



REVIEW ARTICLE

Impact of climate change on plant disease development and management in cold arid regions of Ladakh

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Abstract

Climate change is also impacting plant health and disease management in high-altitude agro-ecosystems like Ladakh, where plant and animal diversity is already threatened due to fragile ecosystems, scarce water resources and limited crop-growing seasons. Temperature rise, changes in snowfall and snowmelt and erratic precipitation, along with an increase in the use of irrigation systems, are facilitating the establishment and proliferation of pests and diseases that were once suppressed by extreme weather conditions. At the same time, abiotic stress factors like temperature rise, drought and varying levels of soil moisture are weakening plant resistance to disease infection. These are some of the emerging plant disease management challenges in high-altitude agro-ecosystems. The increase in protected cultivation and intensive production of vegetables in Ladakh, while promoting livelihood security, has inadvertently contributed to an increase in plant disease management risks, especially from soil- and water-borne diseases and insect-borne viruses. These emerging plant disease management issues are likely to impact the productivity of important crops like barley, wheat, potato, peas and vegetables, with significant implications for food and nutritional security. Moreover, climate change is also affecting the predictability and effectiveness of conventional plant disease management techniques like chemical management, host resistance and biological management. This review highlights the need for developing climate-resilient plant disease management techniques for high-altitude agro-ecosystems. It also emphasises the need to develop plant disease management techniques to strengthen early warning systems, develop climate-resilient crop varieties and promote farmer-centred approaches to climate adaptation, along with the integration of scientific innovations and traditional knowledge to address plant disease management issues in Ladakh.

Keywords: climate change; climate-resilient plant disease management; high-altitude plant disease management; plant diseases; plant-pathogen interactions; soil moisture; temperature

Introduction

Climate change poses an increasing challenge to agricultural sustainability in high-altitude regions such as the Himalayas, where fragile ecosystems, limited water availability and short growing seasons render farming systems highly vulnerable (1). Shifts in temperature, changes in the timing and form of precipitation and the frequency of extreme events (such as late-season frosts, unseasonal rain and flash floods) are already altering local agronomic practices and exposing crops to new abiotic stressors and biotic threats (2). Environmental changes associated with warming, such as longer frost-free periods, altered snowmelt patterns, shifts in irrigation schedules and rising mean temperatures, can favour the range expansion and overwintering capacity of several pests and pathogens (3, 4). These changes may alter disease seasonality and increase both the incidence and severity of plant diseases. Additionally, such shifts can result in earlier or additional infection cycles. In some cases, these changes can facilitate the movement of organisms to higher latitudes or elevations beyond their previous cold-imposed limits (5).

Adaptation by farmers, such as the introduction of new crops, changes in planting dates, or modified irrigation regimes, while essential for livelihood resilience, can inadvertently increase crop exposure to unfamiliar pathogens or vectors. At the same time, host physiology and immune responses often change under climatic stress: drought, heat and elevated atmospheric CO₂ can modify plant growth stages, cuticle properties and defence signalling, with complex consequences for susceptibility and disease progression (6). The interactions among pathogen, host and environment determine disease outcomes; climate change affects each component and the timing of their interactions (7). In high-altitude agroecosystems, where microclimates vary sharply over short distances, even small shifts in temperature or moisture regimes may have outsized effects on pathogen life cycles, spore production, dispersal dynamics and host phenology, thereby complicating the forecasting and management of plant diseases (8). Finally, regional vulnerability is compounded by socio-ecological constraints in Ladakh such as scarce water storage, limited access to diagnostics and extension services and livelihood dependence on a narrow set of crops and livestock (2). Therefore,

integrated adaptation strategies that combine local knowledge (e.g., traditional water harvesting and cropping calendars) with robust disease surveillance, targeted cultivar selection and climate-aware management practices will be critical for reducing future plant disease risks and maintaining food security in high-altitude landscapes.

Effect of climate change on plants and plant diseases

Climate change is increasingly influencing plant growth, health and disease dynamics across diverse agroecosystems. Extreme climatic events such as floods, droughts and heatwaves have become more frequent and intense, posing serious threats to agricultural productivity (9). While sea-level rise and flooding primarily affect coastal regions, drought-induced water scarcity is particularly relevant to high-altitude cold desert regions like Ladakh, where agriculture is already constrained by limited water availability and a short growing season (2). Prolonged moisture stress weakens plants, making them more susceptible to pest infestations and pathogen attacks (7, 10).

Plant diseases remain one of the most significant constraints on global agricultural production, accounting for an estimated 20–30 % yield loss annually, a burden expected to intensify with climate change. Alterations in temperature, rainfall patterns and humidity can accelerate pathogen reproduction, increase the number of disease cycles per season and enhance pest survival during winters (4, 11). In cold regions such as Ladakh, rising temperatures may allow pests and pathogens previously restricted by extreme cold to establish and persist, thereby expanding their geographical and altitudinal ranges (7, 12, 13). Climate-driven changes in farming practices, including altered sowing dates, the introduction of new crops and intensified irrigation, are essential adaptation strategies. However, these adjustments may inadvertently expose crops to unfamiliar pests and diseases. At the same time, climatic stress can induce physiological and genetic changes in host plants, sometimes enhancing disease resistance but often increasing vulnerability, depending on the crop-pathogen system (14, 15).

Temperature plays a critical role in determining plant growth and disease development. Moderate warming in some high-altitude areas may initially benefit certain crops or allow diversification into warm-season vegetables. However, when temperatures exceed optimal thresholds, plants experience heat stress, reduced productivity and increased susceptibility to bacterial and fungal infections (16, 17). Elevated atmospheric carbon dioxide (CO₂) concentrations can further complicate plant-disease interactions. Although increased CO₂ has been shown to stimulate plant growth under controlled conditions, it can also reduce the concentration of essential nutrients such as protein, zinc and iron in staple crops like wheat, rice and legumes, posing indirect risks to human nutrition (18, 19).

Climate change influences both hosts and pathogens in complex ways. Certain temperature regimes may enhance pathogen aggressiveness while simultaneously suppressing host resistance (20). Additionally, elevated CO₂ and warming temperatures can increase insect vector populations by enabling additional life cycles per season, thereby enhancing disease transmission and undermining host resistance mechanisms (12). Shifts in pathogen prevalence have already been documented

globally, with some diseases declining while others emerge or intensify under new climatic conditions) (21).

In the Indian context, climate change has been linked to the emergence and intensification of several plant disease epidemics. Increased outbreaks of *Phytophthora* diseases, rusts, leaf spots, wilts and blights have been reported across major crops. In the Himalayan and northwestern regions, including Jammu and Kashmir, diseases such as rice blast, sheath blight and grain discolouration have caused increasing yield losses under changing climatic conditions. Similar trends may emerge in Ladakh as temperatures rise and irrigation expands, particularly affecting crops such as barley, wheat, potato, peas and vegetables grown under both protected and open-field conditions. Overall, climate change is expected to alter crop-disease spectra, leading to the emergence of previously minor or economically insignificant pathogens as major threats (7, 22). For high-altitude regions like Ladakh, where agricultural resilience is limited, these changes underscore the urgent need for climate-resilient cropping systems, disease surveillance and location-specific management strategies.

Effects of temperature

Temperature is one of the most critical climatic factors influencing plant growth, pathogen activity and disease development. Climate change-induced temperature variations can activate dormant pathogens, particularly bacteria and fungi, leading to sudden disease outbreaks and epidemics. In high-altitude regions such as Ladakh, vulnerability is especially pronounced due to narrow climatic windows, short growing seasons and heavy reliance on meltwater-driven irrigation systems. Although the susceptibility of high-altitude agroecosystems has been widely documented in regions such as the Himalayas Andes and Alps, evidence specific to Ladakh remains limited. Nevertheless, emerging local observations indicate that farmers and pastoral communities are increasingly experiencing higher incidences of crop diseases and pest infestations. These occurrences are often associated with rising temperatures, altered precipitation patterns and shifting seasonal dynamics (2).

Changes in temperature and rainfall regimes significantly influence crop phenology, pathogen development rates, aggressiveness and host plant physiology, including resistance mechanisms (23, 24). Both the intensity and duration of temperature exposure play crucial roles in determining disease severity under changing climatic conditions (13, 20, 25). Rising temperatures may also promote the emergence of new or previously suppressed pathogen races, thereby increasing the likelihood of unexpected epidemics (26, 27). Furthermore, temperature modulates host defence responses. For instance, heat and sunlight can stimulate the production of phytoalexins and defensive pigments, which may either inhibit or facilitate pathogen establishment depending on the specific host-pathogen interaction (28, 29).

In Ladakh, increasing temperatures combined with expanded irrigation have been associated with the development of favourable microclimates for soil- and water-borne pathogens, particularly species of *Phytophthora*, *Pythium* and *Rhizoctonia* (30). These risks may be further amplified under protected cultivation systems, such as polyhouses, which have been widely adopted as a climate adaptation strategy to extend the growing season and diversify vegetable production. While polyhouses enhance crop productivity, they also create warm and humid conditions that

favour the development of both soil-borne and foliar pathogens, as well as insect vectors. As a result, a range of fungal diseases, including wilting, leaf blight, leaf spots, fruit rot and mildews, have been reported in vegetable crops under Ladakh conditions.

Among these, *Fusarium oxysporum* is recognised as an important soil-borne pathogen causing wilt diseases in crops such as bottle gourd, tomato and capsicum under both open-field and protected cultivation systems (31, 32). Its ability to persist in soil for extended periods contributes to recurring infections and yield losses. Reports from Ladakh also indicate the occurrence of *Fusarium*-associated wilt and dry rot in tomatoes across a wide altitudinal range (9000–14000 ft), highlighting its adaptability to high-altitude agroecosystems (30). In addition, polyhouse conditions have been reported to favour foliar diseases such as powdery mildew and downy mildew, along with damping-off caused by *Pythium* spp. and *Rhizoctonia solani*.

These changing microclimatic conditions also support the survival and earlier seasonal activity of insect vectors. Pests such as aphids and whiteflies, previously limited by prolonged and severe winters, are now being observed earlier in the growing season, increasing the likelihood of virus transmission in crops such as peas and leafy vegetables (33). Temperature-driven changes can also significantly influence insect vectors by accelerating development rates, increasing the number of generations per season, expanding geographical ranges and elevating the risk of invasion by alien pest species (34, 35).

Disease management practices may also vary in effectiveness under warming conditions. Proper seed treatment remains an effective strategy for managing wheat diseases such as Karnal bunt (*Tilletia indica*) and common bunt (*Tilletia caries*), particularly in low-productivity or stress-prone agroecosystems under climate change scenarios (36, 37). Conversely, high temperatures exceeding critical thresholds can compromise genetic resistance, as observed in chickpea, where temperatures above 33 °C increase the risk of dry root rot even in *Fusarium* wilt-resistant cultivars (38). Overall, temperature-driven changes under climate change are expected to substantially reshape disease patterns, severity and management challenges, especially in climatically sensitive regions like Ladakh, where even small shifts in thermal regimes can have disproportionately large impacts on plant health and agricultural sustainability.

Effect of soil moisture

Soil moisture is a critical environmental factor influencing plant health, pathogen activity and disease development. Variations in soil water availability directly affect host physiology while simultaneously shaping the survival, infection and spread of plant pathogens. Diseases such as apple scab, potato late blight and several soil- and root-infecting pathogens are strongly associated with increased moisture levels, as their infection processes are closely linked to leaf wetness duration, relative humidity and precipitation patterns (27, 39). Consequently, disease forecasting models for many of these pathogens rely heavily on moisture-related parameters.

In the high-altitude Himalayas, soil moisture dynamics are largely governed by snowmelt, glacier-fed irrigation and limited rainfall. Climate change-induced shifts in precipitation timing, reduced snow cover and irregular irrigation availability have resulted in alternating periods of moisture stress and excess soil

wetness (40, 41). Drought stress weakens plant defence mechanisms, making crops more vulnerable to infections, particularly viral diseases (27, 42). Conversely, episodic increases in soil moisture following unseasonal rainfall or excessive irrigation can create favourable conditions for water-borne pathogens such as *Phytophthora*, *Pythium* and *Rhizoctonia*, especially in vegetable crops and under protected cultivation systems increasingly adopted in Ladakh (43). Poor drainage and temporary waterlogging further exacerbate root diseases, leading to significant yield losses (42).

Effect of rising CO₂ levels

Rising atmospheric carbon dioxide (CO₂) concentrations influence plant-pathogen interactions in complex and sometimes contrasting ways by affecting both host plants and their associated pathogens. Elevated CO₂ levels often stimulate plant growth, resulting in increased leaf area, biomass accumulation and canopy density. While enhanced growth may appear beneficial, the formation of dense canopies can create favourable microclimatic conditions—such as higher humidity and prolonged leaf wetness—that promote the development and spread of moisture-loving bacterial and fungal pathogens (20, 27).

Under elevated CO₂ conditions, increased plant biomass and reduced rates of plant residue decomposition may lead to greater accumulation of crop residues in the field. This can enhance pathogen survival during unfavourable seasons, resulting in higher initial inoculum levels and earlier disease onset in subsequent cropping cycles. Such effects are particularly relevant in high-altitude regions like Ladakh, where cold winters have traditionally limited pathogen survival. Warming trends combined with increased CO₂ may weaken this natural suppression, increasing disease carryover between seasons. Elevated CO₂ can also exert direct effects on pathogen growth and reproduction. In some cases, higher CO₂ concentrations suppress the vegetative growth of certain pathogens; however, sporulation rates may increase, potentially intensifying disease spread once infection is established. Moreover, increased CO₂ alters host plant physiology, including the carbon-nitrogen balance, stomatal behaviour and defence signalling pathways, which can either enhance or reduce disease resistance depending on the crop-pathogen system (6, 39).

Increased CO₂ levels generally enhance photosynthesis and carbohydrate accumulation in host tissues, leading to higher concentrations of sugars such as glucose. These conditions can favour biotrophic pathogens, including rusts and powdery mildews, which rely on living host tissue for nutrition (44). Consequently, increased biomass production may inadvertently raise infection risk by modifying plant architecture and microclimate (45). Dense plant stands tend to retain moisture for longer periods and buffer temperature fluctuations, creating conditions that favour foliar bacterial diseases (46).

In Ladakh, where agriculture is increasingly shifting towards protected cultivation and intensified vegetable production, rising CO₂ concentrations combined with irrigation and warmer temperatures may significantly alter disease dynamics. While elevated CO₂ may enhance crop growth under controlled environments, its interaction with limited nutrient availability, water stress, weed competition and pest pressure ultimately determines yield outcomes. Furthermore, the combined effects of elevated CO₂ and other atmospheric pollutants, such as ozone, may exacerbate disease severity in certain host-pathogen systems,

although higher CO₂ concentrations may partially mitigate ozone-induced damage (47, 48).

Impact of climate change on disease management practices

Climate change is expected to substantially influence plant disease management by modifying pathogen biology, host resistance mechanisms and the effectiveness of control strategies. Changes in temperature, atmospheric carbon dioxide concentration, rainfall pattern and relative humidity can alter pathogen life cycles, rates of evolution and virulence, thereby challenging existing disease management approaches (27, 39). These shifts may also reduce the reliability of conventional chemical, biological and host resistance-based control measures (23).

The effectiveness of chemical disease management is particularly sensitive to climatic variability. Increased frequency and intensity of rainfall events can wash off protective fungicides from crop surfaces, reducing their residual activity and necessitating more frequent applications. In high-altitude regions such as Ladakh, where short growing seasons require precise and timely interventions, this can increase production costs and compromise disease control efficiency. Additionally, crops grown under elevated CO₂ and higher temperatures often exhibit morphological and physiological changes, such as thicker epicuticular wax layers and altered stomatal behaviour, which can reduce the absorption and translocation of systemic fungicides (37, 39). Conversely, higher temperatures may accelerate plant metabolic activity, leading to faster uptake of certain agrochemicals. While this may improve fungicide efficacy in some cases, it can also increase the risk of phytotoxicity, particularly under protected cultivation systems increasingly adopted in Ladakh. Furthermore, larger and denser canopies formed under elevated CO₂ conditions may hinder uniform spray coverage, leaving untreated zones that favour disease persistence and spread.

Climate change also presents major challenges to host resistance-based disease management. Although genetic mutations and physiological adjustments under changing climate conditions may enhance resistance to specific pathogens, rapid pathogen reproduction and shortened disease cycles can accelerate the breakdown of resistance genes. This increases the likelihood of pathogens evolving new races capable of overcoming existing resistance, particularly in monocropped or genetically uniform cropping systems (36). Similarly, the performance and reliability of biological control agents are strongly influenced by climate variability. Changes in temperature and humidity can affect population dynamics and competitive interactions between biocontrol organisms and pathogens. While beneficial microorganisms may suppress disease development under favourable conditions, environmental changes may also shift the balance in favour of pathogens, thereby reducing biocontrol efficacy and increasing uncertainty under future climate scenarios (49). In high-altitude agroecosystems, increasing connectivity through the exchange of seed, seedling and planting material further elevates the risk of introducing new and unexpected pathogens. Climate change may further enhance the establishment potential of such introduced organisms, as changing environmental conditions can promote pathogen adaptation, evolution and geographic expansion (7, 28). This makes quarantine, sanitation and disease surveillance more challenging for regulatory authorities.

Overall, climate change is likely to increase the complexity of plant disease management by reducing the predictability and

effectiveness of existing control measures. Variations in temperature, precipitation and extreme weather events significantly influence pathogen virulence, dispersal and host susceptibility (7, 17, 50). Furthermore, climate change can alter the efficiency of chemical and biological control methods, necessitating adaptive and integrated approaches (51, 52). In fragile agroecosystems like Ladakh, this underscores the need for integrated disease management strategies that combine climate-resilient cultivars, improved forecasting systems, adaptive chemical use, biological control and strong phytosanitary regulations to ensure sustainable crop production (53, 54).

Adaptation strategies

Recent projections indicate that climate extremes such as irregular precipitation, temperature fluctuations and shifting agro-ecological zones are becoming more frequent worldwide, signalling that climate change impacts are already underway (40–43). These changes are particularly evident in fragile mountain ecosystems, where even small climatic shifts can have pronounced effects on agricultural productivity and stability (17, 50). Climate change alters temperature, precipitation and the frequency of extreme weather events, thereby influencing crop growth, disease dynamics and overall agricultural sustainability (17, 50). In regions like Ladakh, warming trends, shrinking glaciers and altered snowfall patterns are reshaping traditional farming systems and increasing vulnerability to climatic risks, particularly due to strong dependence on glacier- and snowmelt-fed irrigation systems.

Effective adaptation to climate change requires an integrated approach combining scientific and indigenous knowledge systems, as emphasised in climate-resilient agricultural frameworks (55, 56). However, the implementation of such approaches in high-altitude regions like Ladakh may be constrained by limited infrastructure and socio-economic factors. Incorporating indigenous practices alongside modern technologies can help policymakers and extension agencies develop practical, location-specific strategies. Strong coordination between public institutions, research organisations and the private sector is essential for designing and implementing resilient agricultural systems suited to high-altitude conditions, as emphasised in climate-resilient disease management frameworks (55, 56). At the farm level, adaptation will involve the adoption of flexible agronomic practices that are already effective under variable climatic conditions. Strategies such as adjusting sowing and harvesting dates, adopting climate-resilient cultivars and diversifying crop rotations are widely recommended as key adaptation measures under changing climatic conditions (57, 58). However, their practical effectiveness in Ladakh may be limited by the region's short growing season, harsh climatic conditions and constraints related to water availability, infrastructure and access to improved inputs, highlighting the need for location-specific adaptation approaches.

At higher levels of adaptation, more transformative changes may be required. These could involve the introduction of new crops or cropping systems better suited to emerging climatic conditions, or even shifts in cultivation zones as temperature regimes and water availability change. Climate change is known to modify agro-climatic zones and influence crop distribution patterns (4). Warmer conditions may accelerate crop development, shortening grain-filling periods and reducing yield potential. This challenge can be partially addressed by adopting cultivars with longer maturity durations, which allow sufficient time for biomass and grain

accumulation under warmer conditions. Land and water management practices will also need to evolve. Transitioning from rainfed to irrigated agriculture may improve yield stability; however, in cold desert regions like Ladakh, water scarcity and dependence on meltwater systems limit this option, as agriculture is highly sensitive to changes in water availability and hydrological variability. Therefore, efficient water-use practices such as micro-irrigation, water harvesting and improved glacier-fed irrigation management will be crucial components of climate adaptation.

Despite these options, it is unrealistic to expect complete or uniform adaptation to future climate conditions. Some strategies, such as adjusting planting dates or improving crop management, are likely to be effective in reducing climate stress. Others, such as large-scale changes in crop types, rotations, or farming regions, may not fully offset the impacts of extreme events like droughts, floods, or unseasonal frosts. Climate change is known to increase the frequency of extreme weather events, thereby complicating disease management and reducing the effectiveness of control measures (7, 9). Moreover, adaptation is not solely a technical challenge; social, cultural and economic factors strongly influence farmers' willingness and capacity to adopt new practices. In Ladakh, community traditions, labour availability, access to markets and institutional support significantly shape adaptation outcomes and the resilience of local farming systems. Overall, climate change adaptation in high-altitude agriculture must be flexible, locally relevant and socially inclusive, ensuring that scientific innovations align with farmers' needs, resources and traditional knowledge systems. Such integrated approaches are essential for developing sustainable and resilient agricultural systems under changing climatic conditions.

Mitigation strategies

Climate variability is increasingly recognised as a key driver necessitating a shift from static to adaptive disease management approaches, as changes in temperature and atmospheric CO₂ alter pathogen distribution, virulence and epidemic dynamics (39, 59). A critical challenge for chemical mitigation is the environmental fate of fungicides under intensified weather events. Research on mancozeb wash-off indicates that fungicide loss follows a hyperbolic decay curve, where 5 mm of torrential rain can remove up to 90 % of surface residues, compared to only 50 % under light precipitation. Furthermore, extending drying windows from 2 to 24 hr significantly enhances rainfastness (60). Consequently, synchronising pesticide applications with high-resolution meteorological forecasts to ensure adequate drying time is a vital adaptive strategy for maintaining efficacy amid shifting precipitation regimes driven by climate change. Reliable medium-range weather forecasts further enable precise pesticide timing, avoiding rain to boost efficacy and counter wash-off risks from intensifying precipitation, thereby minimising losses and enhancing integrated disease management (IDM) resilience (61).

In addition to precipitation-driven effects on pesticide performance, rising atmospheric CO₂ introduces further complexity in plant-pathogen-pesticide interactions. Beyond moisture, physiological adaptations to elevated CO₂ fundamentally alter host-pathogen-pesticide interactions. Morphological changes, such as increased cuticular wax deposition and leaf thickness, create physical barriers that hinder the penetration and translocation of non-systemic fungicides (62). These shifts necessitate a transition

toward systemic products or advanced formulations to overcome enhanced cuticular defences. Additionally, CO₂ induces stomatal closure, which reduces transpiration and alters the canopy microclimate (63). This vegetation feedback can lead to localised warming and increased humidity within the canopy, potentially creating niches that accelerate pathogen sporulation and shift periods of maximum disease susceptibility (39, 63). Effective mitigation in high-altitude regions must therefore integrate IDM frameworks that combine climate-resilient product selection with adjusted spray phenology and the use of biological control agents capable of functioning across wide diurnal temperature ranges.

Proactive disease management requires robust monitoring and forecasting systems. The changing climate is altering pathogen distribution and virulence, as seen with *Fusarium pseudograminearum*, which favours drier and colder conditions during early growth stages (64). Therefore, localised, real-time data on weather variables (temperature, humidity, rainfall) and pathogen presence is essential. Participatory surveillance, engaging farmers and local agricultural extension officers, can complement formal monitoring efforts, as demonstrated by research on changing disease and pest status in the Indian Himalayas.

In addition to adaptive chemical use and surveillance, the deployment of genetically resistant varieties offers the most sustainable long-term defence. Recent studies have identified quantitative trait loci (QTLs) for rust resistance specifically suited to high-altitude Himalayan conditions. A major adult plant resistance (APR) QTL, QYr.cau-1DL on chromosome 1DL (320.6–325.8 Mb), from landrace Qishanmai (southern Gansu, near Himalayas), reduces disease severity by 44–48 % across environments and demonstrates durability in *Puccinia striiformis* f. sp. *tritici* (Pst) hotspots. Additionally, a novel locus on DS (QYr.uzh-3D.1) from a Nepalese landrace provides stable field resistance in NAM trials (65). These genetic resources are critical for developing climate-resilient wheat varieties for the Himalayan region, highlighting the importance of integrating host resistance with adaptive management strategies under changing climatic conditions. However, the effectiveness of these mitigation strategies may vary across locations due to resource constraints, variability in farmer adoption and the dynamic nature of climate-disease interactions, particularly in remote high-altitude regions like Ladakh.

Conclusion and Future directions

Agriculture in mountainous regions is facing growing uncertainty as environmental changes continue to influence crop performance and plant health. Changing climatic conditions are altering biological interactions, often giving rise to unexpected disease patterns and increasing risks to productivity. These emerging challenges highlight the limitations of conventional practices and underline the need for more flexible, informed and responsive approaches. Looking ahead, greater attention should be given to early warning systems, region-specific research and the development of crop varieties that can tolerate multiple stresses. Strengthening field-level monitoring, improving the efficient use of resources and supporting adaptive farm practices will be important steps forward. Equally vital is bridging scientific knowledge with farmers' practical experience, backed by strong institutional support. Ultimately, a collaborative and forward-thinking approach

will be essential to sustain agriculture and build long-term resilience in these vulnerable environments.

Authors' contributions

SD conceptualised the review, conducted the literature survey and prepared the original draft. PT data interpretation, critical revision of the manuscript and refinement of the scientific content. JL technical guidance and structure of review. TL provide technical guidance and editing of the review. All authors read and approved the final manuscript.

Compliance with ethical standards

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to improve language clarity, grammar and overall readability and to assist in structuring the scientific content. All authors critically reviewed and edited the generated content and take collective responsibility for the accuracy, integrity and originality of the final manuscript. The use of this tool did not replace the authors' intellectual contributions or scientific interpretation.

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