Climate Change and Pulses: Impacts, Adaptation Mechanisms, and Resilience Strategies

Abstract

Climate change poses a significant threat to pulse crops across various agroecological zones. Rising temperatures, erratic rainfall, and extreme events reduce yield stability and quality. Elevated carbon dioxide alters physiology but does not offset heat and drought stress. Salinity and waterlogging issues are expanding in coastal and irrigated zones. Pests and diseases shift ranges and intensities. This article synthesisesthe impacts across major pulses, including chickpea, pigeonpea, lentil, black gram, green gram, cowpea, and common bean. It reviews physiological responses, yield effects, and nutritional consequences. It then details adaptation options from gene to field to policy. The article uses case studies and data to illustrate practical pathways. It concludes with a discussion of research gaps and a policy roadmap to safeguard productivity, livelihoods, and dietary protein.

Keywords: Pulses, Climate risk, Heat and drought tolerance, Breeding and seed systems Climate services

1. Introduction

Pulses are central to food and nutritional security. They provide 20–25 percent protein, essential amino acids such as lysine, dietary fibre, and micronutrients including iron, zinc, and folate. (1,2)They are cultivated on about 90 million hectares globally, contributing around 95 million tonnes annually according to FAO 2023 statistics. India, Canada, Myanmar, China, Brazil, and several African nations are leading producers. In many countries, pulses are the cheapest source of protein for low-income populations. (2,3)

Pulses also play a critical role in sustainable agriculture. They fix atmospheric nitrogen through symbiosis with rhizobia, thereby reducing fertiliser use and improving soil health.(3,4) They enhance crop rotations, break pest and disease cycles, and reduce greenhouse gas emissions when compared with cereal-only systems. Their cultivation supports biodiversity in agroecosystems and provides resilience to smallholder farmers who often operate in marginal lands. (4,5)

However, pulses are highly sensitive to climate stress. They are primarily grown in rainfed systems, where exposure to climate variability is high. Short growing seasons and reproductive sensitivity to heat make them vulnerable. In India, more than 85 percent of pulse production is rainfed, and yield fluctuations strongly correlate with rainfall variability. Global projections indicate that by 2050, average growing season temperature will rise by 1.5–2.0 °C in major pulse zones, with more frequent extremes. (6,7)

Climate change, therefore, poses a dual risk: reduced and unstable yields, as well as erosion of nutritional quality. At the same time, demand for pulses is projected to increase due to population growth, dietary diversification, and promotion of plant-based protein. Meeting this demand under a changing climate requires urgent scientific, agronomic, and policy interventions. (3,9)

This article reviews the impact of climate change on pulses with an emphasis on physiological responses, yield impacts, and quality outcomes. It examines adaptation mechanisms at the field and genetic levels, resilience strategies for farmers, and enabling policies. Case studies from Asia, Africa, and Latin America are used to illustrate practical approaches. The goal is to provide an integrated framework that links climate risks to concrete pathways of adaptation and resilience. (3,11)

2. Global importance of pulses and production patterns

Pulses are vital to global food systems. They account for nearly seven percent of total legume production worldwide when soybean is excluded. According to FAO estimates for 2023, they occupy between 92 and 94 million hectares and contribute approximately 95 million tonnes of grain each year. (10,11) Cultivation is spread across more than 170 countries, but unlike cereals, pulses are concentrated in semi-arid and marginal regions where input levels are low. This characteristic makes them central to sustainable farming and to low-carbon agriculture. Their role in nitrogen fixation is vital. On average, pulses fix between 30 and 200 kilograms of nitrogen per hectare annually, depending on the crop and soil type. This reduces dependence on synthetic fertilisers, lowers greenhouse gas emissions, and enhances soil fertility for succeeding crops. (12,13)

Production is not evenly distributed across regions. South Asia dominates the global pulse area, with India alone contributing between one-quarter and one-third of global output. Chickpea, pigeon pea, lentil, black gram, and green gram are the most important crops in this region. Sub-Saharan Africa accounts for around one-fifth of total production, primarily through cowpeas and common beans, with Nigeria, Tanzania, and Uganda as the leading producers. (14,15) Latin America contributes between twelve and fifteen percent, where Brazil and Mexico lead in common bean and dry bean varieties. Canada and the United States are major exporters of lentils, dry peas, and chickpeas, with Canada being the largest supplier of lentils to South Asia and the Middle East. Mediterranean and West Asian countries, such as Turkey, Iran, and Syria, produce chickpeas and lentils under winter rainfall conditions and serve as key suppliers to regional markets. (16,17)

Pulses are integral to cereal-based systems. In South Asia, chickpeas are commonly planted after rice or wheat, utilising residual soil moisture. In Africa, cowpea is often intercropped with sorghum and millet. In Latin America, beans are rotated with maize or cassava. In developed systems, lentils and peas are usually integrated into wheat and barley rotations. These practices maintain soil fertility, reduce pest and disease build-up, and enhance the resilience of farming systems. However, they also remain susceptible to rainfall onset, withdrawal, and winter temperatures. Delays in monsoon or irregular winter rains often shorten sowing windows and reduce yield potential. (18,19)

Global production of pulses has grown by nearly seventy percent since the 1990s, but consumption demand has increased even faster. South Asia records the highest per capita consumption, at approximately 20 to 25 kilograms per person per year, compared to the global average of 7 to 8 kilograms. Urbanisation and income growth are driving demand for higher-quality lentil, chickpea, and beans in emerging markets. International trade in pulses has expanded accordingly. India alone imports between four and six million tonnes annually to cover deficits, while Canada, Australia, Myanmar, and Tanzania are among the largest exporters. This interdependence has transformed pulses into a global commodity. As a result, climate-related production shocks in one region often lead to rapid price volatility in international markets.(20,21)

Production systems remain vulnerable. A majority of pulse cultivation relies on rainfed conditions, which exposes farmers to rainfall variability and seasonal drought. Many crops are grown on marginal soils with low fertility and poor water-holding capacity. Smallholder systems dominate, often with limited irrigation facilities and low access to modern technology. Moreover, reproductive stages of pulses are susceptible to heat and drought, which magnifies yield variability. Yield gaps between on-station potential and on-farm performance remain wide. For example, chickpea yields in India average 1.1 to 1.3 tonnes per hectare, whereas research stations achieve 2.5 to 3.0 tonnes under best management. Similar gaps are reported for lentils, pigeon peas, and cowpeas. Climate variability is one of the primary reasons why this potential remains unrealised. (22,23)

3. Climate hazards that affect pulses

Climate change exposes pulse crops to multiple hazards that interact across time and space. The most significant include heat stress, drought, erratic rainfall, excess water and flooding, salinity, elevated carbon dioxide, pests and diseases, and extreme weather events. Each hazard influences physiology, yield, and quality in specific ways, and their combined effects are often more damaging than the effects of individual stresses. (7,19)

Heat stress is one of the most critical hazards. Pulses are highly sensitive to temperatures above 30 to 35 °C during flowering and pod filling. At these thresholds, pollen viability declines, flower drop increases, and successful fertilisation is reduced. Even short episodes of high temperature during the reproductive phase can cause significant yield losses. Night temperatures that remain elevated further intensify stress because they increase respiration and reduce the availability of net carbohydrates. Studies in chickpea-growing areas of central India have shown that heat waves in late February can reduce yields by up to 30 percent compared with regular seasons. Similar patterns have been observed in common bean production in Central America, where flowering coincides with peak seasonal heat. (22,23)

Drought and erratic rainfall represent another major challenge. Soil moisture deficits during vegetative stages reduce root development and canopy expansion, while deficits during flowering and pod filling are particularly damaging. When dry spells coincide with reproductive stages, yield losses can exceed 40 percent. The irregular distribution of rainfall within a season is equally important. In East Africa, common bean crops often face alternating periods of drought and intense rainfall, creating stop-start growth cycles that reduce harvest index and seed uniformity. In India, the shortening of the rabi season has increased the frequency of terminal drought in chickpea and lentil. (24,25)

Excess rainfall and waterlogging are emerging hazards, particularly in regions exposed to extreme rainfall events. Many pulses are highly susceptible to oxygen deficits in the root zone. Waterlogging damages nodules, reduces nitrogen fixation, and creates conditions conducive to fungal diseases. In the coastal districts of Bangladesh and Myanmar, pigeon pea and green gram face recurrent inundation, leading to partial or complete crop loss. Heavy rainfall also delays harvesting operations and increases post-harvest spoilage, particularly when drying infrastructure is limited. (26,27)

Salinity and sodicity are growing concerns in irrigated and coastal zones. Sea-level rise and tidal ingress are expanding saline soils in South Asia, while the use of poor-quality groundwater is increasing salinity in arid regions. Pulses are generally less tolerant than cereals to salinity. Germination and early seedling growth are particularly sensitive. Lentil and chickpea often show poor emergence and reduced nodulation in saline soils. Ion toxicity, osmotic imbalance, and membrane damage lead to reduced vigour. In western India, farmers in Gujarat and Rajasthan report yield declines of 20 to 40 per cent in chickpea and mung bean, where irrigation water salinity has increased. (11,12)

Elevated carbon dioxide can have both positive and negative consequences. As C3 plants, pulses can exhibit enhanced photosynthesis under higher carbon dioxide concentrations, which, in theory, may increase biomass and yield. However, the beneficial effect is often offset by concurrent stresses, such as high temperatures, drought, or nutrient limitations. Moreover, elevated carbon dioxide can reduce protein concentration in grains, leading to nutritional dilution. Experimental studies with lentils and chickpeas have shown yield gains under elevated CO2 in controlled environments; however, these benefits largely disappear under field conditions when combined with heat stress. (17,21)

Pests, diseases, and weeds are strongly influenced by climate change. Rising temperature and humidity alter pest lifecycles and geographic ranges. Pod borers, such as Helicoverpa armigera, are expanding into new areas and exhibiting higher population densities. Aphids, whiteflies, and bruchids reproduce faster at warmer temperatures, increasing pressure on pulse crops. Pathogens, including *Fusarium oxysporum*, *Ascochyta rabiei*, rusts, and anthracnose, are reported to intensify under altered rainfall patterns. Warmer winters in India have increased the incidence of chickpea botrytis grey mould. Elevated carbon dioxide and temperature also stimulate weed growth, often giving a competitive advantage to aggressive invasive species that reduce crop yield. (24,25)

Extreme weather events, including floods, hailstorms, cyclones, frost, and high winds, cause direct physical damage. Cyclone events in coastal Andhra Pradesh and Odisha have destroyed standing crops of pigeon pea in recent years. Frost events in West Asia damage lentils during early growth stages, while sudden heatwaves in late spring reduce yields in Mediterranean chickpeas. Compound stresses, such as heat combined with drought, are becoming increasingly common and can devastate crops within days. These compound events are challenging to manage because traditional adaptation measures usually address single hazards. (26,27)

The overall effect of these hazards is an increase in production risk and yield variability. Farmers face higher uncertainty in planning sowing dates, variety choices, and input use. Regional production shocks transmit quickly to markets, creating price volatility and threatening household food security. The following section will examine in detail how pulses respond at physiological and molecular levels when exposed to these stresses. (28,29)

4. Crop physiology and molecular responses

The response of pulses to climate stress is mediated through a set of physiological, biochemical, and molecular mechanisms. These determine how plants grow, reproduce, and allocate resources under stress. Understanding these responses is critical for developing adaptation strategies through breeding, agronomy, and biotechnology. (21,24)

Phenological development is susceptible to climate variability. Rising temperatures accelerate the rates of leaf emergence, floral initiation, and pod development. As a result, the duration of vegetative and reproductive phases becomes shorter. Shortened growth periods reduce biomass accumulation and lower the supply of assimilates available for seed filling. In chickpea and lentil, warm winters have been shown to reduce the length of the flowering-to-maturity phase by more than 15 per cent compared with cooler seasons. Drought also accelerates senescence, forcing plants to complete their cycle more quickly, which often compromises seed size and yield stability. (22,23)

Reproductive biology is especially vulnerable. Successful yield formation in pulses depends on viable pollen, receptive stigmas, and adequate fertilization. Heat stress damages pollen grains, reduces viability, and weakens pollen tube growth. In pigeon pea, studies in central India have shown a significant reduction in pod set when daytime temperatures exceeded 35 °C during flowering. Drought amplifies this effect by desiccating floral tissues, leading to flower abortion. Combined heat and drought stress is particularly destructive, often reducing pod set by half compared with normal conditions. (23,24)

Photosynthetic processes are also disrupted. High temperatures reduce the efficiency of Rubisco, the enzyme responsible for carbon fixation, and increase the rate of photorespiration. This lowers net photosynthesis and carbon gain. Drought induces stomatal closure, which restricts CO_2 uptake and raises leaf temperature. Elevated vapour pressure deficit further accelerates water loss, creating a feedback loop that intensifies stress. The balance between photosynthesis and respiration becomes unfavourable, leaving less energy for reproductive development. (25,26)

Nitrogen fixation is a defining feature of pulses, but it is susceptible to environmental stress. Rhizobia infection and nodule formation require adequate soil moisture and moderate temperatures. Drought reduces root infection and decreases the number and size of nodules. Waterlogging creates hypoxic conditions that kill nodules and impair nitrogenase activity. High soil temperature destabilisesleghemoglobin, a protein critical for oxygen regulation inside nodules, thereby reducing nitrogen fixation efficiency. Salinity suppresses both infection and the function of nodules. These effects limit the supply of fixed nitrogen, minimise protein synthesis, and directly lower yield. (26,27)

Pulses do possess biochemical mechanisms that help mitigate stress. One common mechanism is osmotic adjustment, where plants accumulate solutes such as proline, glycine betaine, sugars, and polyols. These molecules stabilise proteins and membranes, protect enzymatic activity, and maintain cell turgor. Antioxidant defence is another mechanism. Enzymes such as superoxide dismutase, catalase, and peroxidase scavenge reactive oxygen species generated under heat, drought, and salinity. In tolerant genotypes of cowpea and mung bean, antioxidant activity is often higher, reducing oxidative damage to membranes and chloroplasts. (28,29)

Root system architecture strongly influences resilience. Deep taproots with lateral branching enable access to water in deeper soil layers. Fine roots increase surface area for nutrient uptake. Some genotypes develop aerenchyma tissues that improve tolerance to temporary waterlogging by enhancing oxygen diffusion. Root plasticity enables adaptation to varying soil conditions; however, significant genetic variation exists, which can be harnessed through breeding. For example, chickpea lines with deeper rooting have shown superior performance under terminal drought in the semi-arid tropics.(3031)

At the molecular level, stress tolerance involves regulatory proteins and signalling pathways. Heat shock proteins act as molecular chaperones, stabilising proteins and membranes under heat stress. Transcription factors, such as DREB, NAC, and bZIP, regulate networks of stress-responsive genes, including those involved in osmotic adjustment, antioxidant activity, and late embryogenesis abundant (LEA) proteins. Abscisic acid signalling plays a central role in drought response by inducing stomatal closure and regulating stress memory. Quantitative trait loci for traits such as stay-green, pod filling duration, canopy temperature depression, and membrane stability have been identified in chickpea, lentil, and cowpea. Advances in genomics, including CRISPR-Cas9 editing and allele mining in germplasm collections, are providing opportunities for targeted improvement in these regulatory pathways. (32,33)

The interaction of these physiological and molecular responses determines the resilience of pulse crops under climate stress. While individual mechanisms provide partial tolerance, it is the combination of traits such as deeper roots, osmotic adjustment, efficient antioxidant systems, and stable reproductive biology that offers robust adaptation. The following section will examine how these processes translate into impacts on yield, quality, and nutritional outcomes. (29,33)

5. Yield, quality, and nutritional impacts

The impacts of climate change on pulses become most visible in their yield, stability, and nutritional outcomes. The combination of shortened phenological phases, impaired reproductive processes, disrupted photosynthesis, and reduced nitrogen fixation translates into lower harvestable output. In addition to quantitative yield losses, there are also qualitative impacts on grain size, protein concentration, micronutrient content, and storability. (34,35)

Yield is determined by the number of reproductive nodes, the number of pods per plant, the number of seeds per pod, and the seed weight. Climate stress can disrupt each of these components. Heat stress during flowering reduces the number of pods set, while terminal drought shrinks seed size and lowers test weight. (32,33) In chickpea, experiments in central and northern India have shown that exposure to temperatures above 33 °C during flowering can reduce pod set by 20 to 30 percent. Pigeon pea often loses seed size when late-season drought accelerates maturity, resulting in shrivelled grains. Lentil and common bean are highly sensitive to flower abortion under combined heat and drought stress, leading to drastic reductions in pod number. These effects are stage-specific and often occur within short windows of vulnerability. (34,35)

Yield variability has increased across major production regions. In India, where more than 80 percent of pulses are cultivated under rainfed conditions, inter-annual yield variance has widened in the past three decades. Crops such as black gram and green gram, which rely on short growing seasons, are particularly susceptible to variations in rainfall distribution. In

East Africa, typical bean yields fluctuate sharply from year to year due to the alternating occurrence of droughts and floods during the bimodal rainy seasons. This variability translates into greater production risk for farmers and increased price volatility in markets. For consumers, particularly low-income households that rely on pulses for protein, this creates nutritional insecurity. (36,37)

Grain quality is also compromised under climate stress. Heat and drought reduce seed size uniformity, leading to a higher proportion of undersized grains. Market preference in both domestic and international trade favours large, uniform grains, meaning farmers face reduced prices in years of stress. Protein concentration is affected by both elevated carbon dioxide and nitrogen fixation failures. (32,33) Elevated CO_2 often increases carbohydrate accumulation but dilutes protein content. In trials conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), chickpea and pigeon pea grown under elevated CO_2 showed higher biomass but reduced seed protein by 5 to 10 percent. Micronutrient concentration, particularly iron and zinc, also declines under stress. Lentil samples from South Asia and West Asia subjected to high temperature during seed filling recorded lower zinc concentrations compared with crops grown under normal conditions. (34,35)

Nutritional implications extend to household diets. In regions such as South Asia, pulses are the primary source of protein for low-income groups. Declines in both yield and quality directly reduce dietary protein availability. Rising prices compound the problem during years of climate-induced production shortfalls. This undermines efforts to combat malnutrition and micronutrient deficiencies, often referred to as “hidden hunger.” (37,38)

Post-harvest losses further reduce availability. Unseasonal rainfall during harvest increases seed discolouration, sprouting, and fungal infection. Storage pests such as bruchids reproduce more rapidly at higher temperatures. In poorly ventilated storage facilities, higher ambient humidity accelerates fungal growth and aflatoxin contamination. Losses in storage can range from 10 to 20 percent in tropical climates, which represents a significant share of household food supply and marketable surplus. (39,40)

The combined effect of reduced yield, increased variability, lower quality, and higher post-harvest losses threatens both economic returns to farmers and food and nutritional security for consumers. The following section will examine how these impacts vary across regions and provide specific case studies to illustrate vulnerability in different production systems. (41,42)

6. Regional exposure and case studies

The vulnerability of pulses to climate change is not uniform. Each region faces a distinct set of hazards shaped by its agroecological conditions, dominant crops, and production practices. Case studies from South Asia, Africa, West Asia and the Mediterranean, Latin America, and dryland environments illustrate how climate variability and extremes lead to yield losses, food insecurity, and market instability. (43,44)

In South Asia, chickpea and pigeon pea are among the most widely grown pulses. Chickpea is typically cultivated in the post-rainy season on residual soil moisture. Warmer winters have advanced crop phenology and increased the frequency of terminal heat episodes. (45,46) Even brief heat spells during flowering have caused localised yield reductions of up to 30 per cent in northern and central India. (47,48) The problem is particularly acute for Kabuli chickpea, which requires cooler conditions and a longer growing period. Although heat-tolerant desi lines have been introduced, adoption remains uneven due to limited seed availability and farmer preference for grain size and colour. Pigeon peas in coastal belts are exposed to cyclonic storms and heavy rainfall, while crops in rain-fed interiors face terminal drought. In Andhra Pradesh, Cyclone Hudhud in 2014 destroyed large tracts of pigeon pea, while in Maharashtra, recurrent droughts have led to harvest failures. Farmers in some districts are shifting to medium-duration varieties to avoid late-season stress, but yield stability remains a challenge. (49,50)

In East Africa, common bean and cowpea are staple pulses. The bimodal rainfall pattern provides two cropping seasons, but irregularity has become a significant problem. Short rains often fail or end abruptly, leaving beans exposed to mid-season drought. Long rains sometimes bring excessive moisture and flooding. In northern Tanzania, drought during flowering reduced typical bean yields by more than half in 2019. Meanwhile, in Uganda, heavy rainfall in 2020 led to severe waterlogging and outbreaks of root rot. Cowpea, which is more drought-tolerant, offers some buffer, but yields remain low under traditional management. The spread of bruchids in warmer storage conditions adds to post-harvest losses. Improved drought-tolerant bean lines and integrated pest management have stabilised yields in some pilot projects, yet adoption at scale is constrained by input access and weak extension systems. (51,52)

In the Mediterranean and West Asia, lentil and chickpea are major winter pulses. These crops depend on reliable winter rains and moderate spring temperatures. Climate change has introduced both early-season cold spells and late-spring heatwaves. In Turkey and Syria, early frosts followed by sudden warming have damaged lentil crops, while in Iran, chickpea often experiences flowering during periods of high temperature, leading to reduced pod set. Supplemental irrigation has reduced risk in irrigated pockets, but water availability is declining due to competing demands from cereals and horticulture. Farmers in some areas respond by advancing sowing dates, but this strategy sometimes increases exposure to early frost. (47,48)

In Latin America, the common bean is the dominant pulse crop. Beans are often planted in lowland areas where high temperatures during flowering are increasingly problematic. In Brazil, average day temperatures above 32 °C have been shown to cause yield collapse in sensitive cultivars. Shifts in humidity and rainfall also intensify disease complexes. Rust, anthracnose, and angular leaf spot are more aggressive in wetter years. Breeding programs in Brazil and Mexico have produced heat-tolerant lines that maintain pod set under stress, but dissemination across smallholder systems is limited by seed availability and market networks. (49,50)

Dryland and marginal zones present distinct sets of challenges. In arid regions of South Asia, the Middle East, and sub-Saharan Africa, salinity and sodicity are expanding due to rising groundwater tables and the use of low-quality irrigation water. Chickpea and lentil are particularly sensitive in their early growth stages. In Gujarat, India, farmers irrigating chickpea with saline groundwater have reported yield declines of 20 to 40 percent. In coastal Bangladesh, green gram and lentils face recurrent tidal surges that leave saline residues on the soil, reducing germination and nodulation. Adaptation through improved drainage and the use of salt-tolerant genotypes is still in its early stages. (47,48)

Across all these regions, a typical pattern emerges. Climate change is amplifying production risks through heat, drought, excess rainfall, salinity, and pest pressure. Farmers often have limited capacity to adapt, especially where extension services, credit, and seed systems are weak. The diversity of hazards across regions highlights the need for locally tailored strategies. The following section will examine field-level adaptation options, agronomic practices, and soil management approaches that can enhance resilience under these conditions. (49,50)

7. Field level adaptation, agronomy, and soil health

Field-level adaptation represents the first line of defence against climate risks in pulse production. Agronomic interventions, soil health management, and cropping system innovations can reduce vulnerability and stabilise yields even under variable conditions. These measures often require modest investment compared with breeding or biotechnology, making them particularly relevant for smallholder systems. (51,52)

Choice of variety and crop is fundamental. Farmers are increasingly selecting cultivars with early or medium duration to avoid terminal stress. In regions where late-season heat is common, short-duration chickpea and lentil varieties enable crops to complete their life cycle before temperatures rise sharply. Similarly, medium-duration pigeon pea varieties reduce exposure to cyclones in coastal regions and drought in interior drylands. The availability of stress-tolerant cultivars, however, depends on strong seed systems and timely distribution. In areas where such varieties are available, farmers have reported yield stabilisation despite unfavourable weather conditions. (53,54)

Adjustment of sowing windows is another key adaptation. By advancing planting dates, farmers can avoid terminal heat in winter pulses or synchronise flowering with more favourable moisture conditions. In northern India, chickpeas planted in early November perform better than late-sown crops that flower in February, when temperatures often exceed tolerance thresholds. In East Africa, the timing of bean planting in relation to the onset of bimodal rains is crucial. Early sowing ensures adequate moisture during vegetative growth and reduces the risk of drought during flowering. Staggering planting dates across fields further spreads risk by reducing the likelihood that all crops are exposed to the same stress event. (55,56)

Plant population and geometry also influence stress outcomes. Proper seed rate and spacing help balance canopy closure, light interception, and water use efficiency. Under drought-prone conditions, wider row spacing can reduce competition for soil moisture. In areas with heavy rainfall, paired-row planting enhances infiltration and drainage, thereby reducing the risk of lodging. Optimising plant density allows more efficient use of available resources, especially when combined with stress-tolerant varieties. (57,58)

Soil health management provides another layer of resilience. Retaining crop residues reduces soil evaporation, moderates temperature fluctuations, and improves organic matter. The application of farmyard manure or compost increases soil water-holding capacity and nutrient availability. Biochar has shown promise in improving soil structure and enhancing resilience against both drought and salinity. Balanced nutrition is critical, with potassium, sulphur, zinc, and molybdenum playing essential roles in stress tolerance and nodulation. Deficiencies in these nutrients often limit crop response to favourable conditions. Field trials in central India have demonstrated that potassium application enhances chickpea resilience to terminal drought by improving osmotic adjustment. (59,60)

Conservation agriculture practices strengthen adaptation further. Minimum tillage combined with residue retention reduces erosion, improves infiltration, and conserves soil moisture. Permanent raised beds are effective in areas prone to waterlogging, as they improve drainage and root aeration. Cover crops during fallow periods protect soil from degradation, add organic matter, and suppress weeds. Long-term trials in South Asia have demonstrated that conservation agriculture practices maintain higher soil moisture and support stable yields under erratic rainfall conditions. (61,62)

Intercropping and crop rotation offer both biological and economic benefits. Intercropping pigeon pea with sorghum or millet spreads risk across crops with different stress sensitivities. When one crop fails due to drought or a pest attack, the other may still yield, thereby reducing the total loss. Rotating pulses with cereals or oilseeds improves soil fertility, breaks pest and disease cycles, and enhances system resilience. In East Africa, maize-bean rotations have been demonstrated to increase soil nitrogen levels and enhance subsequent cereal yields, while also broadening household diets. (63,64)

Integrated pest and disease management is necessary as climate change alters the dynamics of pests. The use of resistant varieties, clean seed, and proper crop rotation reduces the baseline risk. Regular monitoring of pest thresholds ensures timely interventions. Biological control agents, where available, reduce reliance on synthetic chemicals. Adjusting sowing dates to avoid peak pest pressure has proven effective in managing pod borer infestations in chickpea. Combined approaches are essential because climate-driven shifts in pest populations can quickly render single measures ineffective. (65,66)

Harvest and post-harvest management close the adaptation cycle. Harvesting at physiological maturity prevents seed shattering and quality deterioration. Timely drying on tarpaulins or raised platforms prevents fungal infection. Hermetic storage technologies, such as triple-layer bags, protect against bruchid infestation without the need for chemical treatments. These interventions can reduce post-harvest losses by up to 50 percent in smallholder systems. (67,68)

Together, these field-level adaptations provide a portfolio of options that farmers can tailor to their local context. The challenge lies in disseminating, adopting, and integrating these practices into farming systems that are already constrained by limited resources. Scaling these measures requires effective extension services, reliable seed systems, and supportive policies. The following section will explore how breeding and genetics can complement agronomy by providing inherent stress resilience in pulse crops. (52,69)

8. Breeding and genetics for climate resilience

Breeding provides one of the most durable strategies for adapting pulses to climate change. Unlike agronomic practices, which are often season-specific and management-dependent, genetic improvement delivers resilience that is embedded in the crop itself. Advances in conventional breeding, molecular genetics, and biotechnology have created new opportunities to develop cultivars that can tolerate heat, drought, salinity, and evolving pressures from pests and diseases. (61,62)

The most damaging stresses define trait priorities. Pod set under heat stress is a critical trait across chickpea, lentil, and common bean. The ability to maintain reproductive success under high temperatures differentiates tolerant lines from susceptible ones. Stay-green characteristics, where plants retain photosynthetic activity during late-season stress, extend the period of carbon assimilation and seed filling. Canopy temperature depression, measured through thermal imaging, reflects a crop’s capacity to cool itself through efficient transpiration, which correlates with drought tolerance. Membrane stability under heat stress and seed filling duration under terminal drought are additional traits linked to yield stability. Root system architecture remains a priority, as deeper and more branched roots enhance access to water and nutrients under both drought and salinity conditions. (63,64)

Conventional and marker-assisted breeding remain the backbone of genetic improvement in pulses. Gene banks hold thousands of accessions of chickpea, pigeon pea, lentil, and beans, including wild relatives that carry valuable stress tolerance traits. For example, *Cicer reticulatum*, the wild progenitor of chickpea, provides alleles for drought tolerance. Marker-assisted backcrossing enables the targeted introgression of such traits while retaining the yield and quality characteristics of elite cultivars. Quantitative trait loci (QTLs) linked to attributes such as drought tolerance and resistance to Fusarium wilt have been successfully deployed in chickpea breeding programs in India. Lentil breeding programs in Canada have utilised marker-assisted selection to incorporate tolerance to Ascochyta blight and rust, both of which are anticipated to intensify under climate change. (65,66)

Genomic selection is expanding the scope of breeding by capturing small-effect loci that contribute to complex stress tolerance traits. By utilising genome-wide markers and statistical models, breeders can accurately predict the performance of lines without the need for extensive field testing. (67,68) This approach accelerates selection cycles and allows simultaneous improvement of multiple traits. Speed breeding, which shortens the generation time under controlled conditions, complements genomic selection by producing more cycles per year. In chickpea, speed breeding has reduced generation time to just three months, enabling up to four cycles annually compared with the traditional one or two. (69,70)

Gene editing offers precise opportunities to enhance resilience. CRISPR-Cas9 tools enable the targeted modification of genes that regulate flowering time, stomatal function, and antioxidant activity. For example, editing genes in the DREB and NAC transcription factor families can improve drought response by regulating downstream stress-responsive genes. Modification of flowering time genes can help synchronise reproductive phases with favourable environmental windows. While regulatory approval and public acceptance of gene-edited crops vary across countries, ongoing research in India, Canada, and Australia is generating proof-of-concept for the use of CRISPR in pulses. (61,62)

Symbiotic nitrogen fixation provides another frontier for breeding. Host genotype and rhizobial strains interact strongly under stress. Some chickpea and lentil genotypes exhibit nodulation under high temperatures and drought, particularly when paired with rhizobial isolates that are tolerant to these conditions. (63,64) Breeding programs are now focusing on co-selection of crop genotype and microbial partners to stabilise nitrogen fixation under variable climates. Research on microbiome consortia suggests that combinations of rhizobia, mycorrhizae, and plant growth-promoting bacteria can collectively enhance stress tolerance. (65,66)

Grain quality under climate stress requires parallel attention. Selection for stable protein concentration and micronutrient content ensures that nutritional value is not compromised by elevated CO_2 or heat. Breeding efforts in lentils and common beans are increasingly integrating biofortification targets, such as higher iron and zinc concentrations, into stress-resilient cultivars. Improvements in seed coat integrity and resistance to mechanical damage reduce storage losses under warmer conditions. (67,68)

The effectiveness of breeding depends on integration with phenotyping and field validation. High-throughput phenotyping platforms now enable rapid measurement of canopy temperature, chlorophyll fluorescence, and spectral indices under field stress. These tools increase accuracy in identifying superior lines. Field testing across multiple environments ensures that selected cultivars perform reliably under diverse climate scenarios. Participatory breeding, where farmers are directly involved in the selection process, improves adoption by ensuring that new varieties meet local preferences for grain type, cooking quality, and market traits. (69,70)

9. Seed systems and farmer adoption

The effectiveness of breeding innovations depends on their delivery to farmers. Seed systems determine how new cultivars move from research institutions to the field. For pulses, this step is often the weakest link in adaptation to climate change. Many promising stress-tolerant varieties fail to achieve scale due to bottlenecks in early-generation seed supply, limited private sector engagement, and inadequate distribution networks. Strengthening seed systems is therefore central to building resilience. (71,72)

Breeder, foundation, and certified seed form the backbone of formal seed systems. Public research institutions, such as the Indian Council of Agricultural Research and the International Centre for Agricultural Research in the Dry Areas, generate breeder seed of improved cultivars. This seed is multiplied into foundation and then certified seed through national agencies and licensed companies. For cereals, this pipeline is relatively strong, but in pulses, it is constrained by limited investment and weaker demand forecasting. Breeder seed availability often lags behind demand, resulting in shortages of new varieties in the first few years after release. (73,74)

Community-based seed systems provide an essential complement. Farmer cooperatives, self-help groups, and local enterprises can produce and distribute high-quality seeds in areas not served by formal markets. Truthfully labelled seed, which adheres to quality protocols without formal certification, provides a practical option in resource-limited regions. In East Africa, community seed banks have proven effective in conserving local bean varieties and distributing stress-tolerant lines developed by national programs. In India, initiatives such as the Seed Village Scheme have enabled farmers to access timely supplies of improved seeds for chickpeas and pigeon peas. These decentralised approaches are essential for reaching remote and smallholder-dominated landscapes. (75,76)

Quality assurance and information are critical for adoption. Farmers require confidence that the seed is true to type, viable, and resilient to stresses as advertised. Germination percentage, seed health, and vigour tests should be made transparent at the point of sale. Packaging must include agronomic recommendations, such as optimal sowing time, plant density, and fertiliser requirements. Inadequate or misleading information undermines trust and slows adoption. Extension systems and digital platforms can strengthen awareness by sharing trial results and farmer testimonials. (77,78)

Access and affordability remain barriers. Many smallholders cannot afford certified seed at market prices. Targeted subsidies or vouchers, particularly in climate-vulnerable areas, can help bridge this gap. Bundling seed with crop insurance, credit, or extension services provides additional incentive and reduces risk perception. Private sector involvement in pulses is limited compared to that in cereals, due to lower profit margins and fragmented markets. Creating clear quality standards, streamlining licensing, and encouraging public–private partnerships can expand the role of private companies in pulse seed supply. (79,80)

The timing of delivery is as important as the quantity. Sowing windows for pulses are short, and delays in seed availability often mean missed opportunities. For example, in the semi-arid tropics of India, the late arrival of seed reduces the chance to sow chickpea on residual moisture, forcing farmers either to plant late or switch to less profitable crops. Digital logistics platforms and decentralised multiplication can reduce such delays. Forecasting seed demand under climate variability, using seasonal climate outlooks, is another emerging approach to ensure timely delivery. (81,82)

Farmer preferences beyond yield influence adoption. Grain size, cooking quality, market demand, and taste powerfully shape decisions. A drought-tolerant chickpea may not be adopted if its seed coat colour does not match local consumer preference. Participatory varietal selection, where farmers evaluate and select varieties during field trials, ensures that new cultivars meet both the needs of resilience and market demand. Evidence from participatory programs in Ethiopia and India indicates higher adoption rates when farmers are directly involved in the selection process. (83,84)

10. Water management, irrigation, and watershed approaches

Water is the single most critical factor determining pulse productivity under climate variability. Pulses are predominantly cultivated in rainfed systems, where rainfall is uncertain and unevenly distributed. Drought, delayed onset of rains, mid-season dry spells, and terminal moisture stress reduce yields. At the other extreme, heavy rainfall and poor drainage can cause waterlogging and lead to disease outbreaks. Effective water management, supported by irrigation and watershed planning, is therefore essential for sustaining pulse production under a changing climate. (85,86)

Supplemental irrigation provides one of the most efficient means of stabilising yields. Even one or two carefully timed irrigations can make the difference between crop failure and success. The reproductive stage, notably flowering and pod filling, is most sensitive to water stress. Field studies in India show that a single irrigation at pod initiation in chickpea increases yield by 20 to 40 percent compared with rainfed conditions. In lentil, irrigation during seed filling has been shown to improve grain weight and protein concentration. Because water is scarce in many pulse-growing areas, low-cost and efficient systems such as drip and sprinkler irrigation are preferred. Drip irrigation, though capital-intensive, reduces water use by up to 40 per cent compared with flood irrigation and improves fertiliser efficiency. Low-pressure sprinklers are suitable for smallholder farmers, as they are inexpensive and adaptable to small plots. (87,88)

On-farm water harvesting is another adaptation. Farm ponds, check dams, and contour bunds capture runoff during heavy rains, storing water for later use. This water can be applied as life-saving irrigation during dry spells. In semi-arid districts of Maharashtra, India, farm ponds have supported chickpea cultivation even during years of poor rainfall. In East Africa, micro-dams and small reservoirs constructed through community initiatives have improved moisture availability for beans and cowpea. (89,90) These interventions are most effective when coupled with efficient irrigation technologies, ensuring that harvested water is used judiciously.Drainage management is equally essential in regions prone to excess rainfall and flooding. Waterlogging damages nodules, reduces nitrogen fixation, and increases root diseases such as Fusarium wilt and collar rot. Raised-bed planting has been effective in lentil and chickpea under heavy clay soils in South Asia. By elevating root zones above standing water, raised beds reduce oxygen stress and improve drainage. (51,55) Similarly, surface drains and field levelling facilitate rapid removal of excess water, minimising crop loss after intense rainfall. In coastal areas vulnerable to tidal ingress, salt-tolerant varieties combined with improved drainage infrastructure have reduced yield losses in mung bean and lentil.Watershed-level planning provides a holistic framework for managing water resources across landscapes. Unlike farm-level measures, watershed approaches integrate soil conservation, water harvesting, and recharge structures to ensure sustained availability of water. Interventions such as contour bunding, vegetative barriers, and percolation tanks enhance groundwater recharge and reduce erosion. These measures benefit not only pulses but also other crops in rotation. For example, integrated watershed management programs in Madhya Pradesh, India, have demonstrated yield gains of 15 to 25 percent in chickpea and pigeon pea, alongside improved cereal productivity. In Ethiopia, watershed projects that combined terracing, water harvesting, and soil fertility management stabilisedtypical bean yields under erratic rainfall. (56,57)

Water efficiency can be further improved through the use of precision tools. Soil moisture sensors and tensiometers guide irrigation scheduling based on field conditions rather than fixed calendars. Remote sensing and satellite data are increasingly used to map soil moisture and predict drought risk. Linking these tools with farmer advisories helps optimise irrigation timing and minimise waste. Community-based irrigation scheduling, where water distribution is coordinated among farmers, reduces conflict and ensures equitable access. (58,59)

Policy support remains crucial. Subsidies for micro-irrigation systems, incentives for rainwater harvesting, and investments in watershed development can significantly expand adoption. Credit schemes tailored to water management infrastructure reduce upfront costs for farmers. Integration of water management with crop insurance ensures that investments are protected against extreme events. At the same time, governance frameworks are needed to prevent overextraction of groundwater, which can create long-term sustainability challenges. (71,72)

11. Research gaps and priorities

Despite progress in understanding climate impacts on pulses, several gaps remain. Reproductive resilience is the most urgent priority. Pod set under combined heat and drought stress is poorly understood, and few cultivars consistently maintain yield under these conditions. High-throughput phenotyping tools are still limited in field environments, especially for root architecture and nodulation traits that determine water and nitrogen use efficiency.The interaction between pulses and their microbiome requires more systematic study. (52,53) Rhizobia performance under high temperature, salinity, and drought varies widely, yet breeding programs rarely integrate host–microbe compatibility. Research on microbial consortia, including mycorrhizae and plant growth-promoting bacteria, has the potential to enhancethe stability of nitrogen fixation under stress.Nutritional quality under elevated carbon dioxide also presents a research frontier. While dilution of protein and micronutrients has been observed, the mechanisms underlying this phenomenon remain unclear. Breeding strategies for stable nutritional traits, combined with biofortification, need targeted investment.Modelling tools must evolve to integrate genetics, management, and climate projections. Multi-model ensembles provide broad scenarios but lack resolution for farm-level decisions. Linking crop models with socioeconomic analysis will improve risk assessment and guide investment in adaptation.Socioeconomic adoption pathways require deeper study. Many stress-tolerant varieties are underutilised because of weak seed systems, mismatched consumer preferences, or gender-based access barriers. Research should investigate how incentives, policies, and extension methods impact the adoption of innovations at scale. (63,64)Finally, risk transfer tools such as index insurance must reduce basis risk through denser weather data and integration with satellite information. Research on financial models that combine insurance, credit, and seed delivery could reduce vulnerability of smallholders in climate-prone zones. (71,78)

Conclusion

Climate change disrupts pulse production through heat stress, erratic rainfall, salinity, and extreme events. Elevated carbon dioxide levels offer limited compensation and often reduce nutritional quality. These stresses increase yield variability and pose a threat to food security.Resilience depends on multiple strategies. At the genetic level, breeding for traits such as stable pod set, deep rooting, and stress tolerance is essential. At the farm level, improved sowing windows, soil health management, intercropping, and conservation practices help stabilise production. Supplemental irrigation, water harvesting, and watershed planning reduce vulnerability to drought and waterlogging. Digital tools, early warnings, and risk transfer mechanisms improve decision-making.Adoption requires robust seed systems, transparent quality assurance, and participatory approaches that align with farmer preferences and market demands. Policies must support micro-irrigation, seed distribution, and market stability while ensuring inclusivity.The path forward lies in integration. Breeding, agronomy, water management, and digital services should be linked into coherent packages tailored to local contexts. With coordinated action across science, extension, and policy, pulses can continue to be reliable sources of protein, micronutrients, and soil fertility in a changing climate.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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