptibility to disease (34). To cope with these stresses, crops have developed various tolerance mechanisms that can be categorised into 3 main strategies: escape, avoidance and tolerance.

One of the primary mechanisms for flood tolerance is aerenchyma formation, a process where specialised air-filled cavities develop in roots and stems to facilitate oxygen transport under hypoxic conditions (35). This trait is observed in flood-tolerant rice, which possesses constitutive aerenchyma that allows continued root respiration even in submerged conditions. Additionally, some plants exhibit stem elongation, enabling leaves to remain above water and maintain photosynthetic activity. This trait is particularly beneficial in deep-water rice, where internode elongation prevents complete submergence.

Another important strategy is submergence tolerance, which allows plants to survive complete flooding for extended periods by slowing down metabolic processes. The *SUB1A* gene, identified in rice, regulates this response by suppressing excessive

Table 1. Breeding strategies and mechanisms for enhancing yield stability under drought and heat stress

Strategy category	Key traits / mechanisms	Crop	Breeding / technological approach	References
Morphological adaptations	Deep root systems, stay-green phenotype, leaf rolling, waxy cuticle, early maturity	Sorghum, pearl millet, rice, maize, chickpea	Conventional breeding, landrace selection	(13, 22)
Physiological mechanisms	Reduced stomatal conductance, osmotic adjustment, ABA-mediated signaling, antioxidant defense (SOD, catalase)	Rice, wheat, maize	Phenotypic selection, physiological screening	(14, 23)
Molecular stress responses	Heat shock proteins (HSPs), drought-responsive TFs (DREB, NAC, MYB)	Rice, wheat	Transgenic approaches, functional genomics	(14, 23)
Use of wild relatives	Natural stress tolerance genes	Rice (*Oryza rufipogon*), wheat (*Aegilops* spp.), maize (*Zea diploperennis*)	Pre-breeding, introgression	(15, 24)
Marker-assisted selection (MAS)	QTLs for drought, root traits, osmotic balance (*qDTY1.1, qDTY3.1*); Sub1, Saltol	Rice	MAS-based breeding	(16, 25)
Genomic selection (GS)	Genome-wide prediction of drought and heat tolerance	Maize (DTMA hybrids)	Genomic selection pipelines	(17, 26)
Genetic engineering	Overexpression of DREB, HSPs; C4 trait engineering	Rice, wheat	Transgenic technology	(27)
Genome editing	Targeted editing of *OsNAC14*, ABA-related genes, HSFA2	Rice, wheat	CRISPR-Cas9	(18, 28)
Agronomic integration	Mulching, drip irrigation, conservation tillage, cover crops	Multiple crops	Climate-smart agriculture	(29, 30)
Emerging approaches	AI-based prediction, big data analytics, synthetic biology	Cross-crop systems	Advanced breeding platforms	(31–33)

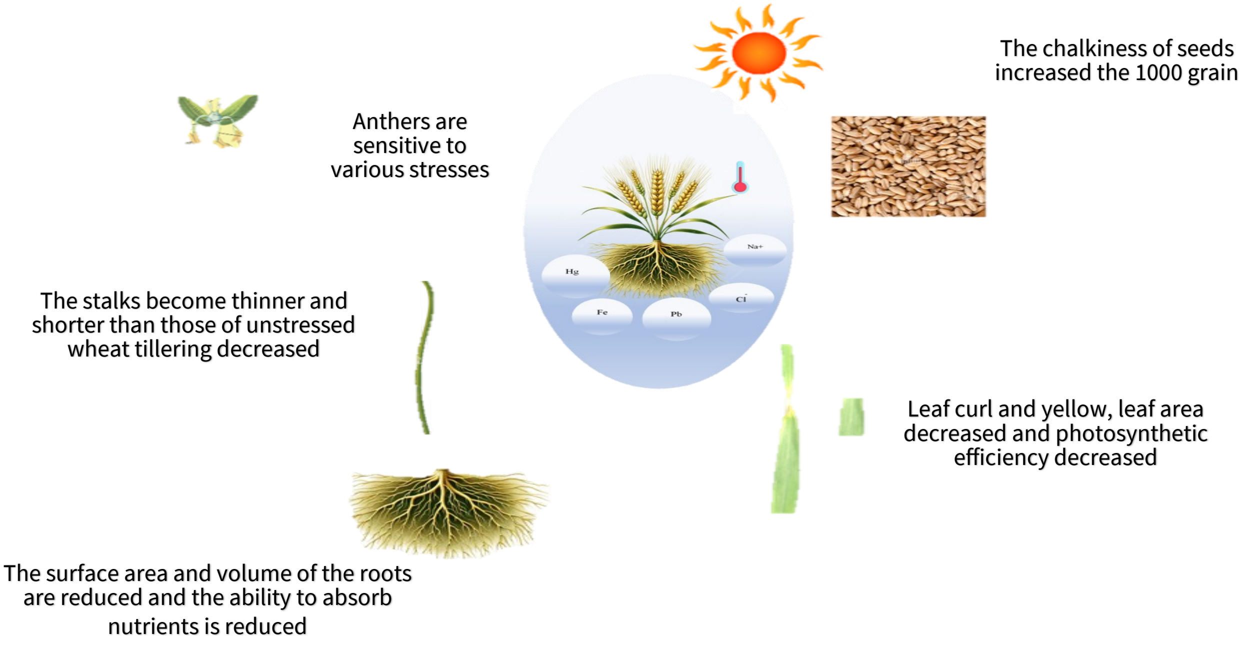

Fig. 1. Abiotic stress adaptations in drought-resilient varieties.

elongation and conserving energy reserves until floodwaters recede (36). This gene has been successfully introgressed into high-yielding rice varieties, significantly improving their flood resilience (37).

Beyond genetic adaptations, crops employ physiological and biochemical responses to mitigate waterlogging stress. The production of ethylene, ROS and antioxidant enzymes plays a crucial role in signalling and stress mitigation (38). Ethylene accumulation under waterlogged conditions triggers a cascade of adaptive responses, including aerenchyma formation and adventitious root growth. Furthermore, antioxidant enzymes such as SOD and catalase (CAT) help neutralise oxidative damage caused by ROS accumulation (39).

Agronomic and breeding strategies have been extensively explored to enhance flood tolerance in crops. Conventional breeding and MAS have enabled the development of flood-resistant varieties by incorporating genes like SUB1A in rice and RTQ1 in maize (40). Additionally, GS and transgenic approaches are being explored to enhance tolerance traits across various crops. Emerging biotechnological advancements, such as CRISPR-Cas9 gene editing, hold promise for precise modification of flood tolerance genes, accelerating crop improvement efforts (41). Besides genetic improvements, agronomic practices such as raised bed planting, drainage management and soil amendments can mitigate waterlogging effects (42). Incorporating cover crops and organic matter improves soil structure and aeration, reducing the impact of excessive moisture. Furthermore, integrating stress-tolerant crop rotations and mixed cropping systems can enhance overall field resilience (43).

In the context of climate change, developing flood-tolerant crops remains a critical priority for ensuring global food security (44). A multi-disciplinary approach combining genomics, breeding, agronomy and climate modelling will be essential to enhance yield stability in flood-prone regions. By leveraging advanced breeding techniques and sustainable farming practices, it is possible to mitigate the adverse impacts of waterlogging, securing food production in challenging climates (45). Mechanisms and strategies contributing to flooding and waterlogging tolerance in crops were presented in Table 2.

Pest and disease resistance

Plant diseases and insect pests are major threats to global food production, particularly in the context of climate change, which alters pathogen and pest dynamics, intensifying their impact on crops (46). Effective resistance mechanisms and management strategies are essential to ensure yield stability under challenging environmental conditions. These mechanisms can be categorised into morphological, biochemical and molecular defences, while integrated management strategies include breeding approaches, biotechnological advancements and agronomic practices (47).

Climate change has significantly altered the epidemiology and intensity of crop pests and diseases by expanding pathogen geographical ranges, increasing overwintering survival and accelerating pest life cycles, thereby posing serious threats to yield stability. Empirical evidence from long-term field studies and climate-linked disease models indicates that rising temperatures and humidity favour the rapid evolution and spread of fungal, bacterial and viral pathogens, while also enhancing insect vector populations. Host plant resistance remains the most economically viable and environmentally sustainable strategy for managing these challenges. Both qualitative (major R gene-mediated) and quantitative resistance governed by multiple loci have been widely deployed; however, quantitative resistance is increasingly favoured due to its durability under fluctuating climatic conditions. Advances

Table 2. Mechanisms and strategies contributing to flooding and waterlogging tolerance in crops

Category	Mechanism / strategy	Functional role under flooding or waterlogging	References
Morphological adaptations	Aerenchyma formation	Development of air-filled spaces in roots and stems to facilitate internal oxygen transport under hypoxic or anoxic conditions.	(35)
	Stem and internode elongation (escape strategy)	Rapid elongation enables leaves to remain above floodwater, maintaining gas exchange and photosynthesis.	(35)
	Adventitious root formation	Formation of secondary roots near the soil surface enhances oxygen uptake and nutrient absorption.	(38, 39)
Physiological and biochemical responses	Submergence tolerance (quiescence strategy)	Suppression of growth and metabolism to conserve carbohydrates during prolonged submergence.	(36, 37)
	Ethylene signalling	Ethylene accumulation triggers adaptive responses such as aerenchyma development and adventitious rooting.	(38)
	Antioxidant defence (ROS scavenging)	Enzymes such as SOD and catalase mitigate oxidative damage caused by reactive oxygen species.	(39)
Molecular and genetic mechanisms	Submergence tolerance genes (e.g., *SUB1A*)	Regulation of energy conservation and growth suppression under complete submergence.	(36, 37)
	Hypoxia-responsive transcription factors	Activation of anaerobic metabolism and stress-response pathways under oxygen deficiency.	(38)
	Genome engineering and CRISPR-based editing	Precise modification of flood-tolerance genes to enhance stress resilience.	(41)
Breeding strategies	Marker-assisted selection (MAS)	Introgression of flood-tolerance genes such as *SUB1A* in rice and *RTQ1* in maize.	(40)
	Genomic selection	Genome-wide prediction models for improving complex flood-tolerance traits.	(40)
Agronomic management practices	Raised bed and ridge planting	Improves soil aeration and reduces water stagnation around the root zone.	(42)
	Soil amendments and organic matter	Enhances soil structure, porosity and oxygen diffusion.	(42, 43)
	Drainage management	Prevents prolonged waterlogging and associated yield losses.	(42)
Integrated farming strategies	Crop diversification and rotation	Reduces risk and enhances system resilience under flooding stress.	(43)
	Mixed cropping systems	Inclusion of flood-tolerant crops or varieties to stabilise productivity.	(43, 44)

in MAS and GS have enabled the pyramiding of resistance genes and QTLs into elite cultivars, resulting in improved resistance stability across environments. Furthermore, genome-editing technologies such as CRISPR/Cas have facilitated precise modification of susceptibility genes and regulatory pathways, offering new avenues for broad-spectrum and durable resistance. Integration of genetic resistance with IPM practices, including biological control, crop diversification and precision monitoring, has been shown to significantly reduce yield losses while enhancing long-term agro-ecosystem resilience under climate variability. Mechanisms and management strategies for pest and disease resistance for yield stability were presented in Table 3.

Improved nutrient use efficiency

Nutrient use efficiency (NUE) enhances crop productivity by optimising nutrient uptake and use. It involves physiological, molecular and genetic adaptations, including improved root traits, transcription factors and gene editing. Breeding, transgenic approaches and microbiome-based solutions are vital to improving NUE, especially under climate change-induced nutrient stress. Improved NUE is a critical determinant of yield stability under climate change, as rising temperatures, erratic rainfall and soil degradation increasingly limit nutrient availability and uptake. Extensive field and molecular studies have demonstrated that crops with enhanced NUE maintain productivity under nutrient- and water-limited conditions by optimising nutrient acquisition, assimilation and remobilisation. Key physiological traits such as improved root system architecture, increased root-microbe interactions and efficient transporter activity enhance nitrogen, phosphorus and potassium uptake under stress. At the molecular level, transcription factors and nutrient transporter genes regulate nutrient signalling pathways that coordinate growth and stress responses. Genomics-assisted breeding, MAS and GS have successfully improved NUE in cereals and legumes by integrating multiple small-effect loci controlling nutrient uptake and utilisation. More recently, CRISPR/Cas-based genome editing has enabled targeted modification of genes involved in nutrient transport and assimilation, resulting in higher yields with reduced fertiliser inputs. Additionally, microbiome-based interventions, including plant growth-promoting rhizobacteria and mycorrhizal associations, have been shown to improve nutrient availability and uptake efficiency, particularly under drought and heat stress. Collectively, integrating genetic improvement with precision nutrient management and sustainable soil practices offers a viable pathway to enhance NUE, reduce input dependency and ensure stable crop yields under changing climatic conditions. Different methods to improve NUE under challenging climate were presented in Table 4.

Marker-assisted selection and genomic selection

Marker-assisted selection (MAS) is a molecular breeding technique that uses genetic markers to accelerate plant breeding. It identifies QTLs for stress tolerance, disease resistance and yield traits and uses DNA markers to track these traits. Strategies for MAS include drought and heat tolerance, salt and waterlogging tolerance, disease resistance and nutrient use efficiency. This reduces time and cost in seedling selection. Fig. 2 depicts the progression from conventional DNA marker-based approaches to advanced GS strategies for breeding climate-resilient crops. It highlights how high-throughput

Table 3. Mechanisms and management strategies for pest and disease resistance for yield stability

Aspect	Description	References
Morphological barriers	First line of defense against pathogens and pests. Examples: Thick cuticles, trichomes and lignified cell walls prevent pathogen entry and insect feeding. Specific cases: Cotton trichomes deter insects, waxy cuticles in cereals reduce fungal infections and stomatal closure limits pathogen entry.	(20)
Biochemical defence mechanisms	Plants produce antimicrobial compounds and secondary metabolites. Pathogenesis-related (PR) proteins: Chitinases and glucanases degrade fungal cell walls. Phytoalexins & phenolics: Act as natural pesticides, inhibiting microbial growth. Volatile organic compounds (VOCs): Attract natural predators of pests (e.g., maize releases (E)-β-caryophyllene to attract wasps that prey on stem borers).	(21)
Gene-mediated resistance	Qualitative resistance: Single resistance (R) genes follow a gene-for-gene model but can be short-lived due to pathogen evolution. Quantitative resistance: Controlled by multiple genes (QTLs), providing durable protection. Examples: Rust and blight resistance QTLs incorporated into wheat and rice breeding.	(23)
Breeding strategies for resistance	Conventional breeding and MAS: Used to introgress resistance genes into elite cultivars. Examples: *Xa21* gene in rice for bacterial blight resistance; maize streak virus resistance through MAS. Genomic selection & Transgenic approaches: GM crops expressing Bt toxins for pest control in maize, cotton and soybean.	(26)
Gene editing innovations	CRISPR-Cas9: Enhances resistance against fungal and viral pathogens (e.g., tomatoes, wheat). RNA interference (RNAi): Silences essential pest genes, disrupting growth and development.	(27)
Integrated pest and disease management	Biological control: Use of beneficial microbes and natural predators. Examples: Trichoderma spp. and Pseudomonas fluorescens act as biocontrol agents against fungal pathogens. Cultural practices: Crop rotation, intercropping and residue management reduce pathogen carryover and pest infestations. Climate-smart agriculture: Precision farming and remote sensing for early outbreak detection and intervention.	(28)
IPM	Biocontrol agents against fungal pathogens. Cultural practices: Crop rotation, intercropping and residue management reduce pathogen carryover and pest infestations. Climate-smart agriculture: Precision farming and remote sensing for early outbreak detection and intervention.	(29)
Climate change and future research	Essential for global food security. Combines genetic resistance, biotechnology and sustainable management. Future directions: Identifying novel resistance genes, improving host-pathogen interaction models and developing resilient cropping systems.	(30)

Table 4. Different methods to improve nutrient use efficiency (NUE) under challenging climate

Aspect	Description	References
CRISPR-Cas9 vs. Transgenic technology	CRISPR-Cas9 enables precise modifications of endogenous genes without introducing foreign DNA. Allows targeted gene knockouts, insertions, or modifications to enhance crop resilience.	(12)
Examples of CRISPR-edited crops	*OsNRT1.1B* gene in rice: Improved nitrogen uptake, leading to higher yields with lower fertiliser inputs. *OsSPL14* gene in rice: Increased tiller number and grain yield.	(22)
Abiotic stress tolerance	Drought resistance: Editing genes like ERF and SnRK2 improved water retention and stomatal conductance in wheat and soybean. Salinity tolerance: Modifications in *SOS1* enhanced salt tolerance in tomato and rice.	(23)
Disease & pest resistance	MLO (Mildew Locus O) mutations: Conferred resistance to powdery mildew in wheat and barley.	(24)
Enhancing yield & quality	*GS3* and *GW2* gene edits in rice: Increased grain size and yield, supporting food production under climate variability.	(25)
Regulatory frameworks & adoption	CRISPR-edited crops with small, precise gene changes are gaining regulatory approval in multiple countries.	(26)
Future directions	Expand genome-editing tools and improve gene delivery systems. Enhance public acceptance through transparent regulatory policies.	(27)

genotyping, genome-wide prediction models and integration of multi-trait data enhance selection accuracy and accelerate the development of yield-stable cultivars under variable climatic conditions.

The GS is a breeding technique that uses whole-genome marker data to predict plant performance, enabling the rapid selection of superior genotypes. It uses high-throughput genotyping to analyse thousands of SNP markers across the genome, generating genomic estimated breeding values (GEBVs) for complex traits. The GS can be used to improve yield under climate change, such as multi-trait selection, speed breeding and stress-resilient hybrids. Genetic engineering and CRISPR-based approaches have emerged as powerful tools to enhance crop resilience and productivity under adverse conditions. Transgenic crops, such as Bt maize and insect-resistant cotton, have successfully incorporated genes to confer resistance against pests and improve water-use efficiency (WUE).

Physiological and morphological adaptations

Root system architecture (RSA) and water-use efficiency (WUE)

Root system architecture (RSA) plays a crucial role in plant adaptation to water availability and overall yield stability under changing climate conditions. Root system architecture (RSA) determines how efficiently plants can explore the soil for water and nutrients, influencing their ability to withstand drought and other environmental stresses. Key root traits such as root depth, density, length and angle contribute to water uptake efficiency and resource acquisition. Deeper roots, for example, can access deeper soil moisture, making crops more resilient to prolonged dry periods. Meanwhile, root plasticity allows plants to adjust their growth in response to fluctuating water availability, enhancing survival under drought conditions.

Water-use efficiency is another critical factor in improving crop productivity under water-limited conditions. Mechanisms such as stomatal regulation, osmotic adjustment and improved hydraulic conductance help plants optimise water use without compromising biomass production. Recent advancements in molecular breeding and gene editing have identified key genes regulating RSA and WUE, enabling the development of drought-resistant crop varieties with improved resource-use efficiency (48).

In addition to genetic improvements, agronomic strategies such as optimised irrigation techniques, soil moisture conservation practices and intercropping systems play a significant role in enhancing yield stability. Precision agriculture technologies, including sensor-based irrigation and remote sensing, allow farmers to manage water resources more efficiently, reducing waste and improving productivity (49). To ensure food security in the face of climate change, an integrated approach combining RSA optimisation, WUE enhancement and sustainable agronomic practices is essential. Future research should focus on leveraging advanced breeding techniques, improving soil management strategies and developing climate-smart cropping systems to enhance root function and water-use dynamics. A multidisciplinary approach integrating genetics, physiology and agronomy will be crucial in developing resilient crops capable of sustaining yield stability in changing environmental conditions (50). Fig. 3 illustrates the role of root system architecture and WUE in enhancing crop resilience under climate stress. The figure highlights key root traits, physiological processes and management interventions that optimise water acquisition, reduce transpiration losses and contribute to sustained yield stability in water-limited environments.

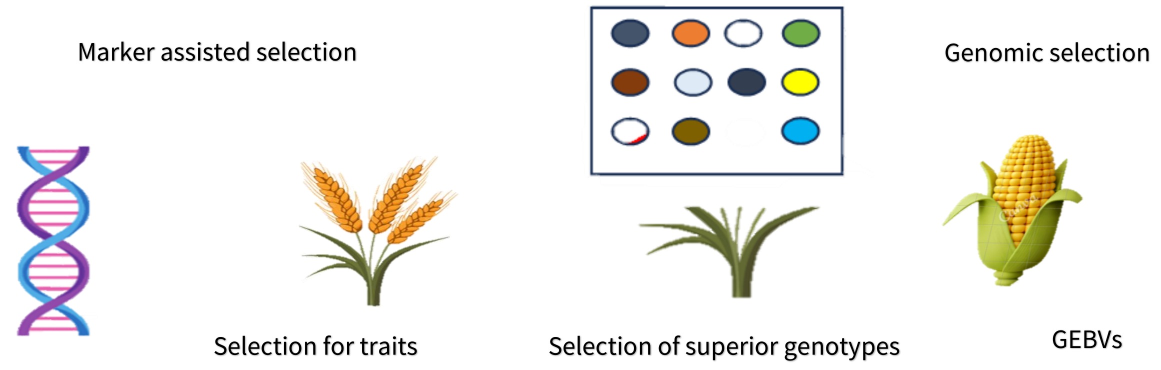

Fig. 2. From DNA markers to genomic selection: Breeding for resilience.

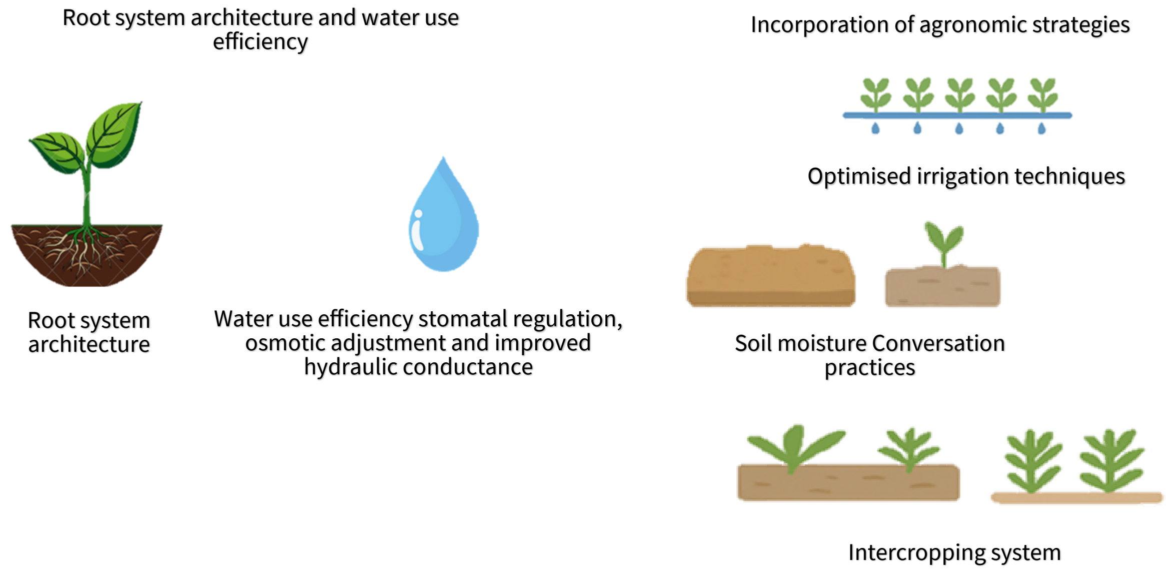

Fig. 3 Root system architecture and water-use efficiency: Strategies for climate-resilient crops.

Leaf morphology and stomatal regulation

Regulating stomatal conductance helps optimise water use while maintaining photosynthesis under stress conditions (51). Research has focused on breeding crops with improved stomatal function and cuticular properties to minimise water loss.

Osmoprotectant accumulation

Osmoprotectant accumulation is a crucial mechanism that helps plants cope with water stress and maintain yield stability under changing climate conditions. Osmoprotectants, also known as compatible solutes, are small organic molecules such as proline, glycine betaine, trehalose and sugars that accumulate in plant cells during drought, salinity and temperature stress (52). These compounds play a significant role in osmotic adjustment by maintaining cell turgor, stabilising proteins and membranes and scavenging ROS, thereby protecting plants from oxidative damage (53). The accumulation of osmoprotectants enhances water retention in cells, reduces transpiration loss and ensures proper metabolic function under stress conditions.

Plants regulate osmoprotectant biosynthesis through complex signalling pathways involving stress-responsive genes and transcription factors such as DREB, NAC and WRKY. Genetic engineering and breeding approaches have been employed to enhance osmoprotectant accumulation in crops, lseading to improved drought and salinity tolerance (54). For instance, overexpression of genes involved in proline and glycine betaine biosynthesis has been shown to improve plant WUE and biomass retention under stress conditions. Additionally, metabolic engineering strategies targeting sugar and polyol pathways have contributed to enhanced stress resilience in various crops.

Beyond genetic approaches, agronomic strategies such as exogenous application of osmoprotectants, biostimulants and microbial inoculants have shown promise in enhancing stress tolerance and maintaining yield stability. Foliar spraying or seed priming with proline, betaine, or trehalose has been reported to improve plant growth and physiological performance under drought and salinity stress (55). Moreover, beneficial soil microbes, including plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, can enhance osmoprotectant synthesis in plants by improving nutrient uptake and stress signalling (56).

In the context of climate change, integrating osmoprotectant-based strategies with other adaptive measures such as improved RSA, WUE and sustainable agronomic practices can help ensure crop productivity under adverse environmental conditions. Future research should focus on identifying stress-responsive genes, optimising osmoprotectant biosynthesis pathways and developing innovative agronomic interventions to enhance plant resilience and ensure global food security in a changing climate.

Conclusion

Climate change has intensified the frequency and severity of abiotic and biotic stresses, posing a significant challenge to stable crop production worldwide. This review highlights that yield stability under such challenging climatic conditions cannot be achieved through single-trait or isolated interventions. Instead, it requires an integrated approach combining genetic improvement, genomic-assisted breeding, genome-editing technologies, physiological adaptations and climate-smart agronomic practices. Advances in MAS, GS and CRISPR/Cas-based genome editing have accelerated the development of stress-resilient cultivars by enabling precise and efficient manipulation of complex traits associated with drought, heat, flooding, NUE and pest–disease resistance. Concurrently, understanding plant physiological mechanisms such as root system architecture, WUE, osmotic adjustment and antioxidant defence has strengthened the linkage between molecular innovations and field-level performance. Looking ahead, future research should prioritise systems-based breeding strategies that integrate multi-omics data, high-throughput phenotyping and artificial intelligence-driven prediction models to enhance selection accuracy across diverse environments. Greater emphasis on microbiome-assisted crop improvement, speed breeding and resilient seed systems will be essential for rapid deployment of climate-resilient varieties. Additionally, strengthening policy support, farmer-centric dissemination frameworks and participatory breeding approaches will be critical for translating scientific advances into sustainable agricultural practices. Collectively, these integrated efforts will play a pivotal role in ensuring long-term yield stability, food security and agricultural sustainability under increasing climate variability.

Authors' contributions

S and GP conceptualised the review framework and coordinated the overall structure of the manuscript. GN, SJ and PS contributed to literature collection, data compilation and drafting of specific thematic sections. BRD and AT assisted in critical analysis, interpretation of findings and refinement of technical content. VKP, TAA and VKG contributed to editing, validation of scientific accuracy and improvement of manuscript coherence and GP and SD supervised the review process, provided critical revisions and finalised the manuscript. All authors read and approved the final version of the manuscript.

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