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Review Paper

Adaptation strategies of major pulse crops under diverse climatic conditions

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ABSTRACT

Climate change is intensifying abiotic stresses such as drought, heat, cold, salinity, and flooding, posing serious threats to the productivity of pulse crops cultivated largely in rainfed and marginal environments. Major pulses, including chickpea (*Cicer arietinum* L.), pigeonpea (*Cajanus cajan* L.), lentil (*Lens culinaris* Medik.), mungbean (*Vigna radiata* L.), urdbean (*Vigna mungo* L.), cowpea (*Vigna unguiculata* L.), and field pea (*Pisum sativum* L.) are particularly vulnerable during reproductive stages. This review critically synthesizes morphological, physiological, biochemical, molecular, genetic, and agronomic adaptation strategies that enable pulses to cope with diverse climatic conditions. Emphasis is placed on oxidative stress management, hormonal and MAPK signaling, and climate-smart agronomy, with a special focus on Indian agroclimatic zones and ICAR-led initiatives. Integrating stress-resilient genotypes with adaptive management practices is highlighted as a key pathway for sustaining pulse productivity under climate change.

Key words: Pulse crops, Climate change adaptation, Drought and heat stress, Reactive oxygen species, MAPK signalling, Climate-smart agriculture

INTRODUCTION

Pulse crops are central to global and Indian food and nutritional security due to their high protein content, dietary fiber, and role in improving soil fertility through biological nitrogen fixation. India accounts for a major share of global pulse acreage and production, cultivating pulses across diverse agro-climatic zones ranging from arid and semi-arid tropics to sub-humid and temperate regions. However, climate change–induced variability in temperature and rainfall, along with increased frequency of extreme events, has significantly destabilized pulse yields (IPCC 2019; ICAR 2023). Pulses are particularly sensitive to abiotic stresses during flowering and pod filling, necessitating a comprehensive understanding of adaptation strategies at morphological, physiological, molecular, and agronomic levels. Heat stress represents one of the most severe abiotic challenges to crop plants worldwide, particularly under ongoing climate change. Elevated temperatures affect plant growth, development, physiological performance, and yield quality. Heat tolerance refers to the ability of plants to withstand high temperature stress without severe functional damage over short or extended periods. Heat tolerance in plants refers to their capacity to maintain growth, cellular integrity, and reproductive success under high temperature conditions. Unlike acute heat shock, which involves short-term exposure to extreme temperatures, chronic heat stress imposes prolonged thermal pressure that requires complex adaptive responses. These responses involve coordinated changes at morphological, physiological, biochemical, molecular, and genetic levels.

MAJOR CLIMATIC STRESSES AFFECTING PULSE CROPS

Drought stress

Drought stress reduces leaf water potential, induces stomatal closure, limits carbon assimilation, and enhances oxidative stress, ultimately leading to flower drop and poor seed filling in pulses such as chickpea and lentil (Tardieu *et al.* 2018; Singh and Saxena 2020).

Heat stress

High temperatures (≥30–35 °C) during reproductive stages impair pollen viability, anther dehiscence, and pod set in chickpea, lentil, and cowpea (Kumar *et al.* 2022; Bhandari *et al.* 2023).

Cold and frost stress

Low temperature stress during early growth and flowering affects membrane integrity, enzyme activity, and nodulation in winter pulses grown in northern India (Sharma *et al.* 2021).

Salinity and sodicity stress

Salinity stress disrupts ionic homeostasis, water uptake, and symbiotic nitrogen fixation, particularly in chickpea, mungbean, and field pea cultivated in irrigated and coastal ecosystems (Munns and Tester 2008; Hasanuzzaman *et al.* 2021).

Flooding and waterlogging

Waterlogging causes root-zone hypoxia, ethylene accumulation, and reduced nodulation, severely affecting mungbean, pigeonpea and urdbean productivity (Sairam *et al.* 2009).

MORPHOLOGICAL AND PHENOLOGICAL ADAPTATION STRATEGIES

Deep and plastic root systems, early flowering, and canopy modifications contribute significantly to stress avoidance and escape in pulses (Blum 2011).

Root system architecture

Chickpea and pigeonpea possess deep taproot systems that enhance access to subsoil moisture under terminal drought (Kashiwagi *et al.* 2015).

Phenological adjustment

Early maturity and short-duration growth habits in mungbean and urdbean enable escape from terminal drought and heat stress (Pratap *et al.* 2021).

Canopy and leaf traits

Reduced leaf area, erect leaves, and waxy cuticles lower transpiration losses and canopy temperature under heat stress (Reynolds *et al.* 2017).

IMPACT OF HEAT STRESS ON PLANTS

Physiological Effects

High temperature stress negatively impacts several major physiological processes:

Photosynthesis

High temperature alters chloroplast structure, disrupts photosystem II activity, and declines chlorophyll content, leading to reduced CO_2 assimilation and net photosynthesis rates. Severe heat can inhibit enzyme activities crucial for carbon fixation and ATP production. Photosynthesis is among the most heat-sensitive physiological processes. High temperature stress disrupts chloroplast ultrastructure, reduces chlorophyll content, and impairs photosystem II (PSII) activity. The oxygen-evolving complex of PSII is particularly vulnerable, leading to reduced electron transport efficiency and photoinhibition.Rubisco activase, a key enzyme regulating carbon fixation, is highly heat-labile. Heat-induced inactivation of Rubisco activase limits CO_2 assimilation even when Rubisco itself remains functional. Concurrently, respiration rates increase under heat stress, resulting in a negative carbon balance and reduced growth efficiency.

Respiration and water relations

Heat stress can increase plant respiration rates, exacerbate water loss via transpiration, and cause stomatal closure that further limits CO_2 uptake.

Growth and development

Heat stress significantly affects plant growth and developmental processes. Elevated temperatures accelerate phenological development, leading to shortened vegetative and reproductive phases. While rapid development may help plants escape stress, it often compromises biomass accumulation and yield formation. High temperatures reduce leaf area, inhibit root growth, and accelerate leaf senescence, ultimately limiting photosynthetic capacity. Seed germination and seedling establishment are also highly sensitive to heat stress. High temperatures impair enzymatic activities involved in starch mobilization, reduce seed vigour, and increase seedling mortality. In perennial and annual crops alike, prolonged heat exposure reduces plant stature and alters source–sink relationships. High temperatures reduce root and shoot growth, inhibit seed germination, shorten phenological stages like grain filling, and can lead to leaf scorching and senescence.

Reproductive failure

The reproductive phase is the most heat-sensitive stage in most crop species. Heat stress during flowering causes pollen sterility, reduced pollen viability, impaired anther dehiscence, and abnormal stigma receptivity. In cereals, high temperature during anthesis and grain filling reduces grain number, grain weight, and overall yield. In legumes and oilseed crops, heat stress disrupts ovule fertilization and pod development, leading to flower drop and poor seed set. These reproductive failures are the primary contributors to yield losses under heat stress conditions. Heat stress impairs pollen viability, pollen tube growth, fertilization, and seed set, often resulting in significant declines in crop yield.

Cellular and metabolic disturbances

At the cellular level, heat stress causes protein denaturation, enzyme inactivation, and membrane destabilization. Increased membrane fluidity leads to electrolyte leakage and loss of compartmentalization. Metabolically, heat stress alters carbohydrate partitioning, nitrogen metabolism, and lipid composition, further impairing plant performance.

Biochemical Disruptions

Heat stress induces cellular damage through:

Protein denaturation and aggregation

Elevated temperatures cause unfolding or misfolding of proteins, adversely affecting enzyme function and metabolic processes.

Membrane instability

Heat alters membrane fluidity, increases electrolyte leakage, and disrupts transport functions across the plasma membrane.

Reactive oxygen species (ROS) accumulation

Heat triggers excessive ROS (e.g., hydrogen peroxide, superoxide radicals), leading to lipid peroxidation, protein oxidation, and DNA damage when production overwhelms detoxification systems.

PHYSIOLOGICAL ADAPTATION MECHANISMS

Stomatal regulation and water use efficiency

Improved stomatal sensitivity and higher intrinsic water use efficiency help maintain photosynthesis under water-limited conditions (Condon *et al.* 2004).

Photosynthetic stability

Heat- and drought-tolerant pulse genotypes maintain chlorophyll content, PSII efficiency (Fv/Fm), and RuBisCO/RuBP activase activity (Crafts-Brandner and Salvucci 2000; Kumar *et al.* 2022).

Osmotic adjustment

Active accumulation of compatible solutes such as proline, glycine betaine, trehalose, and soluble sugars under drought, salinity, and heat stress maintains cellular turgor (Ashraf and Foolad 2007), enabling plants to delay senescence.

OXIDATIVE STRESS MANAGEMENT AND BIOCHEMICAL ADAPTATION

Abiotic stresses enhance the generation of reactive oxygen species (ROS), including superoxide radicals, hydrogen peroxide, and hydroxyl ions, leading to oxidative damage if not efficiently scavenged (Mittler 2017).

Antioxidant enzyme system

Stress-tolerant pulse genotypes exhibit higher activities of superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), glutathione reductase (GR), and peroxidases, ensuring redox homeostasis (Hasanuzzaman *et al.* 2020; Kumar *et al.* 2021).

Non-enzymatic antioxidants

Ascorbate, glutathione, carotenoids, flavonoids, and tocopherols play critical roles in ROS detoxification and membrane protection (Gill and Tuteja 2010).

MOLECULAR, HORMONAL, AND MAPK SIGNALING PATHWAYS

Stress perception activates calcium influx, ROS signaling, and mitogen-activated protein kinase (MAPK) cascades, resulting in transcriptional reprogramming (Zhang *et al.* 2018). Abscisic acid regulates drought-induced stomatal closure, while salicylic acid and jasmonic acid modulate antioxidant defense and stress tolerance; strigolactones influence root architecture and drought adaptation (Fahad *et al.* 2015; Visentin *et al.* 2020).

Heat shock proteins (HSP70, HSP90), late embryogenesis abundant (LEA) proteins, and dehydrins act as molecular chaperones stabilizing proteins and membranes under stress (Vierling 1991; Battaglia *et al.* 2008).

GENETIC AND OMICS-BASED ADAPTATION STRATEGIES

Conventional and physiological breeding

Selection based on yield stability, root traits, canopy temperature depression, and stress indices has resulted in climate-resilient pulse cultivars (Blum 2011; ICAR 2023).

Molecular breeding and genomics

QTLs for drought, heat tolerance, and water use efficiency have been identified in chickpea, cowpea, and mungbean, enabling marker-assisted and genomic selection (Varshney *et al.* 2021; Kudapa *et al.* 2022).

Omics and genome editing

Transcriptomics, proteomics, metabolomics, and CRISPR/Cas-based genome editing provide powerful tools for dissecting and improving stress tolerance in pulses (Chen *et al.* 2019; Jaganathan *et al.* 2020).

AGRONOMIC AND CLIMATE-SMART ADAPTATION STRATEGIES

Crop diversification and intercropping

Intercropping systems such as pigeonpea–sorghum enhance system productivity and resilience under variable climates (Lithourgidis *et al.* 2011).

Soil and water management

Mulching, conservation tillage, ridge–furrow planting, and rainwater harvesting improve soil moisture conservation and pulse productivity under drought (Hobbs *et al.* 2008).

Seed priming and biostimulants

Hydropriming, osmopriming, and biopriming with beneficial microbes enhance seedling vigor and stress tolerance (Paparella *et al.* 2015).

Digital and Decision-Support Tools

Climate forecasting, ICT-based advisories, and precision nutrient management support adaptive pulse cultivation.

Crop-Specific Adaptation Strategies in Major Pulses

Chickpea (Cicer arietinum L.)

Deep rooting, early maturity, reproductive heat tolerance, and strong antioxidant capacity.

Pigeonpea (Cajanus cajan L.)

Perennial growth habit, drought resilience, and adaptability to intercropping systems.

Lentil (Lens culinaris Medik.)

Cold tolerance at early stages and improved heat tolerance at flowering.

Mungbean and Urdbean (Vigna radiata & V. mungo)

Short duration, rapid phenology, and suitability for stress escape.

Cowpea (Vigna unguiculata L.)

Exceptional tolerance to heat and drought with efficient stomatal control.

Table 1. Summarizes major climatic stresses and corresponding adaptation strategies in important pulse crops

Pulse crop	Major climatic stress	Key adaptation traits
Chickpea	Drought, heat	Deep roots, early maturity, strong antioxidant system
Pigeonpea	Drought, heat	Perennial habit, deep rooting, intercropping adaptability
Lentil	Cold, heat	Cold tolerance, reproductive heat tolerance
Mungbean	Drought, heat	Short duration, rapid phenology
Urdbean	Waterlogging, heat	Stress escape, improved nodulation
Cowpea	Heat, drought	Efficient stomatal control, high WUE

CONCEPTUAL FRAMEWORK OF CLIMATE ADAPTATION IN PULSE CROPS

Figure 1 presents an integrated conceptual model illustrating how pulse crops perceive climatic stresses and deploy multi-level adaptation mechanisms. Climatic drivers such as drought, heat, cold, salinity, and flooding act as primary stress signals. These stresses trigger early perception mechanisms, including membrane perturbation, calcium influx, and reactive oxygen species (ROS) bursts, which activate downstream signalling pathways such as mitogen-activated protein kinase (MAPK) cascades and hormonal networks involving abscisic acid, salicylic acid, jasmonic acid, and strigolactones. At the molecular level, stress signalling induces transcriptional reprogramming and synthesis of protective proteins including heat shock proteins, late embryogenesis abundant proteins, and dehydrins. Physiological responses such as stomatal regulation, osmotic adjustment, antioxidant activation, and maintenance of photosynthetic efficiency collectively reduce cellular damage. Morphological and phenological traits, including deep root systems, altered canopy architecture, and stress escape through early maturity, further enhance adaptation. Integration of these plant-level mechanisms with genetic improvement and climate-smart agronomic practices ultimately leads to improved resilience, yield stability, and sustainability of pulse-based cropping systems under climate change.

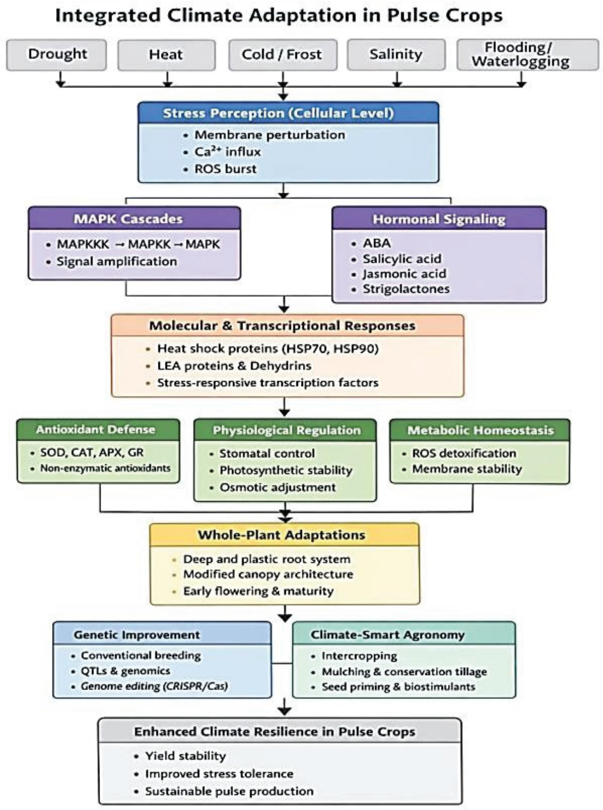

Fig. 1. Diagrammatic representation of an integrated conceptual model illustrating how pulse crops perceive climatic stresses and deploy multi-level adaptation mechanisms

Integrated Climate-Smart Adaptation Approaches

Integration of genetic, agronomic, and technological interventions, supported by climate forecasting and decision-support systems, is essential for sustainable pulse production under changing climates.

Indian Agro-Climatic Perspective and ICAR Initiatives

India's pulses are cultivated across arid (Rajasthan), semi-arid (Deccan Plateau), sub-humid (Indo-Gangetic plains), and coastal ecosystems. ICAR-led programs have developed climate-resilient pulse varieties, promoted integrated nutrient and water management, and supported farmer-participatory breeding under the National Food Security Mission and NICRA projects.

FUTURE PERSPECTIVES AND RESEARCH NEEDS

Future research should focus on multi-stress tolerance, exploitation of wild relatives, high-throughput phenomics, systems biology, integration of genomics with climate modeling and farmer-participatory breeding to enhance climate resilience in pulses.

CONCLUSION

Adaptation of major pulse crops to diverse climatic conditions requires a holistic understanding of plant responses at multiple levels. Combining physiological and molecular insights with breeding and agronomic innovations will be key to sustaining pulse productivity under climate change. Enhancing climate resilience in pulse crops requires an integrated approach combining physiological understanding, molecular breeding, and climate-smart agronomy. Such holistic strategies are essential for sustaining pulse productivity and nutritional security under changing climatic conditions.

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