Journal of Food Legumes
39 (Special issue - NC Pulses 2026): 175-188, 2026
DOI: 10.53550/jfl.v39.ncpspl.334

Review Paper

Biotic stress dynamics in legumes under a changing climate

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ABSTRACT

Legumes are fundamental to sustainable agriculture and human nutrition, yet the effects of climate change and biotic stress increasingly threaten their productivity. This review briefly analyses how rising temperatures, elevated CO_2, and altered rainfall patterns reshape the ecology and severity of pests, pathogens, nematodes, and parasitic weeds in legume systems. Details of the physiological and molecular crosstalk between abiotic and biotic stress responses, emphasising defence signalling pathways mediated by phytohormones, such as salicylic acid, jasmonic acid, and ethylene, were discussed. In response to these emerging challenges, the paper evaluates a suite of adaptive management strategies, including advanced genetic, climate-smart agronomic interventions, and AI-driven digital agriculture. By synthesising insights from advances in molecular biology, agronomy, digital innovation, and policy science, this review provides a comprehensive overview for developing climate-resilient legume production systems that can support global food security under escalating environmental variability.

Key words: Legumes, Climate change, Biotic stress, Pest-pathogen dynamics, Stress crosstalk

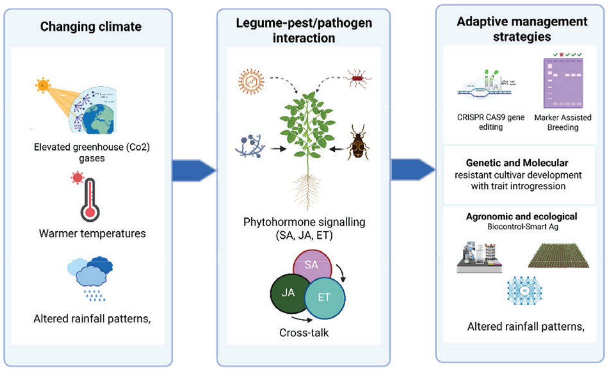

Fig. 1. Impact of climate change on legume–pest/ pathogen interactions and adaptive management strategies

INTRODUCTION

Legumes are indispensable role in global agricultural sustainability and nutritional security, serving as the primary source of plant-based protein, dietary fibre, and essential micronutrients such as iron and zinc for billions. As the global population is projected to exceed 10 billion by 2050, necessitating a 60-100% surge in food supply, legumes have become central to addressing the dual crises of food scarcity and "hidden hunger" (Hunter *et al*. 2017, Foyer *et al*. 2016). Beyond their nutritional density, these crops enhance ecosystem dynamics by fixing atmospheric nitrogen through symbiosis with Rhizobia bacteria and improving soil carbon sequestration (Peoples *et al*. 2009, Jensen *et al*. 2012). However, the stability of legume-based farming systems is currently being undermined by the escalating frequency of anthropogenic climate change. Environmental factors such as rising temperatures, elevated atmospheric CO_2 (eCO2), and erratic rainfall patterns are projected to cause yield reductions of 10–49% by mid-century for critical crops, including soybeans, lentils, and common beans (Daryanto *et al*. 2015, Bishop *et al*. 2015). While historical research has prioritised abiotic constraints like drought and salinity, climate change is now acting as a contemporary catalyst that is fundamentally restructuring the landscape of biotic pressures.

The shifts in global thermal niches are expanding the geographic range of pests and pathogens, introducing unprecedented volatility into production systems. Rising temperatures act as a primary physiological driver for poikilothermic insect pests, such as aphids, whiteflies, and the pod borer (*Helicoverpa armigera*), by shortening their developmental cycles and increasing metabolic rates. This thermal acceleration allows for additional pest generations per season and facilitates the migration of tropical pests into higher latitudes. Simultaneously, eCO2 creates a "nutritional dilution" effect, decreasing nitrogen concentrations in legume tissues and triggering compensatory feeding behaviours in herbivores, leading to greater defoliation and yield loss.

Furthermore, altered precipitation patterns create divergent risks: excessive humidity fuels foliar fungal epidemics like Ascochyta blight, while water scarcity weakens plant immunity, predisposing legumes to opportunistic soil-borne pathogens like charcoal rot (*Macrophomina phaseolina*). This complex "crosstalk" between abiotic and biotic stress often leads to a loss of phenological synchrony between legumes and their natural biocontrol agents, resulting in unchecked pest population growth. Beyond the field, these disruptions exacerbate socio-economic vulnerabilities, particularly among smallholder farmers who face a "pesticide treadmill" as they struggle to manage escalating outbreaks. To meet escalating global demands—including the requirement to boost annual pulse output by 4.2% to achieve 2030 targets—a paradigm shift from "single-stress" research toward integrated, climate-smart management is essential. This transition requires the strategic deployment of advanced genomic tools, including Marker-Assisted Selection (MAS), Genome-Wide Association Studies (GWAS), and CRISPR/Cas9-mediated genome editing (Razzaq *et al*. 2019), alongside digital precision agriculture and ecological engineering. This review evaluates the multifaceted dynamics of biotic stress in legumes under a changing climate and explores the technological and policy frameworks necessary to secure resilient and sustainable production in an increasingly volatile global environment (Figure 1).

CLIMATE CHANGE: THE DRIVER OF ALTERED BIOTIC DYNAMICS

Climate change is no longer a distant threat but a contemporary catalyst that is fundamentally restructuring the interactions between legume hosts and their associated biotic stressors. As global mean temperatures rise and atmospheric compositions shift, the traditional boundaries of pest and pathogen niches are expanding, leading to intensified pressure on legume productivity (Varshney *et al*. 2018, Dave *et al*. 2024).

Rising temperatures and insect proliferation

The surge in global temperatures acts as a primary physiological driver for insect pests, which are poikilothermic (cold-blooded) and thus highly sensitive to environmental thermal conditions. Elevated temperatures significantly shorten the developmental time and increase the metabolic rates of legume pests, such as aphids and whiteflies (Bebber *et al*. 2013). This allows for additional generations per cropping season, leading to rapid population explosions. Rising temperatures facilitate the migration of tropical and subtropical pests into higher latitudes and altitudes where they were previously unable to overwinter (Skendžić *et al*. 2021). Climate-driven changes in host plant physiology can modify resistance mechanisms, potentially making legumes more susceptible to herbivory. For example, higher temperatures can weaken a plant's thermal tolerance, indirectly benefiting the performance of specialist herbivores (Sharma *et al*. 2023, Kumari *et al*. 2022, Dutta *et al*. 2022).

Elevated CO_2 and nutritional quality

While elevated CO_2 is often viewed through the lens of a "fertilisation effect," its impact on biotic dynamics is multifaceted and often detrimental to plant defence. Under eCO_2, legumes often exhibit increased carbon accumulation but a relative decrease in nitrogen (and protein) content (Singer *et al*. 2020). This diluted nutritional quality can force herbivores to consume more leaf tissue (compensatory feeding) to meet their nitrogen requirements, thereby increasing defoliation (Ebi *et al*. 2021, Soares *et al*. 2019). The shift in leaf chemistry under eCO_2 has been observed to accelerate the infestation of coleopteran defoliators and lepidopteran pod-borers, such as *Helicoverpa armigera*, leading to substantial yield losses (Sandhu *et al*. 2025, Sharma *et al*. 2006). The initial stimulatory effect of CO_2 on yields typically plateaus around 550 ppm, after which the benefits are often negated by compounding climate stressors like heat and drought (Dave *et al*. 2024).

3. Altered rainfall patterns and pathogen dynamics

Changes in the frequency and intensity of precipitation create divergent risks for legume diseases. Periods of excessive rainfall and high humidity create ideal microclimates for foliar fungal pathogens. Diseases such as Ascochyta blight and Botrytis grey mold thrive in these conditions, leading to rapid field-wide epidemics (Mwaipopo *et al*. 2021, Prabhukarthikeyan *et al*. 2017). Conversely, water scarcity can weaken plant immunity, making legumes more prone to "opportunistic" soil-borne pathogens like charcoal rot (*Macrophomina phaseolina*), which capitalises on drought-stressed tissues (Pandey *et al*. 2021, Chilakala *et al*. 2022). Extreme rainfall variability and drought impair the symbiotic relationship between legumes and *Rhizobia*. Nodule damage and reduced nitrogenase enzyme activity under these conditions not only limit growth but also reduce the plant's overall vigor to resist biotic attacks (Nasr Esfahani *et al*. 2014, Dave *et al*. 2024).

Loss of synchrony

Climate change disrupts the temporal alignment between legume development and the life cycles of beneficial organisms. Warmer winters and earlier springs can cause legumes to flower before their natural pollinators or the natural enemies of pests (predators and parasitoids) emerge (Scaven and Rafferty 2013). This "loss of synchrony" can result in a window where pest populations grow unchecked because their natural biological control agents have not yet reached peak activity, leading to increased reliance on chemical interventions (Gregory *et al*. 2009, Staley *et al*. 2007).

MAJOR BIOTIC STRESSES IN LEGUMES: CLIMATE SENSITIVITY AND DYNAMICS

Legumes, fundamental to global food security due to their high protein content and critical role in sustainable agriculture through nitrogen fixation, are increasingly threatened by biotic stresses. This challenge is profoundly amplified by ongoing climate change, which acts as a catalyst for shifting pest and pathogen dynamics (Bagga *et al*. 2024, Priya *et al*. 2025). The escalating frequency and intensity of extreme weather events directly impact the epidemiology of plant pathogens and pests, thereby influencing legume productivity worldwide (Leitão *et al*. 2020, Sharma *et al*. 2021). The climate sensitivity of these biotic stresses is characterised by several key drivers:

Thermal regulation of pathogen life cycles

Rising ambient temperatures significantly shorten the incubation periods of fungal pathogens such as *Uromyces* spp. (rust) and *Ascochyta* spp. (blight). This thermal acceleration allows for more polycyclic generations within a single cropping season, leading to rapid epidemic outbreaks that can outpace traditional chemical control measures.

Altered pest phenology and range expansion

Increasing winter temperatures allow insect pests and viral vectors (e.g., *Aphis craccivora*) to overwinter in higher latitudes, expanding their geographic range into previously temperate legume-growing regions. Furthermore, temperature-induced shifts in legume phenology can lead to a "mismatch" or "synchrony" with pest emergence, often favoring the pest and increasing the transmission rates of phytoplasmas and viruses (Sharma *et al*. 2021).

Hydro-climatic influence on disease predisposition

Erratic precipitation patterns create dual challenges. While prolonged high humidity and flooding events promote the sporulation and dispersal of foliar and soil-borne pathogens like *Phytophthora* and *Fusarium*, intermittent drought stress can weaken the structural integrity of legume tissues, making them more susceptible to opportunistic secondary infections.

Atmospheric CO_2 and host-pathogen interactions

Elevated CO_2 concentrations can lead to increased canopy density, creating a microclimate of high humidity that favors fungal growth. Additionally, the "dilution effect" on nitrogen content in legume tissues under high CO_2 may force insect herbivores to increase their consumption (compensatory feeding), leading to more extensive physical damage and higher entry points for necrotrophic pathogens (Priya *et al*. 2025).

PHYSIOLOGICAL AND MOLECULAR RESPONSES OF LEGUMES

Legumes exhibit complex and interconnected physiological and molecular responses to biotic stresses, which are often modulated by concurrent abiotic stressors (Leitão *et al*. 2020, Rejeb *et al*. 2014).

Crosstalk between abiotic and biotic stress

Plants in natural agroecosystems are rarely exposed to single stressors but rather face a combination of abiotic and biotic challenges simultaneously (Leitão *et al*. 2020, Rejeb *et al*. 2014). The interaction between these stress types is not additive but often synergistic, leading to greater damage than individual stresses alone (Leitão *et al*. 2020, Rejeb *et al*. 2014). For example, drought and root-infecting pathogens together cause more severe damage than either stress independently (Leitão *et al*. 2020). Abiotic stresses such as drought and heat can compromise plant immunity, making legumes more susceptible to pathogenic attacks (Rejeb *et al*. 2014). A prime example is stomatal closure, a crucial plant response to drought to conserve water, which can inadvertently create an entry point for certain pathogens by altering the plant's physiological state and defence readiness (Rejeb *et al*. 2014; Rasheed *et al*. 2024).

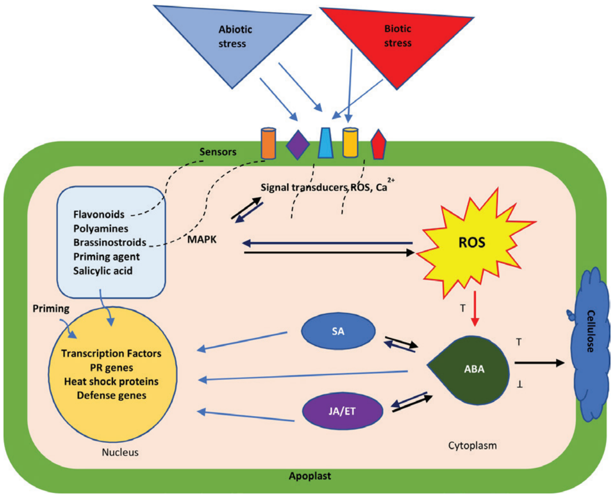

Fig. 2. Illustration of plant stress responses interplay, showing that both biotic and abiotic stresses

This figure illustrates (Fig. 2) the complex interplay of plant stress responses, showing that both biotic and abiotic stresses are sensed by specific receptors, leading to signal transduction via reactive oxygen species (ROS) and calcium ions (Ca^{2+}), and ultimately activating the mitogen-activated protein kinase (MAPK) cascade (Rejeb *et al*. 2014). This cascade, along with phytohormones such as salicylic acid (SA), abscisic acid (ABA), and jasmonic acid/ethylene (JA/ET), modulates transcription factors and defense genes, leading to responses like callose deposition and secondary metabolite production (Rejeb *et al*. 2014). Abiotic stressors such as drought, heat, salinity, and heavy metals can lead to disrupted gene expression, protein denaturation, generation of ROS, and altered hormonal balance, ultimately resulting in stunted growth, wilted leaves, and impaired photosynthesis (Rasheed *et al*. 2024).

Defense signaling pathways

Legumes employ sophisticated defence signalling pathways orchestrated by phytohormones like Salicylic Acid (SA), Jasmonic Acid (JA), and Ethylene (ET) (Raza *et al*. 2020). These hormones act as key regulators, often engaging in intricate crosstalk to fine-tune defense responses against specific threats (Table 1) (Rejeb *et al*. 2014).

Salicylic Acid (SA)

The SA pathway is predominantly activated in response to biotrophic pathogens, which rely on living host cells for nutrients (Rejeb *et al*. 2014). SA mediates systemic acquired resistance (SAR), a long-lasting, broad-spectrum defence mechanism protecting against subsequent infections. The SA pathway often operates antagonistically with the JA/ET pathways (Rejeb *et al*. 2014).

Jasmonic Acid (JA) and Ethylene (ET)

The JA and ET pathways are typically induced by necrotrophic pathogens, which kill host cells to extract nutrients, and by herbivorous insect attacks. JA and ET frequently act synergistically to mount effective and robust defence responses (Rejeb *et al*. 2014). Jasmonic acid is crucial for plant growth and persistence under abiotic stress, influencing various physiological and biochemical processes, such as stomatal opening, the accumulation of amino acids and soluble sugars, and the enhancement of antioxidant defence systems (Raza *et al*. 2020).

Table 1. Functional comparison of JA, SA, and ET in legumes

Stress Category	Stressor Example	Dominant Hormone	Defense Mechanism
Biotic (Biotrophic)	Powdery mildew, viruses	SA	Activation of PR genes and Systemic Acquired Resistance (SAR).
Biotic (Necrotrophic)	*Botrytis cinerea*, Insects	JA & ET	Production of proteinase inhibitors and secondary metabolites (alkaloids).
Abiotic (Physical)	Drought, Salinity	JA (with ABA)	Stomatal closure, accumulation of proline and soluble sugars.
Abiotic (Chemical)	Heavy Metals, Ozone	JA & SA	Enhancement of Antioxidant Systems (SOD, POD, CAT).
Abiotic (Radiative)	UV-radiation	SA	Accumulation of flavonoids to absorb radiation and repair DNA.

The dynamic interaction between abiotic and biotic stress responses, mediated by these signalling pathways, highlights the complexity of plant immunity in a changing climate (Rejeb *et al*. 2014). Advanced biotechnological approaches, including genomics, transcriptomics, proteomics, and metabolomics, are increasingly being employed to decipher these complex mechanisms and to develop legume varieties with enhanced resistance to multiple stresses (Ali *et al*. 2022, Ramalingam *et al*. 2015). For example, QTL mapping has been instrumental in identifying genetic regions associated with abiotic stress tolerance in legumes (Singh *et al*. 2021). Leveraging these insights through breeding and genetic engineering offers promising avenues for adaptive management and ensuring sustainable legume production in the face of ongoing environmental challenges (Dita *et al*. 2006, Ali *et al*. 2022).

ADAPTIVEMANAGEMENTANDMITIGATION STRATEGIES

The management of biotic stress in legumes under a changing climate requires a transition from reactive mitigation to proactive resilience. Addressing the landscape of biotic stress in legumes under climate change requires a multi-approach that bridges molecular biology with field-level agronomy and advanced digital intelligence and genomic precision, ecological engineering, and more advanced breeding methods, which solve modern day problem related to mitigating and overcoming the biotic stress in legume crops. Such integration is essential to stabilise legume production and enhance productivity under increasing climatic variability (Foyer *et al*. 2016, Varshney *et al*. 2021). We can stabilise legume production against the volatile backdrop of climate change. We can focus on increasing production and also productivity. There are various approaches to be prioritized are outlined below:

Advanced genetic and omics-based approaches

The development of 'climate-ready' legumes relies on unlocking genetic potential through advanced molecular scalpels, ancestral germplasm, and using various modern methods.

Modern legume cultivars suffer from a narrow genetic base, which limits their capacity to cope with climate-induced stresses. By screening wild relatives and landraces, researchers can identify 'climate-ready' genes that provide natural resistance to heat-induced pests and drought-loving pathogens. These ancestors often possess robust Défense mechanisms that have been lost in high-yielding varieties. Wild relatives, such as *Cicer reticulatum* (wild chickpea), serve as vital reservoirs for climate-ready genes that provide natural resistance to heat-tolerant pests and drought-induced pathogens. These ancestors often possess unique secondary metabolites and physical barriers, like dense trichomes, that inhibit pest feeding during heatwaves (Coyne *et al*. 2020, Zhang *et al*. 2017). A revolutionary strategy is de novo domestication, where CRISPR/Cas9 is used to edit yield genes in highly resistant wild species, essentially creating a high-yielding crop with an untouched and most progressive wild immune system (Zsögön *et al*. 2017, Razzaq *et al*. 2019).

Alongside the use of wild germplasm and genome editing, modern breeding increasingly integrates marker-assisted selection (MAS) and genomic selection (GS) to achieve multi-stress tolerance. While Marker-Assisted Selection (MAS) is effective for single-gene traits, Genomic Selection (GS) is superior for complex, polygenic traits like "combined-stress resistance". GS uses whole-genome markers to predict the breeding value of a plant, allowing breeders to select for both high yield and multi-pest resistance simultaneously (Heffner *et al*. 2009, Crossa *et al*. 2017). Unlike traditional breeding, GS uses whole-genome markers to predict the performance of polygenic traits. MAS allows breeders to track specific resistance genes through the breeding cycle using DNA markers, significantly accelerating the development of resistant lines. Genomic Selection goes further by using whole-genome markers to predict the performance of polygenic traits, such as combined resistance to both heat and pod borers. Recent studies have successfully used GS to develop lines that maintain high protein content while resisting both drought and heat-induced pathogens, reducing the breeding cycle by up to 30% (Varshney *et al*. 2021, Budhlakoti *et al*. 2022).

In addition to breeding-based resistance, advanced molecular Défense strategies such as host-induced gene silencing (HIGS) provide a highly specific and non-toxic mechanism for pest control. This cutting-edge platform involves engineering the host plant to produce double-stranded RNA (dsRNA) that targets essential genes in an attacking pest. When a pest feeds on the legume, these molecules shut down its survival genes, providing a highly specific, non-toxic Défense mechanism (Koch and Kogel 2014).

Complementing this strategy, CRISPR/Cas9-based gene editing enables targeted resistance by knocking out plant susceptibility (S) genes that pathogens use to gain entry into the plant. A significant advancement is de novo domestication, where breeders take a highly resistant wild relative and use CRISPR to edit a few major yield genes, essentially creating a high-yielding crop with a wild immune system (Borrelli *et al*. 2018, Chen *et al*. 2019)

Microbiome engineering and rhizosphere 'Legacy'

Beyond the plant genome, the 'Holobiont' approach managing the plant together with its associated microbial community is emerging as a critical mitigation strategy for climate-resilient legume protection. Instead of single-strain inoculants, researchers are assembling synthetic microbial communities (SynComs) that mimic natural, stable microbiomes. These communities are engineered to be functionally redundant, meaning if one species fails during a heatwave, others continue to provide Induced Systemic Resistance (ISR) (Toju *et al*. 2018, Trivedi *et al*. 2020). Complementing this approach is the concept of the soil memory or rhizosphere legacy effect, where Legumes grown in diverse rotations train the soil microbiome. This legacy effect, mediated by root exudates, creates a naturally suppressive soil environment that can reduce the incidence of Fusarium wilt in subsequent seasons by up to 40%. When we rotate crops (like chickpea followed by mustard), the soil "remembers." The beneficial microbes from the previous crop stay in the soil, creating a natural Défense system for the next season.

CLIMATE-SMART AGRONOMIC PRACTICES: SPATIAL AND TEMPORAL DISRUPTIONS

Agronomic adjustments provide a physical first line of defense by altering the microclimate to favor the crop over the pest. Climate-smart agronomic practices provide a physical first line of defense against biotic stress by altering the crop microclimate in ways that favor the legume rather than the pest. One of the most effective low-cost strategies is adjusting sowing dates, which can desynchronize the most vulnerable growth stages of legumes from peak pest pressure. Shifting sowing dates ensures that sensitive phenological stages such as flowering and pod formation occur during cooler periods when pest reproductive cycles are slower; for instance, early sowing of pigeon pea can reduce damage from pod borers by avoiding peak infestation windows (Midega *et al*. 2018). In addition to temporal adjustments, intercropping systems and the "push–pull" strategy introduce spatial disruption by diversifying the cropping environment. Intercropping legumes with non-host crops such as mustard interrupts pathogen life cycles, while push–pull systems use repellent intercrops to drive pests away ("push") and attractive border crops to divert them ("pull"), significantly reducing reliance on synthetic pesticides (Khan *et al*. 2018, Gaba *et al*. 2015). These practices are further strengthened through conservation agriculture and soil health management, including minimum tillage and permanent soil cover, which enhance soil microbial diversity. Increased microbial diversity promotes soil suppressiveness, where beneficial microorganisms naturally outcompete soil-borne pathogens such as *Fusarium* and *Macrophomina*, thereby limiting disease proliferation under climate stress conditions (Lal 2015, Pittelkow *et al*. 2015).

NANOTECHNOLOGY AND STIMULI-RESPONSIVE PROTECTION

Nanotechnology bridges the gap between biological potential and field-level efficiency, particularly under extreme climatic conditions. Conventional pesticide sprays often degrade rapidly under high temperatures and intense UV radiation, leading to significant losses of active ingredients. Nano-encapsulated biopesticides, such as neem oil encapsulated in silica-based nanoparticles, protect these active compounds from environmental degradation and enable their controlled release only when triggered by specific stimuli, such as insect gut pH or defined humidity thresholds. This stimuli-responsive behaviour improves crop specificity and insect specificity, thereby increasing efficacy while reducing overall chemical load (Nuruzzaman *et al*. 2016). In parallel, advances in nano-sensor technology are enabling early detection of biotic stress. Soil-embedded nano-sensors can detect stress-related volatile compounds released by plant roots during the earliest stages of nematode or fungal colonisation, allowing for micro-targeted interventions well before visible disease symptoms appear in the field.

DIGITAL AND PRECISION AGRICULTURE: AI AS THE PRIMARY CATALYST

Digital and precision agriculture position artificial intelligence (AI) as the central decision-making engine in modern legume farming systems. AI-based early warning and forecasting models integrate historical weather data, satellite imagery, GIS-based remote sensing, and insect metabolic rates to predict pest and disease outbreaks with high accuracy. These systems shift management from reactive control to predictive prevention, enabling interventions to be applied precisely when risk levels are highest. Studies have demonstrated that AI-driven forecasting significantly improves the timing of biopesticide applications, increasing their efficacy by up to 25% (Liakos *et al*. 2018, Zhang *et al*. 2017). Complementing these models, hyperspectral hotspot detection using UAVs (drones) allows for real-time monitoring of crop health across large areas. Hyperspectral sensors can detect subtle "red-edge" shifts in leaf reflectance, an early, invisible indicator of cellular stress which AI algorithms analyse to identify pest or disease hotspots, enabling localised treatments that can reduce chemical use by as much as 80% (Mahlein, 2016, Sankaran *et al*. 2010). These digital tools integrate seamlessly with nanotechnology-based mitigation strategies, where nano-encapsulated biopesticides provide stimuli-responsive delivery, protecting active ingredients from UV and heat stress and releasing them only under specific environmental or biological cues (Liakos *et al*. 2018, Zhang *et al*. 2017).

BIOLOGICAL AND INTEGRATED PEST MANAGEMENT (IPM)

Biological control and integrated pest management (IPM) strategies leverage natural biological interactions as sustainable alternatives to intensive chemical interventions. Plant growth–promoting rhizobacteria (PGPR), such as *Bacillus* species, play a central role by triggering induced systemic resistance (ISR) in legumes, effectively priming the plant immune system for faster and stronger Défense responses against pests and pathogens, functioning analogously to a plant vaccine (Pieterse *et al*. 2014, Backer *et al*. 2018). To maintain the effectiveness of biological control agents under rising temperatures, researchers are also adopting thermal priming strategies, in which agents such as *Trichoderma* are exposed to sub-lethal heat stress during production. This preconditioning enhances their tolerance to heatwaves and improves their survival and performance when deployed under field conditions increasingly shaped by climate extremes (De La Fuente *et al*. 2013).

SOCIO-ECONOMIC AND POLICY IMPLICATIONS

The biological and digital advancements in legume protection remain inaccessible to the millions of smallholder farmers who produce the bulk of the world's plant-based protein. This section explores the systemic barriers and the policy shifts required to institutionalise climate-resilient legume farming. With this idea, we can overcome the legume production. Consequently, biotic stress under climate change not only affects crop productivity but also exacerbates socio-economic vulnerabilities. Addressing these challenges requires systemic policy reforms to institutionalise climate-resilient legume farming and thereby enhance global food security.

Economic vulnerability and the poverty multiplier

Biotic stress in legumes acts as a major economic shock to rural livelihoods, often trapping smallholder farmers in persistent cycles of poverty and debt. In regions such as Sub-Saharan Africa and South Asia, yield losses ranging from 20-40% due to pod borers or wilt directly translate into reduced household income and compromised protein security. Because legumes frequently function as cash crops for smallholders, such losses force farmers to cut back on essential investments in education, healthcare, and quality agricultural inputs for subsequent seasons, reinforcing long-term vulnerability (FAO 2021). While emerging technologies such as AI-driven precision agriculture tools and gene-edited seeds offer pathways toward resilience, their high initial costs present substantial barriers to adoption. Without targeted subsidies and inclusive financing mechanisms, these technologies risk widening the digital divide, enabling only large-scale industrial farms to benefit from climate-adaptive innovations (Liakos *et al*. 2018, Topol 2019).

Gender dimensions in legume cultivation

Legume cultivation is frequently classified as a "women's crop" in many developing economies, making biotic stress a distinctly gendered challenge. Women farmers typically have 20-30% less access to agricultural extension services, training programs, and digital decision-support tools compared to men. As a result, if AI-based early warning systems and advisory services are delivered primarily through smartphones or formal cooperatives that exclude women, a substantial portion of the agricultural workforce is left behind, limiting the effectiveness of these innovations (Doss *et al*. 2018, FAO 2021). Moreover, increased pest pressure intensifies labour demands in legume fields, leading to more manual weeding and pest removal tasks that are disproportionately performed by women and children. This added labour burden further reduces time available for education, income diversification, and social development, reinforcing intergenerational poverty cycles (Kristjanson *et al*. 2017).

Policy bias: The "Cereal-Centric" hurdle

Global food and agricultural policies have historically prioritised the “Big Three” cereals, wheat, rice, and maize, leaving legumes marginalised as so-called orphan crops. Despite their critical roles in biological nitrogen fixation, soil health improvement, and human nutrition, legumes receive significantly lower levels of public and private investment in research and development compared to cereals. Correcting this imbalance requires targeted policy frameworks that incentivise breeding programs for minor legumes and support the development of digital infrastructure tailored to legume-based farming systems (Varshney *et al*. 2021a). Even when climate-ready, pest-resistant legume varieties are successfully developed, weak and fragmented seed delivery systems often prevent their dissemination to remote and resource-poor regions. Strengthening seed systems through policy-supported community seed banks and decentralised certification mechanisms is essential to ensure rapid adoption and equitable access (Louwaars *et al*. 2013).

Advanced policy: Integrated "One Health" governance

Modern policy frameworks are increasingly shifting toward integrated “One Health” governance models, recognising the interconnectedness of agricultural productivity, environmental sustainability, and human health. Rather than operating in isolation, agricultural and health departments must collaborate through shared institutional platforms. Central to this approach is the creation of “data commons,” where weather data, pest migration patterns, crop health indicators, and human nutrition statistics are openly shared. Such integration enables governments to anticipate cascading risks, such as how crop failure in one region may precipitate malnutrition crises elsewhere (FAO 2020). In parallel, the regulation of emerging technologies such as CRISPR-based gene editing must be harmonised across national borders. Divergent regulatory stances where one country permits gene-edited crops while another bans them create trade barriers that prevent the most resilient legume varieties from reaching the farmers who need them most (Razzaq *et al*. 2019).

Intellectual property and technology sovereignty

Access to innovation remains a central policy debate in climate-resilient legume agriculture. The growing movement toward open-source genomics and seed systems seeks to democratize access to genetic resources, particularly for neglected and underutilised legumes. Policies that promote open sharing of genomic data enable researchers in developing countries to breed locally adapted, pest-resistant varieties without incurring prohibitive licensing costs imposed by multinational corporations (Kloppenburg 2017, Razzaq *et al*. 2019). At the same time, the expansion of AI-driven agriculture raises concerns about data extractivism. As sensors and digital platforms collect vast amounts of field-level data, policy frameworks must safeguard farmers’ data sovereignty, ensuring that insights generated from their land are owned by farmers and used primarily for their benefit (Bronson and Knezevic 2016, Topol 2019).

Food security and human nutrition

Legumes are widely regarded as the “poor man’s protein,” and disruptions in their production have direct consequences for human nutrition. When biotic stressors such as pod borers (*Maruca vitrata*) or *Fusarium wilt* reduce legume yields, the effects extend beyond agriculture into human biology. Yield losses are strongly associated with increased rates of childhood stunting and wasting, particularly in regions where animal-source proteins are economically inaccessible (Mudryj *et al*. 2014, FAO 2020). In addition to reducing quantity, biotic stress compromises grain quality, as fungal pathogens can lower the concentration and bioavailability of essential micronutrients such as iron and zinc, exacerbating hidden hunger among vulnerable populations (Nair *et al*. 2013).

Livelihoods and the "Poverty Trap"

For smallholder farmers, catastrophic yield losses sometimes reaching 50-100% due to outbreaks such as Mungbean Yellow Mosaic Virus represent more than a single-season failure; they constitute long-term financial devastation. In attempts to manage escalating pest pressure, farmers often invest a substantial share of their limited capital in chemical pesticides. This leads to a pesticide treadmill, where increasing pest resistance necessitates ever-higher expenditures on chemical inputs, deepening indebtedness. Simultaneously, the labour burden associated with manual weeding and pest control intensifies, with women and children disproportionately shouldering this unpaid work. The resulting loss of time for education and income-generating activities further entrenches households within a poverty trap.

Market quality and global trade

Beyond yield loss, biotic stress in legumes generates significant invisible economic losses through quality degradation. Many legume exports, such as cowpea from West Africa, face strict phytosanitary barriers in international markets due to pesticide residues or the presence of quarantine pests, limiting foreign exchange earnings for developing countries (Henson and Loader 2001). Additionally, pest-induced stress can predispose crops to secondary fungal infections, particularly by *Aspergillus* species, leading to aflatoxin contamination. Aflatoxin-tainted legumes are not only unmarketable but also pose severe health risks, undermining both trade potential and public health outcomes (Waliyar *et al*. 2015, Williams *et al*. 2004).

Table 2. Regulatory milestones and interventions enhancing resilience against biotic stress in pulse production

Policy	Year	Significance	Specific uses & relevance to biotic stress
National Agricultural Policy	2000	Foundation of modern Indian Agri-policy	Promoted IPM (Integrated Pest Management) as a primary Défense against legume pests.
Plant Quarantine Order	2003	Biosecurity & Trade protection	Regulates the import of legume germplasm to prevent the entry of exotic pests and viruses.
NFSM-Pulses	2007	Targeted production increase in India	Funded the distribution of Bio-pesticides and the "Cluster Frontline Demonstrations" of resistant varieties.
SDG 2: Zero Hunger	2015	Global framework (United Nations)	Positioned legumes as "Climate-Smart" crops, shifting funding toward breeding for biotic resilience.
PM-AASHA	2018	Economic safety net for pulse growers	Provides price support when pest outbreaks crash market supply or quality, ensuring farmer survival.
Global Action for FAW (FAO)	2019-24	Global transboundary pest response	Focused on Fall Armyworm (FAW) which heavily impacts legumes; promoted digital monitoring and bio-controls.
EU Farm to Fork Strategy	2020	Global sustainability standard	Mandated a 50% reduction in chemical pesticides, forcing the development of "Green" legume resistance.
Digital Agriculture Mission	2021	Tech-driven pest management	Uses AI and Remote Sensing (e.g., Krishi Decision Support System) for real-time pest outbreak alerts.
CRISPR Regulatory Memo	2022	Genetic policy breakthrough (India)	Exempted SDN1/SDN2 gene-edited crops from GMO rules, accelerating the breeding of virus-resistant pulses.
Mission for Aatmanirbharta in Pulses	2025	Strategic self-sufficiency (India)	Budget of ₹11,440 cr. Focuses on the SATHI portal for seed traceability and 100% procurement of pest-resistant Tur/Urad.

Table 3. Adaptive management and mitigation strategies for biotic stress in legume crops under climate change

Strategy Category	Intervention	Target Biotic Stress	Mode of Action	Climate Adaptation Benefit	References
Genetic resistance	Resistant cultivars	Fungal, viral, and insect pests	Limits pathogen infection and pest feeding	Stable resistance under climate variability	Bohra *et al*. 2022
Pre-breeding	Wild relatives, landraces	Emerging pathogens	Broad-spectrum resistance genes	Climate-ready gene pools	Pratap *et al*. 2021
Molecular breeding	MAS, Genomic selection	Multiple stresses	Faster development of resistant varieties	Accelerated adaptation	Varshney *et al*. 2021b
Gene editing	CRISPR/Cas9	Specific pathogens/ insects	Precise gene modification	Rapid response to new threats	Akhtter *et al*. 2023
Agronomic management	Crop rotation	Soil-borne diseases	Breaks pathogen life cycle	Reduces climate-driven disease build-up	Page *et al*. 2025
Cultural practices	Intercropping	Insect pests	Habitat disruption	Low-cost climate adaptation	Stagnari *et al*. 2017
Biological control	*Trichoderma, Bacillus*	Fungal pathogens	Antagonism & ISR	Eco-friendly & resilient	Santoyo *et al*. 2024
IPM	Integrated approaches	Multi-pest complex	Minimizes resistance development	Sustainable under warming climates	Na *et al*. 2024
Digital agriculture	Early warning systems	Pest outbreaks	Timely interventions	Climate-smart decision making	Aziz *et al*. 2025

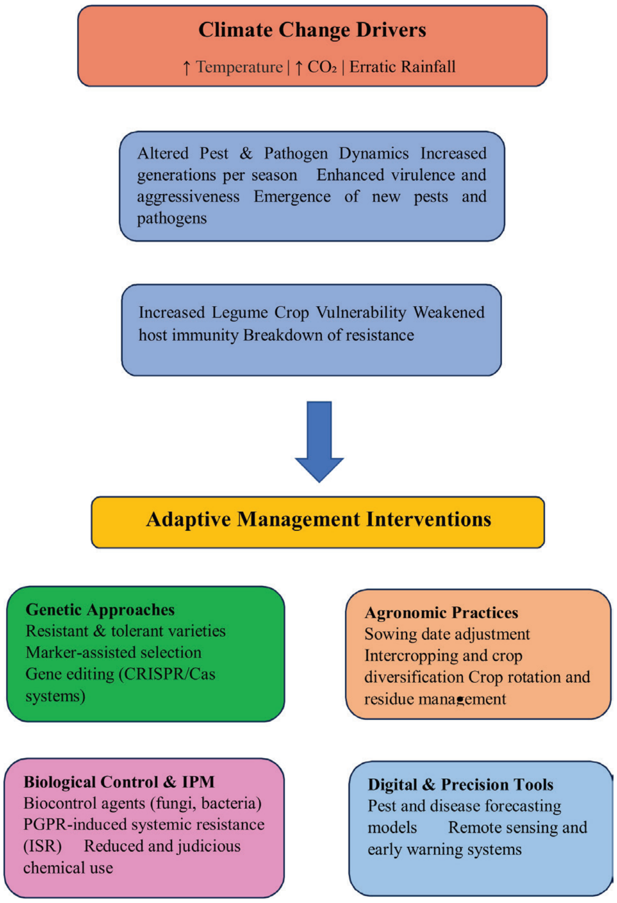

Fig. 3. Adaptive management framework for mitigating biotic stress in legume crops under climate change

CONCLUSION

Climate change fundamentally transforms the threat landscape for legume production, boosting biotic stresses through altered pest dynamics, expanded pathogen ranges, and disrupted ecological synchrony. Addressing these emerging challenges necessitates a paradigm shift from reactive, single-stress management to proactive, systems-based resilience. At the molecular level, leveraging advanced genomics through genomic selection, CRISPR-Cas9 editing, and the exploitation of wild relatives provides a pathway to develop multi-stress-tolerant cultivars with robust, climate-ready genetics. Concurrently, climate-smart agronomic practices, such as temporal sowing adjustments and spatial cropping diversification, offer immediate, low-cost barriers against pest and disease escalation. The integration of microbiome engineering and nanotechnology introduces novel dimensions to crop protection, enhancing natural defence mechanisms and enabling targeted, stimuli-responsive interventions.

Digital agriculture, powered by AI and remote sensing, emerges as a critical catalyst, transforming pest and disease management from a reactive to a predictive and precision-based endeavour. However, the efficacy of these technological advances is contingent upon equitable access and adoption. The persistent socio-economic vulnerabilities of smallholder farmers, deepened by gendered disparities in resource access and a historical policy bias favouring cereals, represent significant barriers to resilience. Therefore, future strategies must include supportive policies that promote open-source innovation, strengthen seed systems, implement parametric insurance models and adopt integrated governance frameworks.

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