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REVIEW

Climate change and plant protection: challenges and innovations in disease forecasting systems in developing countries

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Abstract

Plant disease forecasting plays a crucial role in managing outbreaks and mitigating economic and health impacts, thereby contributing significantly to plant protection efforts. This proactive approach assesses the likelihood of disease outbreaks and increases in disease intensity, enabling timely intervention and resource optimization. However, climate change exacerbates this challenge by altering pathogen evolution and host-pathogen interactions, fostering the emergence of new pathogenic strains, shifting pathogen ranges, and expanding the geographic spread of plant diseases. In developing countries, these changes are compounded by limited resources and inadequate infrastructure, creating significant challenges for forecasting systems and plant protection efforts. The primary objective of this review was to assess the impact of climate change on plant disease forecasting systems, with a focus on biotic and abiotic stresses such as temperature changes, altered precipitation patterns, and extreme weather events. A systematic literature review was conducted using databases such as PubMed, Web of Science, and Google Scholar, selecting peer-reviewed studies published between 2020 and 2024. Key data on research objectives, methodologies, results, and implications were extracted and synthesized, demonstrating how climate-induced stresses affect components of the disease tetrahedron, including host susceptibility, pathogen virulence, environmental conditions, and vector dynamics. The findings reveal that climate change significantly affects forecasting systems and plant protection strategies, emphasizing the need for reliable, and cost-effective forecasting models adaptable to diverse and evolving climate conditions, especially in resource-constrained settings. This review underscores the importance of developing innovative and context-specific strategies to enhance forecasting capabilities and plant protection. Future research should focus on advancing forecasting technologies, addressing data gaps, and adapting systems to evolving climate conditions to better safeguard food security and environmental sustainability.

Keywords: adaptation strategies, biotic and abiotic stresses, digital technologies, early warning systems, food security, host-pathogen interactions

Introduction

Plant disease forecasting is essential for predicting disease occurrences within specific geographical areas, facilitating the timely implementation of plant protection strategies to prevent significant losses (Gonzalez-Dominguez *et al.* 2023). This proactive approach involves assessing the likelihood of disease outbreaks and increased disease intensity, necessitating coordinated efforts and substantial resource allocation, including time, energy, and funding, to effectively manage and protect plants from diseases (Singh 2022). The primary objectives of plant disease forecasting and protection are to minimize production costs and ensure the safety of products for consumers and the environment (Singh *et al.* 2023).

With the advent of climate change (CC), the importance of plant disease forecasting and protection has become even more pronounced. CC exacerbates the risks of pathogen outbreaks through alterations in pathogen evolution and host-pathogen interactions. These changes foster the emergence of new pathogenic strains, shift pathogen ranges, and expand the geographic spread of plant diseases (Mahapatra 2018). For instance, the changing climate influences weather patterns, temperature fluctuations, and humidity levels, which are critical factors in the life cycle of pathogens. Such environmental shifts can extend the growing season for pathogens or facilitate the emergence of more aggressive strains, complicating disease management efforts. Verma *et al.* (2024a) note that the shifting climate has significant consequences for agricultural sustainability, making it even more challenging to predict and manage plant diseases effectively.

Effective forecasting systems rely on understanding the intricate interactions among pathogens, hosts, environments, and vectors, as conceptualized by the disease tetrahedron model (McLeish *et al.* 2020). Accurate predictions are achieved when these factors converge to create conditions conducive to significant disease development and crop loss. This scientific method aims to provide farmers and stakeholders with timely alerts, enabling them to take preventive actions and optimize the use of resources, thereby reducing the economic burden on agricultural systems. Verma *et al.* (2024) also emphasize the importance of adopting regulatory mechanisms that facilitate adaptation to adverse agroclimatic variables which play a critical role in disease management strategies.

In developing countries, where resources for plant disease management and protection are often limited, climate change-induced stresses further complicate disease forecasting systems. Increased frequency and intensity of biotic and abiotic stresses such as elevated temperatures, altered precipitation patterns, and extreme weather events pose unique challenges. These stresses affect the components of the disease tetrahedron, including host susceptibility, pathogen virulence, environmental conditions, and vector dynamics (Bernardo-Cravo *et al.* 2020). Consequently, forecasting systems in these regions must be reliable, user-friendly, cost-effective, and adaptable to the diverse and evolving conditions brought about by climate change. Kumari *et al.* (2023) argue that soil microbes represent a natural solution for mitigating the impacts of climate change, an insight that could be crucial for forecasting and plant protection systems in regions where agroclimatic conditions are rapidly changing. Addressing these challenges requires tailored and locally adaptive models that can effectively respond to the distinct agroecological and socio-economic contexts.

Successful case studies from various regions demonstrate the potential of advanced plant disease forecasting and protection systems. For instance, the International Rice Research Institute (IRRI) in Asia developed a rice disease forecasting system that integrates remote sensing and field observations, significantly reducing disease incidence and improving yield stability (Alfred *et al.* 2021). Similarly, CABI's Plantwise program has built a network of plant clinics across developing countries, improving pest and disease management through localized advice (Adhikari *et al.* 2024). In Uganda, CABI's Pest and Disease Alert System has reduced crop losses and improved food security by utilizing weather data and GIS for localized forecasting. The FAO's early warning systems in Eastern Africa have enhanced the timing and targeting of disease management interventions, while the Horticultural Innovation Lab (HIL) in India has effectively managed horticultural diseases through technology integration (Singh and Parihar, 2024) (Hassanaliyeva *et al.* 2022).

These examples illustrate the effectiveness of integrating technology with local expertise to address plant disease forecasting and protection challenges. This article delves into the biotic and abiotic stresses induced by climate change that impact plant diseases, emphasizing the urgent need for timely and accurate disease forecasting and protection measures. It underscores the necessity for innovative, transformative, and context-specific strategies to enhance forecasting systems and effectively manage these stresses. In an era characterized by the emergence and re-emergence of stress factors, particularly in developing countries, implementing robust forecasting and protection strategies is essential to safeguard global food security and promote environmental sustainability in the face of ongoing climate change.

Materials and Methods

This review adopted a systematic approach to evaluate the effects of climate change on plant disease forecasting and protection systems. A comprehensive literature search was conducted across multiple academic databases, namely PubMed, Web of Science, Google Scholar, Scopus, and the Agricultural and Environmental Science Database (Sarkar *et al.* 2022). Search terms included "climate change", "plant disease forecasting", "plant protection", "biotic stress", and "abiotic stress", with a focus on studies published between 2000 and 2024. The review considered peer-reviewed articles that addressed the impacts of climate change on forecasting and protection systems as well as related biotic and abiotic stresses in developing countries. Non-peer-reviewed sources and irrelevant studies were excluded to ensure methodological rigor and data validity.

Data extraction was performed to gather information on review objectives, methodologies, results, implications, and challenges. This process allowed for the systematic categorization of data, which was then synthesized to assess how various climate change factors such as temperature fluctuations, altered precipitation patterns, and extreme weather events affect plant disease dynamics and protection strategies. The extracted data were organized thematically, identifying strategic solutions for managing the impacts of climate change on disease forecasting and protection systems.

The quality of the studies included in the review was assessed based on the relevance of their content to the research objectives, the rigor of their methodologies, and the clarity of their findings. Additionally, studies were evaluated for their regional applicability, particularly in developing countries where resources and infrastructure may limit forecasting and protection system effectiveness. The findings were organized thematically and presented using tables and figures to provide a comprehensive overview of the challenges and solutions related to climate-induced changes in plant disease dynamics and protection efforts.

The importance of plant disease forecasting and protection systems in developing countries

Plant disease forecasting and protection systems are increasingly vital in developing countries, particularly due to the growing complexity of climate-induced abiotic and biotic stresses (Gowtham *et al.* 2024). Rising global temperatures, altered precipitation patterns, and frequent extreme weather events, such as floods and droughts are direct consequences of climate change. Projections indicate that global temperatures could increase by up to 4.8°C by the end of the century which directly affect plant health and disease dynamics (Shokory *et al.* 2023). This intensifies the need for effective forecasting and protection systems, which have already been adopted in various regions, with tools like FARM-D, DSSAT, CropWatch, and Agro--Meteorological Advisory Services offering predictive solutions based on weather data, satellite imaging, and local forecasts (Tab. 1). However, despite these advancements, challenges such as limited data, inadequate infrastructure, and insufficient expertise continue to hamper their full potential. Enhancing these systems by integrating environmental factors like sunlight, humidity, and temperature is critical for improving disease management under changing conditions. Even highly susceptible plants may resist disease under unfavorable conditions (Chen 2020). This highlights the need for locally adapted plant disease forecasting systems, as climate change alters environmental conditions that influence disease dynamics. Effective forecasting must integrate local climate data and adaptive strategies, utilizing tools like machine learning and GIS to predict and manage disease outbreaks in a changing climate.

Implications of climate change on plant disease forecasting, protection systems and disease dynamics

Climate change significantly impacts plant disease forecasting and protection systems by disrupting the interactions within the disease tetrahedron (Fig. 1)

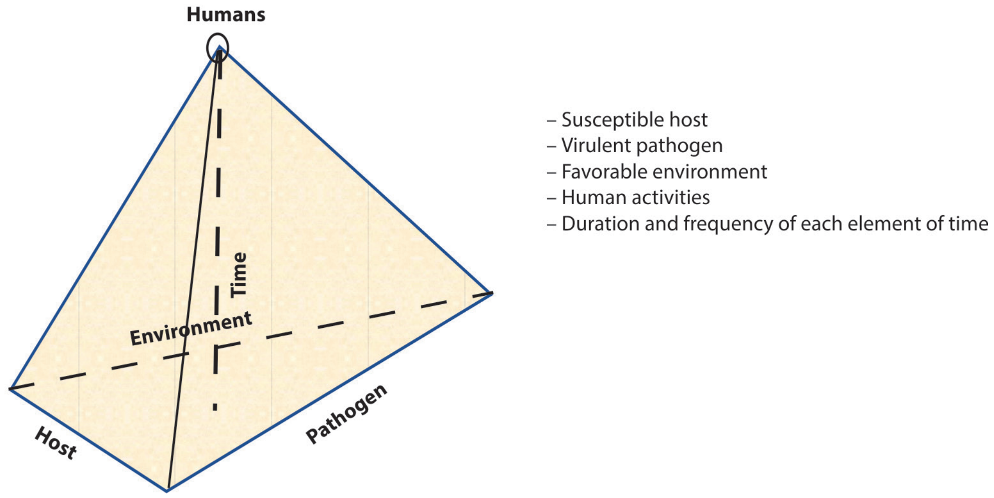

Fig. 1. The classic disease tetrahedron: factors in plant disease epidemics.
This highlights the necessity for sophisticated forecasting systems that can account for these complex interactions and adapt to the evolving challenges posed by climate change

Table 1. Plant disease forecasting systems in developing countries: their functionality, effectiveness, and challenges

System	Functionality	Effectiveness	Challenges	References
FARM-D	integrates weather data, crop models, and historical disease data to offer predictive tools for anticipating disease outbreaks	improves decision-making, reduces crop losses, and enhances resource use efficiency	limited data availability, technological infrastructure, and local expertise	Hegedus and Maxwell (2022)
DSSAT	models effects of agronomic practices and environmental conditions on crop growth and disease, providing predictions about yield, pest, and disease risk	optimizes agricultural practices and improves disease forecasting accuracy	complexity of system and need for detailed input data can be barriers in low-resource settings	Sreeshna *et al.* (2024)
CropWatch	uses satellite data and climate models for real-time monitoring and forecasting of pest and disease risks, offering broad spatial coverage	enhances pest and disease management by providing insights into emerging threats and enabling proactive measures	reliance on satellite data and advanced analytical tools, which may be challenging in regions with limited technology	Nakalembe *et al.* (2021)
Agro-Meteorological Advisory Services	integrates local weather data with disease forecasting models to provide customized recommendations for farmers	delivers localized advice that improves disease management and crop productivity	accuracy and timeliness of weather data, and communication of recommendations for farmers	Bacci *et al.* (2023)

Table 2. Examples of climate-driven changes in disease outbreaks

Disease	Pathogen	Host		Climate variables involved	Impacts	References
		common name	botanical name			
Dry root rot	*Rhizoctonia bataticola*	chickpea	*Cicer arietinum*	temperature shifts	increased incidence when temperatures exceed the thresholds	Rai *et al.* (2022)
Phytophthora blight	*Phytophthora drechsleri* f. sp. *cajani*	pigeon pea	*Cajanus cajan*	increased moisture	significant yield reduction	Satheesh Naik *et al.* (2020)
Common bunt	*Tilletia caries*	wheat	*Triticum aestivum*	general climate change conditions	increased prevalence	Madenova *et al.* (2020)
Karnal bunt	*Tilletia indica*	wheat		general climate change conditions	increased prevalence	Bala *et al.* (2022)
Fusarium wilt		cotton	*Gossypium hirsutum*	soil temperature, moisture	reduced yield	Kumar *et al.* (2021)
Canker diseases		apple	*Malus domestica*	reduced rainfall, intensified dry spells	increased incidences	Kumar *et al.* (2021)
	Phytophthora Infestans	potatoes	*Solanum tuberosum*	drought, changes in root exudates	altered soil microbial communities, influencing the prevalence of soil-borne pathogens	Thines *et al.* (2021)

and altering disease dynamics (Tab. 2). Beyond temperature shifts, climate change affects plant susceptibility, disease timing, and pathogen behaviors, complicating forecasting accuracy. For example, higher temperatures and elevated CO2 levels may accelerate pathogen mutations, potentially resulting in more virulent strains. Additionally, climate change can expand the range of disease vectors, such as insects, further complicating disease management (Bebber *et al*. 2022; Kumari *et al*. 2023; Verma *et al*. 2024b).

Integrating high-resolution satellite imagery, AI-driven algorithms, and climate models with pathogen dynamics can enhance forecasting accuracy, providing better predictions and mitigation strategies for climate-induced stresses on plant diseases. In developing countries, where advanced forecasting systems may be limited, these challenges can be especially pronounced.

Changes in climate also alter microclimates within agricultural systems, increasing humidity and favoring fungal growth, while shifting weather patterns may support a wider range of diseases. These changes affect both pathogen development and the effectiveness of forecasting and protection systems (Fones *et al*. 2020). Furthermore, climate change can expand the range and activity periods of insect vectors, increasing the incidence of vector-borne diseases. For instance, milder winters may improve insect survival rates, intensifying disease transmission and complicating forecasting efforts.

Recent advances in predictive modeling and remote sensing technologies offer promising solutions. High-resolution satellite imagery and advanced AI algorithms can improve forecasting accuracy by providing more detailed, timely data. By integrating climate models with pathogen dynamics, these technologies can enhance our ability to predict and mitigate climate-induced stresses on plant diseases.

Addressing these challenges requires a multifaceted approach that strengthens technological infrastructure, improves data collection, and develops adaptive forecasting models tailored to the unique conditions of developing regions. By leveraging recent technological advancements and focusing on local adaptation, plant disease forecasting and protection systems can be more effectively designed to meet the needs of developing countries in the face of climate change. This underscores the necessity for sophisticated forecasting systems that account for complex climate-disease interactions and adapt to the evolving challenges posed by climate change.

Integrating climate change and disease forecasting systems

To effectively manage the impact of abiotic stresses on plant diseases, enhancing plant disease forecasting systems is essential. Integrating advanced technologies such as remote sensing, Geographical Information Systems (GIS), and predictive modeling can improve the accuracy of disease forecasts under changing climatic conditions (Jeger *et al*. 2021). Real-time data on environmental variables, host susceptibility, and pathogen dynamics can help adapt forecasts to evolving climate scenarios (McRoberts *et al*. 2021). Machine learning and artificial intelligence can further refine these systems by analyzing extensive datasets and identifying patterns related to abiotic stress impacts (Fones *et al*. 2020). Collaborative efforts among researchers, farmers, and policymakers are crucial to develop and implement effective forecasting and management strategies that address both biotic and abiotic stresses exacerbated by climate change. This approach is vital for safeguarding crop health, enhancing food security, and promoting sustainable agricultural practices (Bouri *et al.* 2023). Understanding and integrating these elements into plant disease forecasting systems will help mitigate the adverse effects of climate change, ensuring more resilient and adaptive agricultural practices. Continued research and investment in forecasting technologies and strategies are crucial for effectively managing the evolving challenges in plant disease management.

Challenges and barriers to plant disease forecasting systems in developing countries

Climate change poses significant challenges to plant disease forecasting systems, particularly in developing countries where resources and infrastructure for effective disease management may be limited. Shifts in temperature and precipitation patterns can alter the geographical ranges of pathogens and vectors, impacting the accuracy of disease forecasts and the effectiveness of management strategies (Singh *et al*. 2023). Extreme weather events, such as heavy rainfall or droughts, can either promote disease outbreaks or disrupt established forecasting models and practices (Clarke *et al*. 2022). These challenges are exacerbated by limited infrastructure and resources, including inadequate access to advanced forecasting systems and timely interventions.

Climate-induced changes in host physiology and phenology further complicate disease forecasting. Plants under climate stress may become more susceptible to infections, and altered climatic conditions can shift the distribution and timing of host plants, potentially exposing them to new or more aggressive pathogens (Hunjan and Lore 2020). Adapting forecasting systems to these changing conditions can be particularly challenging for regions heavily reliant on traditional agricultural practices. In addition to these climate-related challenges, specific barriers impede the implementation of advanced forecasting systems in developing countries:

– **Technological and Infrastructural Constraints:** Limited access to modern technologies, inadequate internet connectivity, power supply issues, and lack of technical expertise hinder the deployment of advanced tools such as remote sensing, GIS, and artificial intelligence (AI) (Kumari *et al*. 2022; Quamar *et al*. 2023). The high cost of these technologies further restricts their adoption.
– **Climatic and Agricultural Variability:** The variability in climatic conditions and agricultural practices across different regions necessitates tailored forecasting models. Developing countries often face difficulties in collecting and integrating local data, which is crucial for accurate predictions. The lack of standardized data collection methods and insufficient training for local farmers and extension services impede effective forecasting and management.
– **Capacity Building and Training:** Enhancing local expertise through training programs is vital but often lacking. Many regions struggle with insufficient knowledge and skills to effectively utilize forecasting systems and interpret data.
– **Financial Constraints:** The financial burden of implementing and maintaining advanced forecasting technologies can be prohibitive. Many developing countries struggle to secure adequate funding for infrastructure development, technological advancement, and ongoing research.
– **Policy and Regulatory Frameworks:** There is often a lack of supportive policies and frameworks to facilitate the adoption of forecasting systems. In adequate policy development can hinder the implementation and scaling of these technologies.

Addressing the Challenges of Plant Disease Forecasting in Developing Countries

While climate change complicates plant disease forecasting, several barriers impede the implementation of effective systems in developing countries. Challenges such as technological limitations, lack of infrastructure, and financial constraints limit access to advanced forecasting tools like remote sensing, GIS, and AI technologies. Climatic variability across regions also requires tailored forecasting models, yet the absence of standardized data collection and insufficient training prevent effective adaptation to these local conditions (Verma *et al*. 2020a; Quamar *et al*. 2023). Moreover, financial and policy barriers hinder the widespread adoption of forecasting technologies. Overcoming these challenges requires multifaceted solutions, including enhancing technological infrastructure, building local expertise, and developing region-specific forecasting models.

Impact of biotic and abiotic stresses on plant disease forecasting systems in developing countries

Climate change significantly exacerbates both biotic and abiotic stresses in plants, which profoundly influences plant disease dynamics (Juroszek *et al*. 2020; Verma *et al*. 2020b). These stresses complicate plant disease forecasting systems, particularly in developing countries where forecasting capabilities are often limited. Abiotic stresses, such as temperature extremes and altered precipitation patterns can negatively affect plant health and increase susceptibility to diseases. Concurrently, biotic stresses, including the proliferation of pathogens and pests, further complicate forecasting models.

In developing regions, the impacts of these stresses are exacerbated by limited resources and infrastructure. The interplay between climate change and plant disease dynamics, forecasting systems must provide accurate predictions and management recommendations. This requires integrating a comprehensive conceptual framework that accounts for both biotic and abiotic stresses (Fig. 2) in order to develop robust plant disease forecasting systems, ultimately improving disease management and enhancing agricultural resilience (Verma *et al*. 2022).

Biotic stresses

Climate change significantly impacts various biotic factors affecting plant health, including host resistance, the abundance of susceptible hosts, pathogen evolution, vector activity, and ecosystem dynamics. These changes have profound implications for plant disease forecasting and management. This table summarizes key biotic stresses influenced by climate change and their effects on plant disease dynamics. It also highlights how integrating disease forecasting systems can help address these challenges by incorporating real-time data and predictive models.

Table 3 presents an overview of how different biotic stresses such as shifts in host resistance, increased pathogen virulence, and changes in vector activity impact disease dynamics and forecasting efforts. For each stress, it outlines the climate change impacts, potential implications for plant health, and examples of forecasting systems that incorporate these factors to enhance disease management strategies. By understanding these interactions, researchers and practitioners can develop more effective forecasting tools

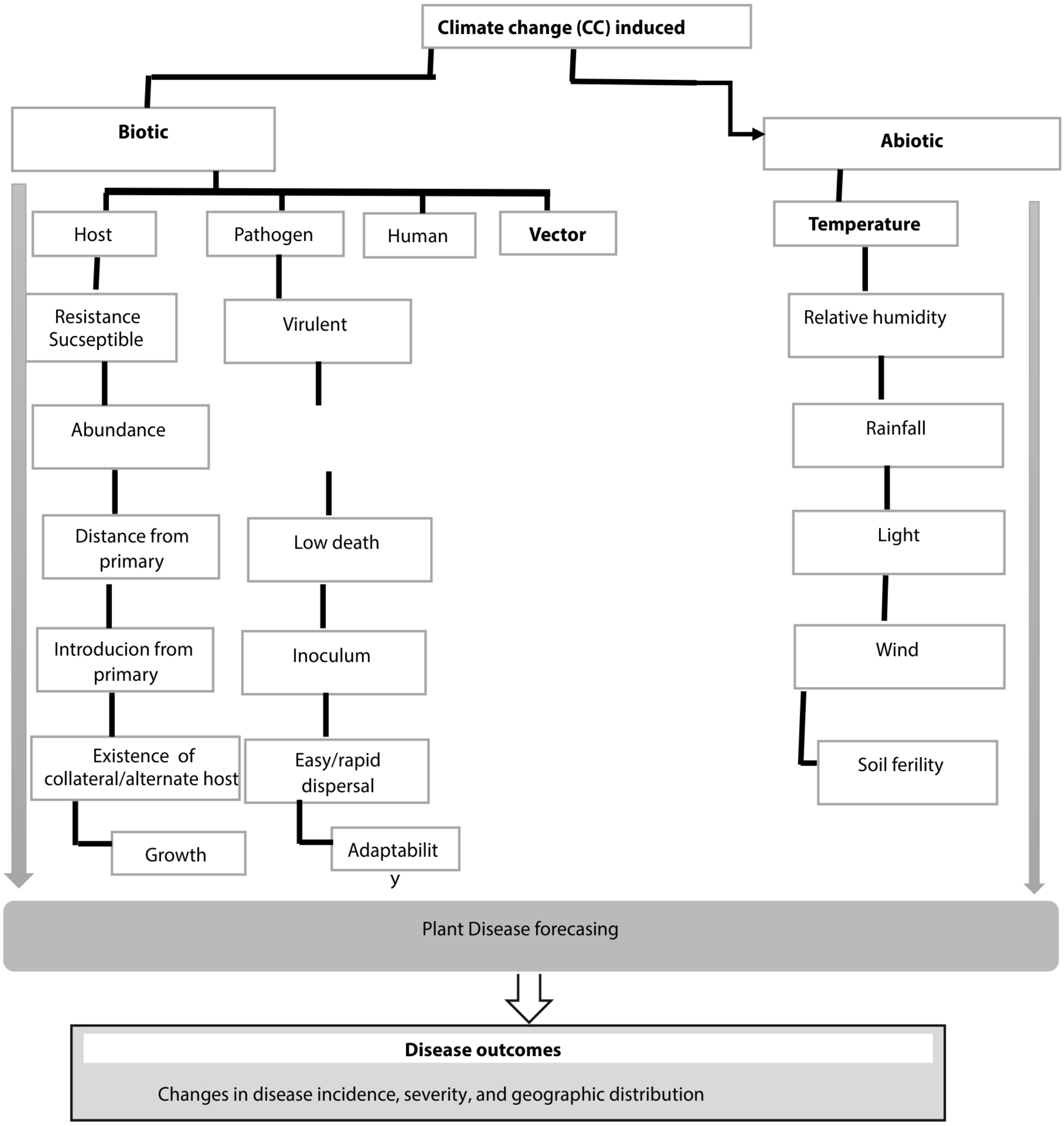

Fig. 2. Conceptual framework of climate change impacts on plant disease

and management practices to mitigate the effects of climate change on agriculture (Tab. 4).

Abiotic stresses

Abiotic stresses, originating from non-living environmental factors, have a significant impact on plant health and disease dynamics (Tab. 5). Environmental variables such as temperature, humidity, rainfall, light, wind, and soil characteristics play critical roles throughout the disease cycle by influencing processes such as spore germination, colonization, sporulation, and pathogen establishment in new hosts. These interactions between host plants and pathogens are closely linked to environmental conditions, making them key determinants of disease development.

Sustainable monitoring and management strategies for plant disease forecasting systems

Given the increasing risks posed by climate change, there is an urgent need to develop sustainable monitoring and management strategies for plant disease forecasting systems, particularly in developing countries. Effective forecasting systems are essential for enabling

Table 3. Integrating disease forecasting systems to mitigate the impact of climate change on biotic stress

Biotic stress	Description	Climate Change impact	Implications	Forecasting System(s)	References
Host resistance and suscepti-bility	resistance and susceptibility influenced by plant genetics, age, and environmental conditions	elevated temperatures weaken defenses; erratic rainfall and drought stress plants increased CO_2 alters physiology;	increased disease susceptibility misaligned plant phenology	**FARM-D**: incorporates changing plant resistance profiles and adaptation to altered phenology **DSSAT**: models effects of temperature and CO_2 on plant susceptibility	Tenllado and Canto (2020)
Abundance of susceptible hosts	prevalence of susceptible hosts impacts disease dynamics	temperature changes alter host distribution; precipitation changes affect crop growth; elevated CO_2 increases host biomass;	reduced genetic diversity increased pathogen colonization	**CropWatch**: tracks host abundance and distribution changes using satellite data **Agro-Meteorological Advisory Services**: provides recom-mendations based on host prevalence data	Juroszek *et al.* (2020)
Pathogen evolution and adaptation	climate change accelerates pathogen mutation and adaptation	higher temperatures and CO_2 drive rapid evolution; environmental changes favor new strains;	emergence of more virulent strains increased disease outbreaks	**CLIMEX**: models pathogen distribution changes and new strains based on climate data **Disease Warning Systems**: adapts to new strains and evolving pathogen dynamics	Fones *et al.* (2020)
Increased vector activity	climate change affects vec-tors transmitting pathogens	warmer winters and altered weather expand vector range; increased humidity favors vector habitats;	higher incidence of vector-borne diseases complicated disease management;	**FARM-D**: includes vector activity data to predict disease risks **CropWatch**: monitors vector habitats and activities	Fones *et al.* (2020)
Disrupted eco-system dynam-ics	climate change alters ecosystem interactions	shifts disrupt predator-prey relationships; changes affect plant communities and pathogens	increased disease incidence; affects biological control measures	**DSSAT**: accounts for changes in ecosystem dynamics and biological control **Disease Warning Systems**: Adjusts for altered ecosystem interactions affecting disease management	Fontúrbel *et al.* (2021)

Understanding the multifaceted impact of climate change on host susceptibility to pathogens is crucial for developing effective plant disease management strategies. Various climate change factors uniquely affect plant defenses and increase vulnerability to diseases, underscoring the broader implications of these changes on global plant disease pressures (Tab. 4)

Table 4. Impact of climate change factors on host susceptibility to pathogens

Factor	Change description	References
Temperature	elevated temperatures compromise plant defenses, increasing susceptibility to diseases like rusts and blights	Cohen and Leach (2020)
Precipitation patterns	erratic rainfall and prolonged droughts weaken plant defenses, making them more vulnerable to various pathogens	Jagathjothi *et al.* (2024)
Carbon dioxide (CO_2) levels	elevated CO_2 alters plant physiology, potentially reducing defenses against pathogens and increasing disease susceptibility	Smith and Luna (2023)
Changes in plant phenology	shifts in flowering and fruiting times disrupt synchronization with pathogens, exposing plants to infection during vulnerable growth stages	Yadav *et al.* (2022)
Plant age and growth stage	impact of age and growth stage on disease susceptibility, influenced by climate-induced stressors	Yadav *et al.* (2022)
Cultivar selection	vulnerability of late-maturing cultivars to diseases under changing climate conditions	Lv *et al.* (2020)

Table 5. Impact of abiotic stress factors on plant disease dynamics and integration with disease forecasting systems

Abiotic stress	Climate-induced changes	Implications for disease dynamics	Forecasting system(s)	Reference
Temperature extremes	elevated temperatures enhance pathogen virulence and compromise plant defenses cold stress weakens plant vigor, increasing susceptibility	increased canker disease incidence in apple orchards higher incidence of bacterial diseases (e.g., *Ralstonia solanacearum*) pathogens like Fusarium wilt thrive at specific temperatures (26–28°C)	integrate temperature data to predict pathogen activity and risk periods e.g. CropWatch and DSSAT	Kumar *et al.* (2022)
Drought and water stress	drought reduces stomatal conductance, alters hormone levels, and weakens cell walls changes in root exudates disrupt soil microbial communities	increased susceptibility to diseases like Fusarium wilt in tomatoes altered prevalence of soil-borne pathogens like *Phytophthora infestans*	incorporate drought indices to predict increased disease risk and inform water management practices e.g., FARM-D	Finger *et al.* (2022)
Salinity stress	high soil salinity disrupts osmotic balance and nutrient uptake alters root microbiome and promotes pathogenic fungi growth	increased susceptibility to root rot growth of pathogenic fungi like *Pythium* species	include salinity stress indicators to assess potential impacts on plant health and disease risk	Phour and Sindhu (2023)
Pollution	air pollutants damage plant tissues and impair defense mechanisms pollutants like ozone and sulfur dioxide contribute to soil acidification	reduced defense gene expression increases susceptibility to diseases like powdery mildew soil-borne pathogens like *Rhizoctonia solani* thrive	integration of pollution data into forecasting models can help predict increased disease susceptibility and guide mitigation strategies	Khan *et al.* (2022)
Soil fertility	soil fertility impacts both soil- and air-borne disease development well-fertilized soils support biotrophic pathogen growth	poor fertility increases susceptibility due to weakened plant defenses enhanced pathogen growth in well-fertilized soils	use soil fertility data to predict pathogen prevalence and recommend fertility management strategies	Sharma (2021)
Relative humidity	increased humidity supports fungal growth and pathogen development variability in humidity affects pathogen life cycles and plant health	enhanced growth of fungal pathogens like powdery mildew and rusts increased disease severity and spread	integrate humidity data to predict fungal disease outbreaks and provide timely alerts	Mieslerová *et al.* (2022)
Soil pH	changes in soil pH affect nutrient availability and microbial community composition acidic or alkaline conditions impact pathogen development	altered soil pH can influence the prevalence of soil-borne pathogens acidic conditions may enhance growth of pathogens like Rhizoctonia	use soil pH data to predict pathogen prevalence and optimize soil management practices	Akber and Fang (2024)
Soil moisture	variations in soil moisture affect pathogen development and plant health excessive or inadequate moisture impacts root health and pathogen spread	increased incidence of diseases related to soil moisture, such as damping-off and root rot changes in pathogen life cycles due to moisture levels	integrate soil moisture data to anticipate disease risks and provide recommendations for irrigation and drainage	Moura *et al.* (2022)

proactive and transformative interventions in plant disease management. They can guide practices such as crop rotation, the selection of resistant cultivars, and the precise application of pesticides, which are critical for managing diseases and minimizing economic losses (Fones *et al*. 2020).

To effectively manage the increasing risks associated with climate change, the development of sustainable monitoring and management strategies is necessary. These systems can guide practices like crop rotation, selecting resistant cultivars, and reducing pesticide use. However, the challenges of limited resources in developing regions necessitate the incorporation of locally relevant data and adapting forecasting models to regional conditions. Through targeted management strategies, regions can overcome resource limitations while improving disease management accuracy.

Transforming plant disease forecasting systems through technology integration, collaboration, and local adaptation in developing countries

The transformation of forecasting systems requires a combination of advanced technologies (such as remote sensing, GIS, and AI) and strong collaborative efforts between researchers, policymakers, and farmers. Mobile applications and online platforms are pivotal in improving forecasting systems by providing timely, actionable data. Expanding monitoring networks and investing in local capacity-building initiatives will also enhance forecasting effectiveness. Additionally, fostering public-private partnerships and securing funding for technological advancements are essential for long-term sustainability. Ensuring that these systems are adapted to local needs and conditions will make them more accessible and impactful for farmers in developing countries.

Addressing the challenges posed by climate change requires a comprehensive transformation of plant disease forecasting systems in developing countries. Integrating disease forecasting with Integrated Pest Management (IPM) strategies is essential for optimizing management practices, reducing reliance on chemical treatments, and promoting sustainable agricultural practices (Bebber *et al*. 2022). The use of advanced technologies such as remote sensing and GIS is critical for monitoring large areas, tracking environmental changes, and modeling disease spread, thus ensuring accurate forecasting (Fones *et al*. 2020). Furthermore, leveraging machine learning and AI can refine predictions by analyzing extensive datasets, adapting forecasts to local conditions, and improving overall accuracy (McRoberts *et al*. 2021).

Digital tools, including mobile applications and online platforms, play a pivotal role in enhancing forecasting systems by facilitating real-time data collection and dissemination. These tools provide farmers with timely alerts and actionable recommendations, improving disease management. Expanding monitoring networks to gather comprehensive data on weather patterns, host susceptibility, and pathogen dynamics will enhance the ability to assess and manage disease risks effectively (McRoberts *et al*. 2021).

Collaboration among researchers, agronomists, and policymakers is essential for translating scientific advancements into practical and actionable management strategies (Fones *et al*. 2020). Strengthening collaborative networks facilitates information sharing, optimizes resource allocation, and improves disease response capabilities. Additionally, public awareness

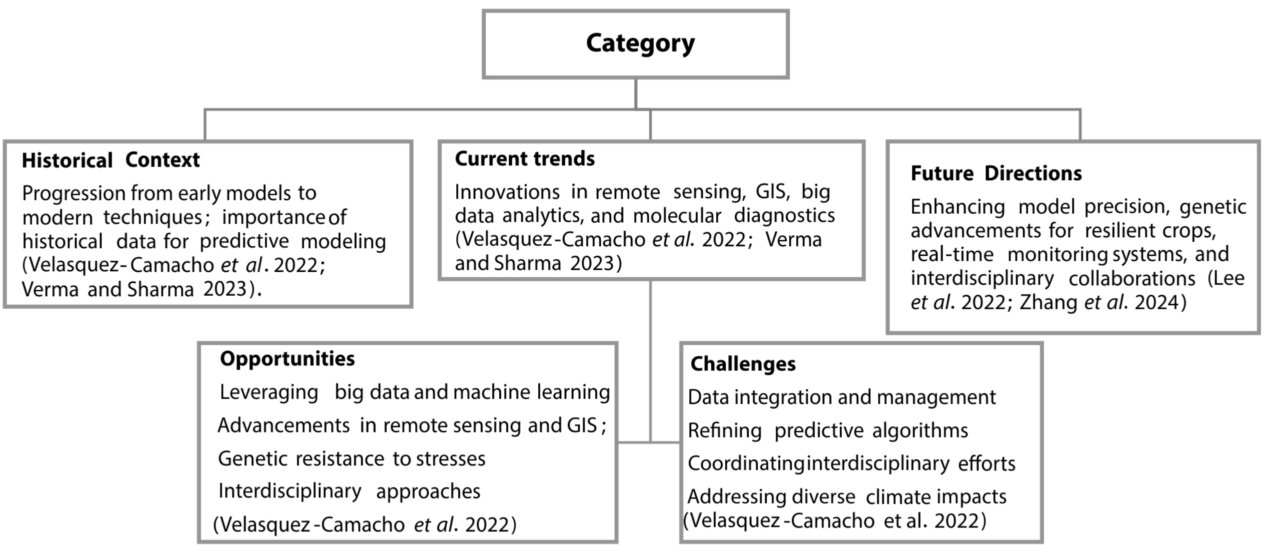

Fig. 3. Evolution and future direction of plant disease forecasting systems: historical and current trends, emerging opportunities and challenges

and training programs are critical for educating farmers and agricultural workers on the use of disease forecasting systems and digital tools, thereby enhancing system adoption and effectiveness.

Capacity building and training are fundamental for developing local expertise and ensuring that stakeholders are proficient in utilizing forecasting systems. Engaging local communities in the development and implementation of these systems ensures that solutions are tailored to their specific needs and conditions. Public-private partnerships can also leverage resources, foster innovation, and support the deployment of advanced forecasting technologies. Securing adequate funding and resource allocation is crucial for infrastructure development, technological advancement, and ongoing research.

Efforts should focus on enhancing the accuracy of forecasting systems through local data collection and integration. Adapting technology for low-resource settings, such as developing mobile-based applications or low-cost sensors, is also essential. Policy development and support are necessary to promote research and technology adoption, advocating for policies that facilitate the implementation of forecasting systems. Historical trends, future directions, opportunities, and challenges associated with plant disease forecasting systems highlight the evolution of these systems and the need for continued innovation and adaptation in the face of emerging threats and opportunities (Fig. 3).

Conclusion and recommendations

Enhancing plant disease forecasting systems is crucial for effective plant protection, particularly in developing countries facing significant impacts from climate change. As climate shifts exacerbate plant disease risks, refining forecasting and management strategies becomes essential for safeguarding crops and ensuring food security.

The recommendations outlined herein emphasize a comprehensive approach to addressing these challenges. Advancements in technology, including remote sensing, GIS, and predictive modeling, are key for improving forecasting accuracy and resilience. Integrating real-time data on environmental variables, host susceptibility, and pathogen dynamics will allow for more precise and adaptive plant protection strategies under changing climatic conditions.

Investment in infrastructure, technology, and local capacity is essential. Public-private partnerships can play a pivotal role in leveraging resources and driving innovation. Moreover, developing and adapting technologies for low resource settings such as mobile-based applications and low-cost sensors will make advanced forecasting systems more accessible and practical in regions with limited resources.

Localized data collection and targeted training programs are critical for ensuring that forecasting systems are practical and effective. Accurate forecasts depend on detailed regional data on weather patterns, crop health, and pathogen dynamics. Training programs should focus on enhancing the skills of farmers, agricultural workers, and researchers to maximize the effectiveness of these systems.

Policy development should support the implementation and scaling of these systems by creating favorable frameworks and providing financial support. Policies must prioritize building local capacity, integrating localized data collection methods, and adapting technology to meet the needs of developing regions.

Addressing the challenges of climate variability, data integration, and interdisciplinary coordination is vital for transforming plant disease forecasting systems. Future research should focus on improving system precision through high-resolution data, artificial intelligence (AI), and real-time monitoring solutions. The development of integrated models that combine weather data, plant health metrics, and pathogen dynamics will be critical for anticipating disease outbreaks more effectively. Additionally, exploring the role of genomics in understanding pathogen evolution and resistance mechanisms will provide new insights into disease management strategies.

Fostering collaboration between research institutions, governments, and the private sector will be central to advancing plant disease forecasting systems. Collaborative platforms can facilitate the exchange of data, resources, and expertise, which will accelerate the development of more robust forecasting models. Furthermore, the adaptation of these systems to different agroecological zones and the incorporation of local knowledge will enhance their effectiveness.

Key limitations of this review include its focus on recent literature (2020-2024), which may overlook earlier significant studies. The emphasis on developing countries also limits the broader applicability of insights to other regions. Challenges such as inconsistent data quality, limited access to advanced technologies, and barriers to adopting tools such as AI and GIS in resource-constrained settings hinder the effective implementation of forecasting systems. Addressing these gaps through improved data integration, greater access to technology, and context-specific strategies is essential for advancing plant disease forecasting efforts.

Therefore, continued research, investment, and commitment to these strategies will be essential for the successful evolution of plant disease forecasting systems. By embracing technological innovations and fostering collaboration, future research can significantly enhance the resilience and sustainability of agricultural practices, contributing to the global effort to protect plant health in the face of climate change.

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