



REVIEW ARTICLE

Drought stress responses and adaptive strategies in Indian mustard: A comprehensive review

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Abstract

Indian mustard (*Brassica juncea* (L.) Czern. & Coss.) contributes significantly to the edible oil production and an important oilseed crop for rural livelihoods in the semi-arid region and grown extensively in regions like India, China and South Asia. However, its productivity is severely constrained by repeated drought stress, particularly in arid and semi-arid areas. Drought stress adversely affects Indian mustard at morphological, physiological, biochemical and molecular levels, disrupting water relations, photosynthesis, nutrient uptake and metabolic activities. In response, the crop develops adaptive strategies including deep rooting, solute accumulation, antioxidant enzyme regulation, hormonal modulation and gene level metabolic adjustments. Understanding these drought-tolerance mechanisms is essential. Drought management strategies can partially mitigate yield losses, improving crop efficiency by 20–40 % under moderate stress conditions, although residual yield losses of 10–30 % may still occur depending on stress severity and genotype. Modern molecular breeding methods can be complemented with high throughput screening technologies to improve drought tolerance and mitigate repercussions. This review aims to provide a comprehensive understanding of drought stress responses and adaptive strategies in Indian mustard to support the development of resilient cultivars under changing climate scenarios.

Keywords: abiotic stress tolerance; antioxidant defence; *Brassica juncea*; molecular breeding; osmolyte accumulation; water use efficiency

Introduction

Indian mustard (*Brassica juncea* (L.) Czern & Coss.) is a commercially important edible oilseed crop of the Brassicaceae family categorised under rapeseed-mustard (RM) group and is widely grown in countries like India, China, Bangladesh and Pakistan (1). In India, it is cultivated on approximately 6.2 million hectares, contributing more than 85 % of total RM area (2). Despite its importance, the national average productivity (1400 kg ha⁻¹) is considerably lower than its potential yield (3500–4000 kg ha⁻¹), primarily due to abiotic stresses (3–5).

Drought stress is one of the most important abiotic constraints affecting crop productivity, especially under rainfed and semi-arid conditions. Irregular rainfall patterns and the increased incidence of heat waves cause a decline in agricultural production and threaten food security. Drought stress adversely affects plant water relations, photosynthesis, nutrient uptake and metabolic activities, ultimately impairing crop performance (6). To maintain cellular homeostasis and survival under limited water availability, Indian mustard exhibits a range of adaptive responses at

morphological, physiological, biochemical and molecular levels. These include deep root development, reduce stomatal conductance and osmotic adjustment by accumulating compatible solutes, such as proline, glycine betaine and sugars and activation of antioxidant enzyme activity to mitigate oxidative damage (7).

Recent advances in molecular biology have highlighted the role of stress-responsive genes, transcription factors and signalling pathways in regulating drought tolerance. Integration of omics technologies (transcriptomics, proteomics and metabolomics) enhances understanding of stress adaptive mechanisms and support the development of improved genotypes through molecular breeding (8). However, improving drought tolerance in Indian mustard remains challenging due to the interaction of multiple physiological and environmental factors, requiring an integrated approach combining genetics, physiology and agronomy for stable productivity. This review hypothesises that integrated physiological, biochemical and molecular mechanisms with advanced breeding and agronomic strategies can enhance drought tolerance and productivity in Indian mustard under challenging climatic conditions.

Drought stress

About 85 % of the total harvested area is used for *B. juncea* 37 % of the area under juncea crops was mostly rainfed (9). Therefore, drought stress significantly impacts Indian mustard crop yield and quality. In India mustard crop damage due to drought stress varies from 17–94 % (10). When the drought tolerance characteristics are incorporated into Indian mustard, various morpho-physiological and biochemical characters that regulate drought-tolerance traits get exchanged (11).

Drought stress negatively impacts plant height, leaf area and chlorophyll content, which in turn affects photosynthetic efficiency and crop biomass. A water deficit during the reproductive stage proves to be harmful. Studies indicate that a yield reduction takes place when stress occurs at flowering or pod filling compared to vegetative stage. For Indian mustard, the sensitive stages are marked by very high sensitivity and even moderate drought can cause significant yield loss due to poor pollination as well as seed setting. Drought susceptibility index (DSI) is a popular tool used to screen genotypes for their adaptability under water deficit conditions. Certain Indian mustard lines exhibit lower DSI values, which indicates comparatively high tolerance (12). Recent studies have targeted such physiological traits, which allows the maintenance of higher relative water content, increasing the root length for better water uptake and enhancing the osmolyte accumulation (proline and soluble sugars), to be considered as the key indicators of drought tolerance. The advancements made in breeding and the use of microbial inoculants further enhance rooting and nutrient/supply uptake under drought to improve stress tolerance. These interdisciplinary technologies are essential for sustainable mustard production in the changing climatic reality with declining water availability and soil health (13). The major drought induced responses in *B. juncea* are illustrated in Fig. 1.

Decoding the internal shield: Core mechanistic and physiological responses

Drought adaptation in Indian mustard involves morphological, physiological, biochemical and molecular reactions as shown in Fig. 2.

Physiological and biochemical pathways of abiotic stress tolerance in Indian mustard

The pronounced activation of the phenylpropanoid biosynthesis pathway suggests its critical roles in scavenging reactive oxygen species (ROS) and reinforcing cellular structures. Moreover, key hormonal signalling pathways - namely auxin, ethylene and abscisic acid (ABA) - undergo significant modulation under drought conditions. Weighted gene co-expression network analysis (WGCNA) further identified notable hub genes, including *novel.12726*, *BjuB027900* and *BjuA005565*, which serve as candidate regulators for breeding drought-resistant cultivars. These hub genes are intricately linked to regulatory modules governing plant development, energy metabolism and stress signal transduction, underscoring their potential in enhancing abiotic stress tolerance through targeted genetic improvement (14).

Antioxidant arsenal: Detoxifying reactive oxygen species under stress

Under water deficit conditions, RH-0406 exhibits elevated levels of critical biochemical protectants such as ascorbic acid, carotenoids, reduced glutathione (GSH) and proline (15). Simultaneously, activities of key antioxidant enzymes - superoxide dismutase (SOD), peroxidase (POX), ascorbate peroxidase (APX) and glutathione reductase (GR) - are significantly enhanced. Coordinated action of these antioxidants is crucial, since enzymes like catalase (CAT) and APX play pivotal roles in efficiently scavenging hydrogen peroxide (H_2O_2), preventing lipid peroxidation and preserving membrane integrity.

Complementing natural plant defences, rhizobacterial priming has shown promise in elevating antioxidant responses. Inoculated plants of both susceptible (Pusa Karishma) and tolerant (NPJ-124) genotypes exhibited increased catalase activity, which correlated with lowered H_2O_2 accumulation and reduced lipid peroxidation, underscoring the potential of beneficial microbe-assisted enhancement of antioxidant machinery under drought (16).

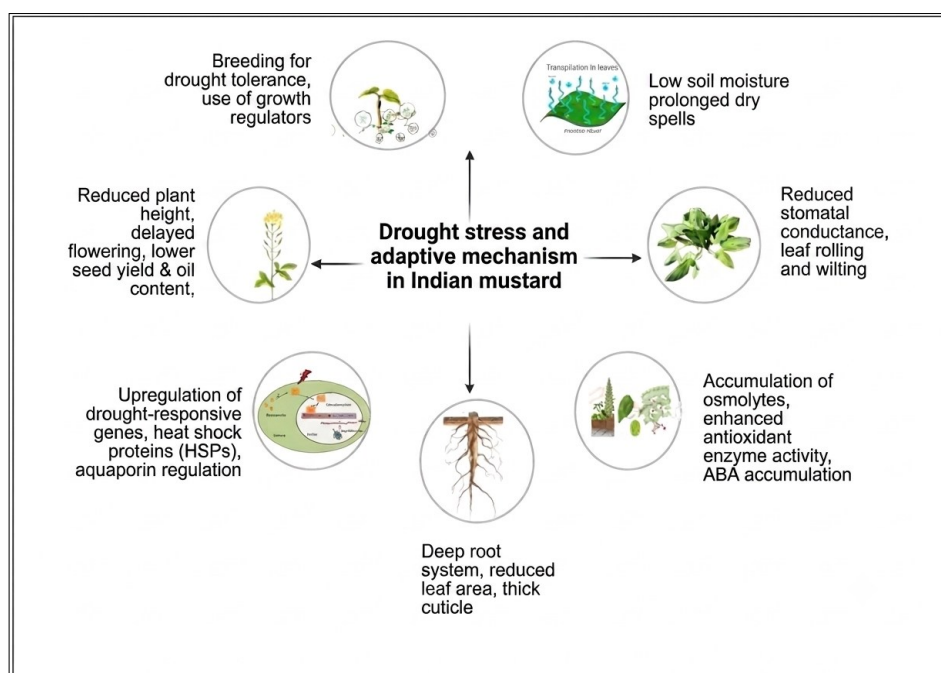


Fig. 1. Drought stress and adaptive mechanisms in *Brassica juncea*.

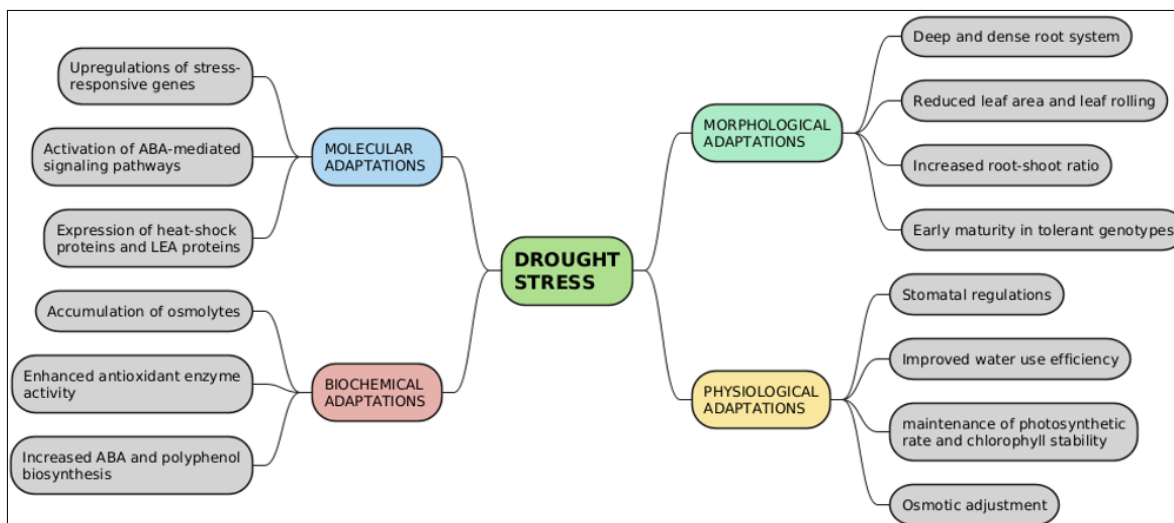


Fig. 2. Morphological, physiological, biochemical and molecular adaptations of *Brassica juncea* under drought stress.

Hormonal crosstalk: Signalling pathways modulating stress response

Transcriptomic analyses have shown significant gene enrichment in abscisic acid (ABA), auxin and ethylene pathways during drought stress (8). Key components like protein phosphatases 2Cs (PP2Cs), ABA-responsive element-binding factors (ABFs), ethylene-responsive transcription factors and receptor-like kinases play vital roles in mediating rapid stress responses, such as stomatal closure, to limit water loss and amplify stress signals. Temporal expression profiling indicates that ABA signalling reaches its peak early during germination, triggering downstream responses to water deficit through activation of stress-responsive genes, osmolyte biosynthesis and antioxidant pathways. For example, brassinosteroid (BR) signalling has been implicated in drought response, influencing cell wall remodelling and ROS detoxification genes. The BR signalling operates via the BRI1-BAK1 receptor complex, leading to regulation of BES1/BZR1 transcription factors by the BIN2 kinase, which modulate global gene expression related to stress adaptation (17, 18).

Photosynthesis under pressure: Light capture and water use efficiency in stress conditions

Potassium plays a key role in modulating photosynthetic efficiency and water use traits, which are often compromised under osmotic constraints like those induced by drought (11, 19). Key physiological parameters such as net photosynthetic rate (P_n), stomatal conductance, transpiration rate and intercellular CO_2 concentration (C_i) were significantly affected under ionic stress. A hallmark drought-adaptive response in *B. juncea* is partial stomatal closure, a mechanism to conserve water at the expense of gas exchange. Despite this, biochemical adaptations help sustain photosynthetic carbon assimilation by maintaining Rubisco activity and chlorophyll content, preserving the plant's photosynthetic apparatus under water deficit. Potassium supplementation was demonstrated to mitigate the decline in these parameters, most likely by stabilising membrane functions and maintaining osmotic potential, thereby supporting cellular turgor and efficient metabolic activity during stress (20).

Facing the elements: Specific abiotic stresses in Indian mustard

Drought dilemma: Morphological, physiological and molecular adaptations

Morphologically, drought stress induces the development of thicker

cuticles, an increased root-to-shoot ratio facilitating deeper soil water access and a reduction in leaf area to minimise transpiration losses (21). Physiologically, one of the primary responses is stomatal closure to curtail water loss, though this impairs photosynthesis by limiting CO_2 uptake. Concurrently, drought triggers accumulation of compatible solutes such as proline, glycine betaine and soluble sugars that act as osmo-protectants to maintain cell turgor and stabilise proteins and membranes against dehydration (22). At the molecular level, drought stress activates the expression of a suite of stress-responsive genes, including those encoding ABA-responsive transcription factors such as dehydration-responsive element binding (DREB), myeloblastosis (MYB) and NAC (NAM, ATAF1/2 and CUC2) families, as well as dehydrins, aquaporins facilitating water transport and late embryogenesis abundant (LEA) proteins that protect cellular structures. These gene networks coordinate signalling cascades essential for stress adaptation, membrane stability and antioxidant defences, thereby enhancing the plant's capacity to withstand prolonged water deficit (22). With tolerant cultivars like RH-725 exhibiting enhanced osmolyte accumulation, antioxidant enzyme activities and stabilised photosynthetic pigments compared to sensitive genotypes (RH-749) (23).

Salinity stress: Osmotic imbalance and ion homeostasis strategies

Elevated concentrations of sodium (Na^+) and chloride (Cl^-) ions in saline soils cause ionic toxicity and osmotic imbalance, thereby impairing the uptake of essential nutrients such as potassium (K^+) and calcium (Ca^{2+}). To mitigate cytosolic ion toxicity, Indian mustard activates selective ion transporters, including salt overly sensitive 1 (SOS1) and sodium/hydrogen exchanger 1 (NHX1), which respectively facilitate Na^+ efflux from the cytoplasm and its sequestration into vacuoles (24). Concomitantly, Indian mustard accumulates osmolytes and compatible solutes such as proline and polyols, which act to reduce osmotic stress by balancing cellular water potential. Salinity-induced oxidative stress triggers a robust antioxidant response characterised by increased activities of SOD, CAT and APX, thereby detoxifying ROS generated during ion imbalance. Transcriptome analyses reveal differential expression of genes related to calcium-dependent protein kinases, ABA signalling components and salt-responsive pathways (25).

Heat waves and survival: Mechanisms of thermotolerance

The crop employs several adaptive thermotolerance mechanisms beginning with morphological modifications including early

flowering, decreased leaf area and altered leaf angles to reduce heat load and radiation interception (26). At the cellular level, heat stress induces synthesis of heat shock proteins (HSPs), which act as molecular chaperones to refold denatured proteins and maintain membrane stability, preserving cellular integrity under thermal stress. The HSFs orchestrate the transcription of major HSP families including HSP70, HSP90 and small HSPs (27). Physiological adjustments include the modification of photosynthetic enzymes and enhancement of antioxidant enzyme activities that scavenge ROS induced by heat stress. Hormonal signalling pathways, particularly those involving ethylene and ABA, are modulated during heat stress to facilitate stress signalling and regulate protective stomatal behaviour (26). Screening studies have identified diverse genotypes varying in heat tolerance, with traits like cell membrane stability, relative leaf water content and acquired thermal tolerance serving as reliable indicators for breeding programs aimed at enhancing thermotolerance (11).

Cold snap defence: Acclimation and metabolic adjustment in low temperature stress

A critical adaptation to cold stress involves modifications in membrane lipid composition, notably an increase in unsaturated fatty acids (28). Furthermore, the accumulation of cryoprotectants such as proline, sugars and polyamines acts to stabilise proteins and membranes, reducing cellular damage caused by freezing or chilling stress. At the molecular level, Indian mustard induces the expression of cold-responsive (*COR*) genes, including those encoding antifreeze proteins and dehydrins, which mitigate ice crystal formation and protect cellular structures. The regulation of these genes is mediated by the CBF/DREB1 transcription factor pathway, a conserved mechanism also observed in related species (29). Additionally, antioxidant defences are enhanced to counteract ROS generated during cold exposure. Recent transcriptomic studies have shown upregulation of key regulators such as ICE1 and ICE2, homologs that activate the CBF pathway and improve freezing tolerance. Crosstalk between cold signalling and ABA pathways, mediated by proteins like OST1 kinase, further stabilises cold-responsive transcription factors.

Heavy metal hazards: Uptake, accumulation and detoxification mechanisms

Toxic metals like cadmium (Cd), lead (Pb) and arsenic (As) impair plant growth and productivity by inducing oxidative stress and disrupting cellular homeostasis. Indian mustard counters these effects through multiple detoxification strategies beginning with the secretion of phytochelatins and organic acids into the rhizosphere, which chelate and immobilise heavy metals, limiting their bioavailability to roots (30). Once inside the plant, metallothioneins - cysteine-rich proteins and vacuolar sequestration isolate these toxins intracellularly. At the genetic level, metal transporter genes such as heavy metal ATPases (HMA) and zinc-regulated transporter/iron-regulated transporter-like protein (ZIP) families are tightly regulated by stress-responsive transcription factors. Concurrently, enhanced antioxidant enzyme activities (SOD, CAT, APX) scavenge reactive oxygen species generated during metal stress (31). Genetically enhanced cultivars with elevated glutathione and phytochelatin levels, such as those overexpressing γ -glutamylcysteine synthetase, demonstrate improved tolerance and accumulation capacity, making them ideal candidates for soil detoxification efforts.

Genetic blueprints of resilience: Molecular and biotechnological interventions

It emphasises the use of QTL mapping and marker-assisted selection for stress-resilient traits, transcription factor regulatory roles and omics-driven gene discovery (32) (Fig. 3).

Omics revolution: Genomic and transcriptomic insights into stress adaptation

Whole-genome sequencing and transcriptome analyses have identified key gene families that orchestrate stress responses, including those related to hormone signalling, transmembrane transporters, antioxidative defence and signal transduction pathways (33). RNA-Seq data under drought, salinity and heat stress conditions reveal differential expression of transcription factors (such as DREB, MYB and NAC), HSPs, aquaporins facilitating water transport and LEA proteins that protect cells from dehydration.

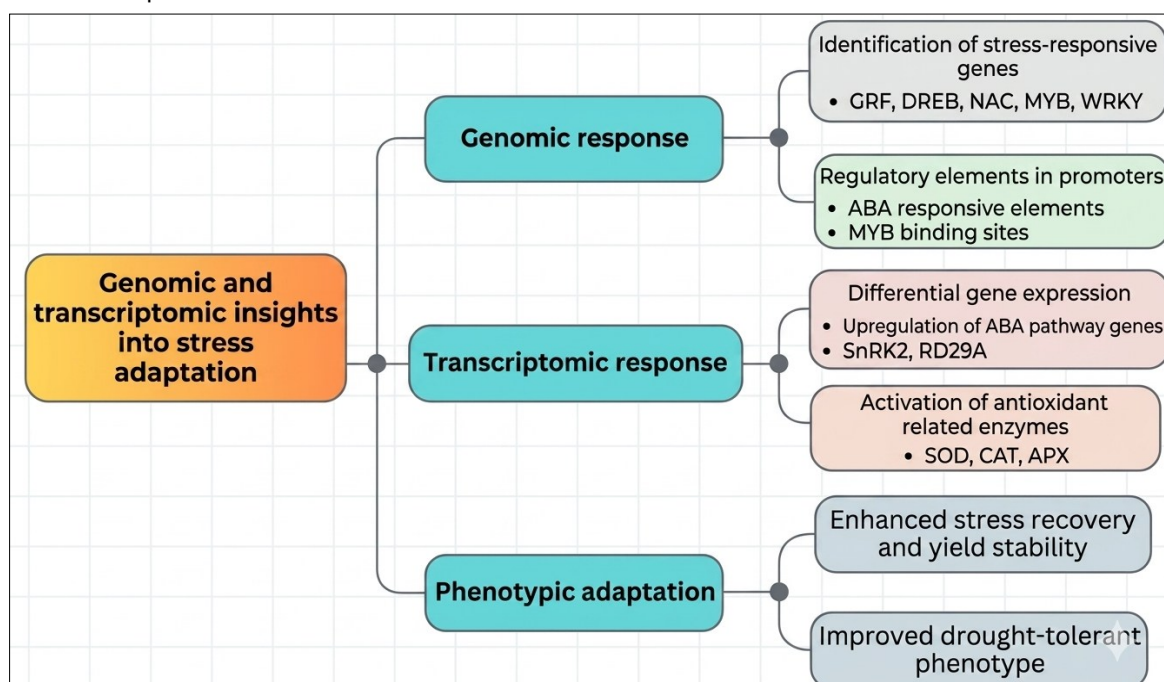


Fig. 3. Genomic and transcriptomic basis of stress adaptation in *Brassica juncea*, highlighting gene expression and regulatory pathways.

Transcription factors as master switches of stress tolerance genes

Key transcription factor (TF) families such as DREB, MYB, WRKY, NAC, bZIP and heat shock factors (HSFs) have been extensively characterised for their roles in activating defence mechanisms under heat, drought, cold and salinity stress (34). For example, DREB and NAC TFs regulate genes involved in osmolyte biosynthesis, antioxidant defences and membrane stabilisation, whereas HSFs predominantly modulate heat shock protein expression to maintain protein homeostasis under thermal stress. Transgenic plants overexpressing individual TFs show improved physiological traits such as better water retention, ROS scavenging and sustained photosynthesis under stress conditions (35).

Mapping resilience: Quantitative trait loci and marker-assisted selection for stress-tolerance traits

Using molecular markers such as simple sequence repeats (SSR), single nucleotide polymorphisms (SNP) and genotyping-by-sequencing (GBS), researchers have identified key loci associated with important stress-adaptive traits, including root architecture, chlorophyll retention, osmolyte accumulation and membrane stability under drought, salinity and heat stress conditions (36). Marker-assisted introgression of these loci into elite cultivars shortens the breeding cycle and improves selection accuracy, enabling the development of varieties that maintain yield and quality under adverse environmental conditions (32). High-density linkage maps and genome-wide association studies (GWAS) have recently pinpointed candidate genes involved in lipid metabolism, antioxidant response and stress signalling, which are tightly linked with quantitative traits such as seed oil content and drought susceptibility. Introgression lines developed from wild relatives like *Brassica tournefortii* Gouan and Ethiopian mustard (*Brassica carinata* A.Braun) have broadened the genetic base, enhancing the pool of stress-resilience alleles available for breeding (36).

Engineering the future: Biotechnological strategies for enhanced stress resistance

Overexpression of key stress tolerance genes such as DREB1A, SOS1 (salt overly sensitive 1), NHX1 (sodium/hydrogen exchanger), P5CS (pyrroline-5-carboxylate synthetase) and SOD (superoxide dismutase) has demonstrated significant improvements in mustard's ability to withstand drought, heat and salinity stresses (37). Transplastomic approaches further offer means to engineer chloroplast genomes for expression of stress-tolerance traits, while

RNA interference (RNAi) strategies enable gene silencing of negative regulators of stress responses.

Smart farming tactics: Agronomic and ecological strategies

Abiotic stressors like heat and drought pose serious yield threat to *B. juncea* in India's semi-arid growing regions. The foundation of sustainable stress adaptation is smart farming frameworks, which combine ecological consciousness with agronomic accuracy. To create a resilient cropping paradigm, these frameworks combine rhizosphere bioengineering, growth regulators, soil-plant health, nutrient economy and crop system design (38).

Soil health and nutrient management for stress mitigation

In Indian mustard, potassium (K⁺) plays a pivotal role in osmotic regulation and stomatal function, thereby stabilising membrane integrity and photosynthetic capacity during drought. Foliar sprays or fertigation of potassium have been shown to moderate physiological decline and support yield stability effectively (37). These micronutrients enhance antioxidant enzyme functions and hormonal balance, thus strengthening the plant's intrinsic defence network.

Plant growth regulators and stress shields: Role of plant growth regulators

Plant growth regulators (PGRs) modulate physiological and molecular responses to environmental stresses in *Brassica* species including *B. juncea*, *Brassica napus* L. and *Brassica rapa* L. Exogenous application of regulators such as gibberellic acid (GA₃), salicylic acid (SA) and brassinosteroids (BRs) enhances key chlorophyll content, photosynthetic efficiency and antioxidant enzyme activities under drought and salinity stresses (39). These PGRs help modulate antioxidant defence systems by elevating activities of SOD, CAT, APX and polyphenol oxidase, thereby alleviating oxidative damage, as listed in Table 1. Additionally, PGRs influence hormonal signalling pathways and osmotic regulation, contributing to improved stomatal behaviour, membrane stability and stress signalling cascades.

Microbial allies: Harnessing the rhizosphere microbiome for tolerance boost

These microbes enhance water uptake, stimulate root growth, solubilise essential nutrients and activate plant defence mechanisms against oxidative stress, ultimately improving plant

Table 1. Role of plant growth regulators (PGR) in enhancing abiotic stress in *Brassica juncea*

PGR	Key function under stress	Application strategy	Notable outcomes	Reference
Salicylic acid (SA)	Enhances antioxidant enzyme activity (SOD, APX, GR); regulate photosynthesis and ROS detoxification	Foliar application during flowering to early pod stage	Improved chlorophyll stability, photosynthetic efficiency and oxidative stress tolerance	(14, 37)
Gibberellic acid (GA ₃)	Improves relative water content and nutrient mobilisation	Foliar spray at vegetative phase	Enhanced leaf turgor, biomass accumulation and growth under stress	(37)
Brassinosteroids (BR)	Regulates antioxidant system and membrane stability	Foliar spray at early growth and stress onset	Increased antioxidant enzyme activity and membrane integrity under salt and drought stress	(15, 16)
Triacantanol (TRIA)	Enhance protein synthesis and antioxidant enzyme activity (CAT, APX)	Foliar application under stress condition	Enhanced growth parameters and improved salt stress tolerance	(37)
Absciscic acid (ABA)	Mediates stomatal closure and activates osmolyte and antioxidant biosynthesis	Seed priming or foliar spray during stress	Improved water use efficiency and stress signalling	(33, 37)

SOD: superoxide dismutase; APX: ascorbate peroxidase; GR: glutathione reductase; CAT: catalase, ROS: reactive oxygen species.

resilience under limited irrigation conditions (40). Field trials utilising plant growth-promoting rhizobacteria (PGPR) strains like *Enterobacter hormaechei*, *Pantoea dispersa* and *Acinetobacter* sp. have shown significant improvements in relative water content (RWC), seed production, oil content and water use efficiency (WUE). These changes help maintain cellular homeostasis, improve membrane integrity and reduce oxidative damage during water stress (14).

Resilient farming: Integrated crop management for abiotic stress

Integrated crop management (ICM) provides a system-based approach that combines genetic, nutritional, microbiological and irrigation strategies to improve stress adaptation in Indian mustard (*B. juncea*), as listed in Table 2. Key to ICM is the prioritisation of drought-tolerant genotypes such as RH-0406 and DRMCI 72, 80 and 89, which exhibit yield stability under moisture deficit and enhanced relative water content, which collectively contribute to their resilience (41). Agronomic practices such as early sowing (mid-October) in rainfed farming systems optimise the crop growth period to avoid terminal drought. Mulching conserves soil moisture, reduces evapotranspiration and moderates soil temperature, while timely, strategic irrigation during critical phenological stages such as flowering and pod-filling preserves grain yield and improves water use efficiency (42). The integration of PGR and PGPR further enhance antioxidant activity, osmotic balance and stress tolerance in Indian mustard. These combined practices strengthen the crop's physiological resilience and contribute to stable productivity under drought-prone conditions.

Climate-smart mustard: Sustainability and future decisions

Future proofing Indian mustard against the growing difficulties of climate change requires -smart policies. This section examines how eco-friendly methods, adaptive breeding and cutting-edge technologies work together to create resilient and sustainable mustard farming.

Climate change and the rising tide of abiotic stresses

Climate change is reshaping the challenges faced by Indian mustard cultivation in South Asia's semi-arid and desert regions. Characterised by unpredictable rainfall, prolonged dry periods and

escalating temperatures, climate variability increasingly threatens *B. juncea*. Salinity stress has become more prevalent in irrigated areas, high temperatures adversely impact blooming and pod-filling stages and terminal dryness further constrains productivity (26, 43). Recent studies highlight that climatic variability is narrowing the optimal growing window for mustard, particularly in rainfed systems, necessitating adaptive strategies for sustained production (35, 44). Integrating resilient genotypes, innovative agronomy, microbial alliances, precision irrigation and biotechnological advancements to enhance resilience and sustain productivity under challenging climatic conditions (44, 45).

Breeding for the future: Climate-resilient mustard varieties

Breeding programs for *B. juncea* are progressively oriented towards developing stress-resilient ideotypes to secure productivity amidst climate change challenges. These efforts employ traditional selection methods alongside advanced molecular breeding tools such as marker-assisted breeding, genomic selection and speed breeding to shorten generation cycles and accelerate genetic gain (46). Promising cultivars combine traits like early maturity, deep root systems for efficient water extraction, enhanced proline biosynthesis and superior ROS detoxification capacity. Elite cultivars such as RH-749 and NRCDR 2 demonstrate stable yields under persistent heat and moisture stress, validated through rigorous on-field phenotyping and simulated stress trials (43).

Towards sustainability: Eco-friendly practices to combat abiotic stress

Conservation agriculture practices such as zero tillage, residue retention and legume intercropping are vital in enhancing soil organic matter, water retention capacity and buffering against abiotic stresses like drought and salinity (47). Organic amendments such as vermicompost and biochar improve soil health and increasing plant resilience during stressful periods (44). Microbial consortia, particularly strains of *Trichoderma*, *Azospirillum* and *Bacillus* boost stress tolerance in *B. juncea* (48). In Indian mustard, these practices improve soil moisture conservation and enhance stress tolerance under rainfed and semi-arid conditions. Eco-friendly practices for abiotic stress mitigation in Indian mustard are summarised in Fig. 4.

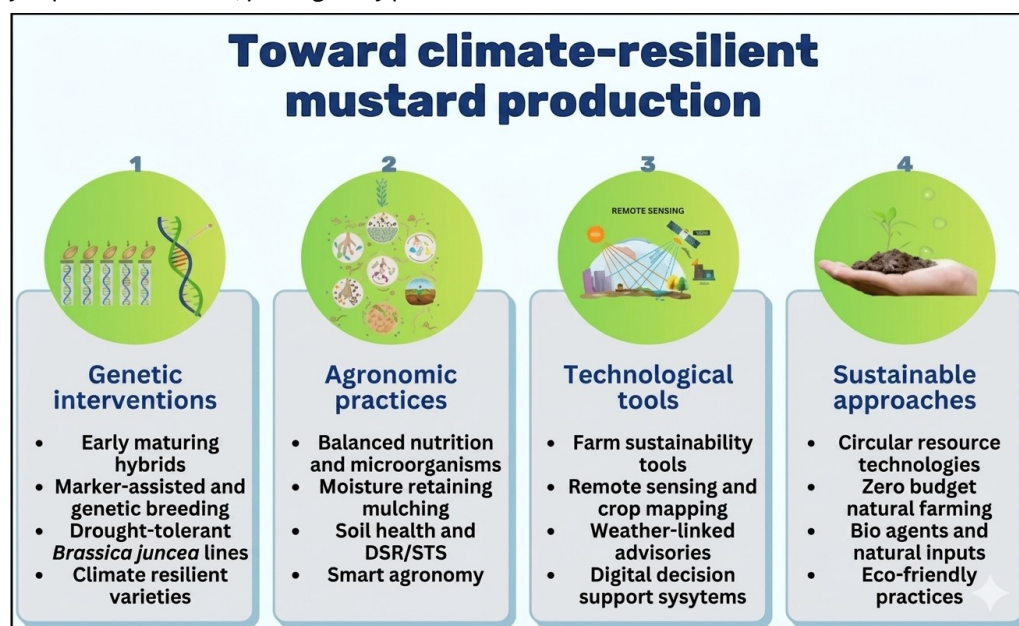


Fig. 4. Pathways for developing climate resilient *Brassica juncea*.

Table 2. Integrated crop management (ICM) strategies for enhancing abiotic stress tolerance in *Brassica juncea*

ICM	Practices	Impact under stress conditions	Reference
Sowing scheduling and mulching	Mid Oct sowing with residue mulch	Reduced soil evaporation and improved moisture retention	(41)
Irrigation and fertigation	Limited irrigation (1–2 irrigations) with optimised nutrient supply	Improved WUE and better crop performance under water deficit	(41)
Irrigation and bioinoculant synergy	Irrigation combined with CRIDA MI-II or Biophos inoculation	Increased yield, improved WUE and better plant water status under drought stress	(41)

RWC: relative water content; WUE: water use efficiency; PGR: plant growth regulator; SA: salicylic acid; GA₃: gibberellic acid.

Conclusion

Indian mustard (*Brassica juncea*) holds great importance nutritionally, economically and culturally, but suffers substantial yield losses due to abiotic stresses such as drought, salinity, heat and terminal moisture deficit. These stresses impact major growth stages, particularly germination, flowering and seed development, leading to yield reductions ranging between 17 and 94 % annually depending on severity and region. Climate variability and increasing environmental extremes exacerbate these challenges, threatening crop productivity and seed quality. Cultivar level evaluations indicate that genotypes such as RH-0406, RH-749 and DRMRI 72-89 consistently exhibit higher relative water content, improved antioxidant activity and better yield stability under drought and heat stress conditions, demonstrating their superior stress-use efficiency and adaptability in semi-arid conditions.

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Authors' contributions

KC prepared the original draft of the manuscript. VK, DKP and RC conceptualised the study. ANY reviewed and edited the manuscript. MS and KKV assisted in the preparation of manuscript diagrams. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

- Choudhury S, Asrani P, Kashyap A, Rao M, Prasad K, Pant U, et al. Whole genome resequencing of advanced introgression lines of *Brassica juncea* L. Czern. for characterizing alien introgression from *Diplotaxis erucoides* L. DC. Indian J Genet Plant Breed. 2023;83:217–23. <https://doi.org/10.31742/ISGPB.83.2.7>
- Singh KH, Singh L, Parmar N, Kumar S, Nanjundan J, Singh G, et al. Molecular characterization and genetic diversity analysis in Indian mustard (*Brassica juncea*) varieties using SSR markers. PLoS One. 2022;17:e0272914. <https://doi.org/10.1371/journal.pone.0272914>
- Manchanda SC, Passi SJ. Selecting healthy edible oil in the Indian context. Indian Heart J. 2016;68:447. <https://doi.org/10.1016/j.ihj.2016.05.004>
- Thakur AK, Parmar N, Singh KH, Nanjundan J. Current achievements and future prospects of genetic engineering in Indian mustard (*Brassica juncea*). Planta. 2020;252:1–20. <https://doi.org/10.1007/s00425-020-03461-8>
- Ananthanarayan L, Dubey KK, Muley AB, Singhal RS. Indian traditional foods: preparation, processing and nutrition. In: Al-Khusaibi M, Al-Habsi N, Rahman MS, editors. Traditional Foods. Cham: Springer; 2019. p.127–99. https://doi.org/10.1007/978-3-030-24620-4_6
- Verma S, Dubey N, Singh KH, Parmar N, Singh L, Sharma D, et al. Utilization of crop wild relatives for biotic and abiotic stress management in Indian mustard. Front Plant Sci. 2023;14:1277922. <https://doi.org/10.3389/fpls.2023.1277922>
- Gupta S, Kaur R, Sharma T, Bhardwaj A, Sharma S, Sohal JS, et al. Multi-omics approaches for understanding stressor-induced physiological changes in plants. Physiol Mol Plant Pathol. 2023;126:102047. <https://doi.org/10.1016/j.pmpp.2023.102047>
- Wei J, Xu L, Shi Y, Cheng T, Tan W, Zhao Y, et al. Transcriptome profile analysis of Indian mustard during seed germination reveals drought stress-induced genes. Plant Physiol Biochem. 2023;200:107750. <https://doi.org/10.1016/j.plaphy.2023.107750>
- Shekhawat K, Rathore SS, Premi OP, Kandpal BK, Chauhan JS. Advances in agronomic management of Indian mustard: an overview. Int J Agron. 2012;2012:408284. <https://doi.org/10.1155/2012/408284>
- Akanksha K, Srivastava K, Srivastava A, Sinha B. Analysis of drought susceptibility index in Indian mustard. Indian J Agric Res. 2020;55:446–51. <https://doi.org/10.18805/IJARE.A-5526>
- Singh J, Singh V, Vineeth TV, Kumar P, Kumar N, Sharma PC. Differential response of Indian mustard under salinity: photosynthetic traits and gene expression. Physiol Mol Biol Plants. 2019;25(1):71–83. <https://doi.org/10.1007/s12298-018-0631-3>
- Sharma P, Sardana V. Physiological and biochemical traits of drought tolerance in *Brassica juncea*. S Afr J Bot. 2022;146:509–20. <https://doi.org/10.1016/j.sajb.2021.11.019>
- Sheoran AR, Lakra N, Saharan BS, Luhach A, Ahlawat YK, Porcel R, et al. Metabolomic profiling reveals PGPR-driven drought tolerance in *Brassica juncea* genotypes. Metabolites. 2025;15(6):416. <https://doi.org/10.3390/metabo15060416>
- Bandeppa S, Paul S, Thakur JK, Chandrashekar N, Umesh DK, Aggarwal C, et al. Antioxidant, physiological and biochemical responses of mustard genotypes to rhizobacterial inoculation under drought. Plant Physiol Biochem. 2019;143:19–28. <https://doi.org/10.1016/j.plaphy.2019.08.018>
- Khan TA, Kappachery S, Karumannil S, AlHosani M, Almansoori N, Almansoori H, et al. Brassinosteroid signaling pathways: insights into plant responses under abiotic stress. Int J Mol Sci. 2023;24(24):17246. <https://doi.org/10.3390/ijms242417246>
- Lu Z, Ma C, Xie Y, Zeng Y, Peng J, Zhou D, et al. Brassinosteroid-dependent environmental adaptation in Brassicaceae. Plants. 2025;14(10):1554. <https://doi.org/10.3390/plants14101554>
- Wahid A, Faizan M, Arif Y, Alam P, Hayat S. Dose-dependent potassium response in Indian mustard under salt stress. Discover Plants. 2025;2(1):51. <https://doi.org/10.1007/s44372-025-00131-5>
- Zhang L, Jiang Q, Zong J, Guo H, Liu J, Chen J. Supplemental potassium effects under salt stress in *Zoysia matrella*. Horticulturae. 2023;9(1):1. <https://doi.org/10.3390/hort9010001>

- 2023;10(1):31. <https://doi.org/10.3390/horticulturae10010031>
19. Rani P, Rani J, Mittal A, Sheoran N. Assessment of drought tolerance of Indian mustard cultivars. *Arch Curr Res Int.* 2024;24(5):437–50. <https://doi.org/10.9734/acri/2024/v24i5721>
 20. Kumar A, Changwal C, Thapa B, Tanpure RS, Hada A, Singh PK, et al. Transcription factors for abiotic stress tolerance. In: *Stress tolerance in horticultural crops*. Woodhead Publishing; 2021. p.169–92. <https://doi.org/10.1016/C2018-0-04538-7>
 21. Kumar S, Sachdeva S, Bhat KV, Vats S. Plant responses to drought stress. In: *Biotic and abiotic stress tolerance in plants*. Singapore: Springer; 2018. p.1–25. https://doi.org/10.1007/978-981-10-9029-5_1
 22. Hualpa-Ramirez E, Carrasco-Lozano EC, Madrid-Espinoza J, Tejos R, Ruiz-Lara S, Stange C, et al. Stress salinity in plants: new coping strategies. *Plant Physiol Biochem.* 2024;208:108507. <https://doi.org/10.1016/j.plaphy.2024.108507>
 23. Roy D, Vishwanath PD, Sreekanth D, Mahawar H, Ghosh D. Salinity and osmotic stress in field crops. In: *Response of field crops to abiotic stress*. CRC Press; 2022. p.123–38. <https://doi.org/10.1201/9781003258063-11>
 24. Pillai AJ, Walia P. Heat stress in Indian mustard: a critical review. *Plant Cell Biotechnol Mol Biol.* 2024;25(5–6):1–11. <https://doi.org/10.56557/pcbmb/2024/v25i5-68673>
 25. Fragkostefanakis S, Röth S, Schleiff E, Scharf KD. Engineering thermotolerance: current understanding and future directions. *Plant Cell Environ.* 2015;38(9):1881–95. <https://doi.org/10.1111/pce.12396>
 26. Shomo ZD, Li F, Smith CN, Edmonds SR, Roston RL. Membrane lipid remodelling in plant cold response. *Plant Physiol.* 2024;196(3):1737–57. <https://doi.org/10.1093/plphys/kiae382>
 27. Jahed KR, Saini AK, Sherif SM. Coping with the cold: unveiling cryoprotectants, molecular signaling pathways and strategies for cold stress resilience. *Front Plant Sci.* 2023;14:1246093. <https://doi.org/10.3389/fpls.2023.1246093>
 28. Seth CS, Misra V, Chauhan LKS. Accumulation, detoxification and genotoxicity of heavy metals in Indian mustard (*Brassica juncea* L.). *Int J Phytoremediation.* 2012;14(1):1–13. <https://doi.org/10.1080/15226514.2011.555799>
 29. Mahapatra K, Banerjee S, Roy S. The how's and whys of heavy metal-mediated phytotoxicity: an insight. In: *Cellular and molecular phytotoxicity of heavy metals*. Cham: Springer; 2020. p.19–41. https://doi.org/10.1007/978-3-030-45975-8_2
 30. Karthik G, Mehendi S, Kumar TV. Enhancing crop resilience through molecular markers: a review. *J Adv Biol Biotechnol.* 2024;27(7):521–35. <https://doi.org/10.9734/jabb/2024/v27i71013>
 31. Kamali S, Singh A. Genomic and transcriptomic approaches to developing abiotic stress-resilient crops. *Agronomy.* 2023;13(12):2903. <https://doi.org/10.3390/agronomy13122903>
 32. Hrmova M, Hussain SS. Plant transcription factors involved in drought and associated stress. *Int J Mol Sci.* 2021;22(11):5662. <https://doi.org/10.3390/ijms22115662>
 33. Patel R, Jangra S, Avtar R, Yadav NR, Yadav RC. Genetic linkage mapping and QTL identification for salinity tolerance in Indian mustard (*Brassica juncea* L. Czern and Coss.) using SSR markers. *Oil Crop Sci.* 2023;8(3):191–205. <https://doi.org/10.1016/j.ocsci.2023.09.003>
 34. Sahoo CR, Dash M, Acharya N. Biochemical responses of Indian mustard to water stress. *Int J Curr Microbiol Appl Sci.* 2019;8(2):1711–18. <https://doi.org/10.20546/ijcmas.2019.802.201>
 35. Meena SL, Bana RS, Kaur R, Nirmal R, Singh D, Godara S, et al. Long-term moisture conservation and nutrient management improves yield stability and resource use efficiency in pearl millet (*Pennisetum glaucum*)-mustard (*Brassica juncea*) system under rainfed ecosystem. *Front Sustain Food Syst.* 2025;9:1597025. <https://doi.org/10.3389/fsufs.2025.1597025>
 36. Sardans J, Peñuelas J. Potassium control of plant functions: ecological and agricultural implications. *Plants.* 2021;10(2):419. <https://doi.org/10.3390/plants10020419>
 37. Mohapatra R, HM HK, Naan T, Chitra M, Ashwini R, Rout A, et al. A review on biotechnological innovations in developing stress-tolerant crops for adverse environmental conditions. *J Sci Res Rep.* 2024;30(7):901–20. <https://doi.org/10.9734/jsrr/2024/v30i72200>
 38. Islam S, Shah SH, Corpas FJ, Alamri S, Mohammad F. Plant growth regulators mediated mitigation of salt-induced toxicities in mustard (*Brassica juncea* L.) by modifying the inherent defense system. *Plant Physiol Biochem.* 2023;196:1002–18. <https://doi.org/10.1016/j.plaphy.2023.02.053>
 39. Kumar D, Dhillon BS. Effect of irrigation schedules on productivity, quality and water use of Indian mustard (*Brassica juncea*) under staggered sowing in Northwest India. *Indian J Agron.* 2023;68(2):199–204. <https://doi.org/10.59797/ija.v68i2.355>
 40. Prasanth GR, Utharasu S, Ravikesavan R, Sakthivel N, Sivasakthivelan P, Sudha M. Integrative approaches for mustard improvement: bridging conventional breeding, genetics and biotechnological advances. *Plant Sci. Today.* 2025;12:5231. <https://doi.org/10.14719/pst.5231>
 41. Bezboruah M, Sharma SK, Laxman T, Ramesh S, Sampathkumar T, Gulaiya S, et al. Conservation tillage practices and their role in sustainable farming systems. *J Exp Agric Int.* 2024;46(9):946–59. <https://doi.org/10.9734/jeai/2024/v46i92892>
 42. Islam KK, Toppo A, Biswas B, Mankin A, Roy S, Paul A, et al. Conservation agriculture, crop intensification and cultivation of mustard in the northeastern Bangladesh. *Int J Environ Agric Biotechnol.* 2022;7:1. <https://doi.org/10.22161/ijeab>
 43. Choudhary R, Jat R, Yadav K, Singh V. Physiological trait diversity for drought tolerance in Indian mustard (*Brassica juncea*) and genotypes mapping. *J Oilseeds Res.* 2023;37(4). <https://doi.org/10.56739/jor.v37i4.136751>
 44. Sharma A, Chhabra V, Mehta S, Bagal YS, Kumar R, Al-Ansari N, et al. Optimizing cultivation practices to enhance growth and yield of Indian mustard. *Sci Rep.* 2025;15(1):11433. <https://doi.org/10.1038/s41598-025-95313-2>
 45. Kumawat P, Ram M, Jakhar ML, Kumar P, Kumawat GL. Enhancing drought tolerance in Indian mustard (*Brassica juncea*) through microbial inoculants under varying irrigation regimes. *Indian J Agric Sci.* 2024;94(4):345–51. <https://doi.org/10.56093/ijas.v94i4.144818>
 46. Saikanth DRK, Supriya, Singh BV, Rai AK, Bana SR, Sachan DS, et al. Advancing sustainable agriculture: a comprehensive review for optimizing food production and environmental conservation. *Int J Plant Soil Sci.* 2023;35(16):417–25. <https://doi.org/10.9734/ijpss/2023/v35i163169>
 47. Kavamura VN, Santos SN, da Silva JL, Parma MM, Ávila LA, Visconti A, et al. Screening of Brazilian cacti rhizobacteria for plant growth promotion under drought. *Microbiol Res.* 2013;168(4):183–91. <https://doi.org/10.1016/j.micres.2012.12.002>
 48. Mahamud AM, Imran S, Paul NC, Rabbi RHM, Jahan N, Sarker P, et al. An overview and current progress of gibberellic acid-mediated abiotic stress alleviation in plants. *Plant Soil Environ.* 2025;71(7):453–79. <https://doi.org/10.17221/137/2025-PSE>

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