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Impact of climate change on disease dynamics and integrated disease management strategies

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Abstract
Plant disease incidence, severity, and distribution are all changing rapidly as a result of climate change, which is also changing the worldwide agricultural ecosystem. The complex connections between host, pathogen, and environment are being impacted by rising temperatures, unpredictable rainfall patterns, elevated CO_2 levels, and extreme weather events, making important field crops more vulnerable. These modifications weaken plant immune responses, speed up pathogen life cycles, and increase vector habitats, which leads to the emergence of new diseases and the resurgence of already suppressed ones. Adapting integrated disease management solutions is crucial as traditional disease management techniques become more and more inefficient. This review examines the complex effects of climate change on the dynamics of disease in important crops, including wheat, rice, sugarcane, maize and pulses. The adaptive integrated disease management elements that are highlighted include sophisticated cultural practices, biological methods, resistant varieties chemical control and digital surveillance tools. It is stressed that real-time illness monitoring and precision therapies require the combination of digital innovations and climate-smart technologies. This study promotes proactive policy frameworks and robust, interdisciplinary approaches to protect crop health and guarantee sustainable agricultural productivity in a changing environment.

Keywords: Climate change, climate-smart agriculture, disease dynamics, integrated disease management

1. Introduction

Climate change has emerged as a defining global issue with far-reaching implications across ecosystems, human health, and agricultural systems. The agricultural sector is particularly vulnerable, given its direct dependence on climatic variables such as temperature, rainfall, humidity, and atmospheric carbon dioxide (CO_2) levels etc. According to the Intergovernmental Panel on Climate Change (IPCC), global surface temperatures have risen by approximately 1.1 °C above pre-industrial levels, and continued greenhouse gas emissions are likely to intensify the frequency and severity of extreme weather events (IPCC, 2021) [23]. These environmental alterations are not only impacting crop productivity but are also reshaping the dynamics of plant diseases in unprecedented ways.

Plant diseases, which significantly constrain global crop yields and quality, are intimately linked with environmental conditions. Changes in temperature, precipitation, and humidity influence pathogen development, reproduction, dispersal, and survival (Garrett *et al*., 2006; Pautasso *et al*., 2012) [16, 45]. Moreover, elevated CO_2 concentrations can affect host-pathogen interactions by altering plant physiology, susceptibility, and immune responses (Chakraborty & Datta, 2003) [9]. These climate-induced shifts are already resulting in the geographical redistribution of pathogens and their vectors, with increasing evidence of disease outbreaks in previously non-endemic regions (Bebber, 2022; Newton *et al*., 2011) [5, 10].

Several studies report that warming temperatures favor faster pathogen life cycles and expand the temporal windows of infection, especially in temperate zones where constraints such as winter dormancy are being relaxed (Luck *et al*., 2011; Ghini *et al*., 2011) [31, 20]. Similarly, extreme weather events such as droughts and floods have been shown to compromise plant defences, thereby increasing susceptibility to opportunistic pathogens. In addition, certain pathogens, especially fungi and bacteria, have demonstrated increased virulence and mutation rates under changing climatic conditions, further complicating disease management (Eastburn *et al*., 2010) [15]. Given these complex interdependencies, traditional disease control methods are increasingly proving inadequate. There is an urgent need to revise and reorient existing plant protection strategies toward more resilient and adaptive frameworks. Integrated Disease Management (IDM), which combines cultural, biological, genetic, and chemical control measures, must now incorporate climate forecasting, real-time disease surveillance, and precision agriculture tools to effectively manage diseases in a changing environment (Savary *et al*., 2019) [49].

This review aims to synthesize current knowledge on how climate change is altering disease dynamics in field crops and to critically evaluate how IDM strategies can be adapted or redesigned to address these emerging challenges. Emphasis is placed on host-pathogen-environment interactions, case-specific disease outbreaks in major field crops, and the role of interdisciplinary research in shaping future-ready crop protection systems.

2. Climate Change: An Overview in Disease of Crops

Climate change, a consequence of anthropogenic activities, is reshaping global agricultural systems by influencing the distribution, incidence, and severity of plant diseases. The Earth's climate system is undergoing significant transformations, including rising temperatures, altered precipitation patterns, elevated atmospheric carbon dioxide (CO_2) levels, and increased frequency of extreme weather events all of which directly or indirectly affect crop health and pathogen dynamics.

2.1 Rising Global Temperatures

One of the most prominent indicators of climate change is the steady increase in global average surface temperature. The IPCC sixth assessment report (2021) [23] confirmed that the global surface temperature increased by approximately 1.1 °C above pre-industrial levels (1850-1900), with the last decade (2011-2020) being the warmest on record (IPCC, 2021) [23]. This warming trend accelerates the life cycles of many pathogens and vectors, enabling more infection cycles per season and expanding geographic ranges (Chakraborty & Newton, 2011) [10].

2.2 Changes in Precipitation Patterns

Climate change is also causing significant shifts in global precipitation patterns. Some regions are experiencing increased rainfall and humidity, while others suffer from prolonged droughts. According to the IPCC (2021) [23], heavy precipitation events have become more frequent and intense in most regions, particularly at higher latitudes. These changes favor fungal and bacterial pathogens such as *Phytophthora infestans* and *Xanthomonas* spp., which thrive in wet conditions (Pautasso *et al*., 2012) [45]. Conversely, drought stress can compromise plant defenses, making them more susceptible to opportunistic pathogens.

2.3 Elevated Atmospheric CO_2 Concentration

The atmospheric CO_2 concentration has surpassed 420 parts per million as of 2023, a substantial increase from pre-industrial levels of approximately 280 parts per million (NOAA, 2023) [38]. While elevated CO_2 can enhance plant growth and yield, it also alters plant physiology and canopy structure, potentially influencing pathogen infection rates and plant-microbe interactions (Chaloner *et al*., 2021) [11]. For instance, thicker leaf cuticles under high CO_2 may affect pathogen entry, while increased biomass may create favorable microclimates for foliar diseases (Eastburn *et al*., 2010) [15].

2.4 Extreme Weather Events

Climate change has intensified the frequency and severity of extreme weather events such as floods, heatwaves, and hurricanes. These events can cause physical damage to crops, weakening their resistance to pathogens, and can also transport spores or vectors across regions (Garrett *et al*., 2006) [16]. Floods may disseminate soilborne pathogens like *Pythium* and *Fusarium*, while high temperatures may facilitate the emergence of heat-tolerant pathogen strains.

3. Influence of Climate Change on Crop Pathogens

Climate change is profoundly impacting the intricate dynamics of field crop pathosystems. These systems are composed of the host plant, pathogen, environment, and, in many cases, a vector organism. The influence of climate change extends beyond isolated factors, modifying plant susceptibility, altering pathogen life cycles, shifting vector behavior, and even triggering the resurgence of previously controlled diseases. Understanding these influences is crucial to devise adaptive plant protection strategies for sustainable agriculture.

3.1 Alteration in Host Physiology and Susceptibility

Elevated temperatures, increased atmospheric carbon dioxide (CO_2), and erratic precipitation directly affect crop physiology and, consequently, host susceptibility to pathogens. For example, elevated CO_2 often leads to greater biomass and denser canopies, creating a humid microenvironment favorable to foliar diseases like powdery mildew or rusts (Eastburn *et al*., 2010) [15]. Simultaneously, higher temperatures can alter the expression of plant resistance (R) genes and compromise the plant immune response.

Plants experiencing heat or drought stress may suffer from weakened defense signaling pathways, such as those involving salicylic acid and jasmonic acid, making them more vulnerable to opportunistic pathogens (Suzuki *et al*., 2014) [53]. For instance, drought-induced stomatal opening can facilitate pathogen entry in crops like wheat and soybean.

3.2 Changes in Pathogen Biology and Epidemiology

Climate change directly influences the life cycle, virulence, and distribution of many pathogens. Rising temperatures accelerate pathogen reproduction and reduce latent periods, leading to more infection cycles per season. For example, fungal pathogens like *Puccinia striiformis* (stripe rust of wheat) exhibit increased aggressiveness and expanded geographical range due to warmer winters (Milus *et al*., 2009) [35]. Moreover, higher humidity and rainfall promote spore dispersal and germination, facilitating the rapid spread of diseases like late blight in potatoes (*Phytophthora infestans*) and blast in rice (*Magnaporthe oryzae*) (Chakraborty & Newton, 2011) [10]. Additionally, climate-driven evolutionary pressures may select for new pathogen strains with enhanced thermal tolerance or fungicide resistance.

3.3 Shifts in Vector Populations and Their Activity

Vector-borne plant diseases are particularly sensitive to climate variables. Insect vectors such as aphids, whiteflies, and leafhoppers respond rapidly to changes in temperature, which influences their population dynamics, migration patterns, and feeding behavior. For instance, higher temperatures have been linked to increased reproduction and earlier spring activity in aphids (*Myzus persicae*), leading to greater transmission of viruses like Barley yellow dwarf virus and Potato virus Y. Climate-induced expansion of vector habitats can also introduce diseases into previously unaffected regions. An example is the spread of Maize streak virus and Tomato yellow leaf curl virus, whose whitefly and leafhopper vectors are thriving in warmer and dry climate (Jones, 2016) [24].

3.4 Emergence of New and Re-emergence of Latent Diseases

Climate change can lead to the appearance of previously unknown pathogens or the reactivation of diseases that were historically insignificant or suppressed (latent diseases). Warmer winters and extended growing seasons have allowed overwintering of pathogens and increased primary inoculum levels in spring. Diseases such as Cercospora leaf spot in sugar beet and Fusarium head blight in cereals are resurging in regions where they were once rare (Chaloner *et al*., 2021 [11].

4. Disease Dynamics in Major Crops under Climate Stress

Climate stress manifesting through elevated temperatures, irregular rainfall, prolonged droughts, and increased carbon dioxide (CO_2) levels has significantly altered the disease profiles of major field crops. These environmental changes influence host-pathogen interactions, pathogen virulence, and crop susceptibility. The following section provides an overview of how climate change is impacting disease dynamics in key staple crops in agriculture.

4.1 Wheat

Wheat, a staple cereal crop cultivated worldwide, is increasingly affected by climate-induced shifts in disease epidemiology. Rising temperatures and erratic precipitation have enhanced the prevalence of rust diseases, particularly stem rust (*Puccinia graminis* f. sp. *tritici*), leaf rust (*P. triticina*), and stripe rust (*P. striiformis*) (Chakraborty & Newton, 2011) [10]. The emergence of the highly virulent Ug-99 strain and its variants in East Africa and beyond highlights the growing threat under warming scenarios. According to Milus *et al*. (2009) [35], stripe rust has spread to warmer areas, such as the central and southern plains of the U.S., due to the adaptation of new pathogen races to higher temperatures. Warmer winters also allow for pathogen overwintering, enabling early infection and increased severity (Beddow *et al*., 2015) [6]. Additionally, climate-induced changes in crop phenology can misalign crop resistance mechanisms with pathogen attack stages.

4.2 Rice

Rice diseases are also intensifying under climate stress, particularly *Magnaporthe oryzae* (rice blast) and *Xanthomonas oryzae* pv. *oryzae* (bacterial blight). Increased temperature and humidity hallmarks of a changing climate favor the proliferation of blast spores, increasing the disease incidence and severity (Tang *et al*., 2017) [54]. Prolonged leaf wetness due to unpredictable rainfall further promotes disease development. Bacterial blight has shown expanded distribution due to climate variability. Higher temperatures and erratic rainfall encourage epiphytic bacterial populations, contributing to systemic infection during the reproductive phase (Adhikari *et al*., 1995) [1]. Additionally, shifting monsoon patterns affect the timing and efficacy of chemical treatments, complicating integrated disease management.

4.3 Sugarcane

Sugarcane, a important cash crop, is vulnerable to multiple diseases exacerbated by climate extremes. Namely, red rot (*Colletotrichum falcatum*), smut (*Sporisorium scitamineum*), and ratoon stunting disease (RSD) caused *by Leifsonia xyli* subsp. *xyli* are major concerns. Increased humidity and waterlogging favor red rot incidence, while warmer and drier conditions stimulate smut development (Viswanathan & Rao, 2011) [56]. In India, the frequency and severity of red rot have increased in eastern and southern regions due to erratic monsoons and warmer winters. Moreover, the latent infection period is shortened under higher temperatures, leading to earlier symptom expression and reduced yields.

4.4 Maize

In maize, foliar diseases such as northern leaf blight (*Exserohilum turcicum*) and southern rust (*Puccinia polysora*) are increasingly problematic under elevated temperatures and humidity. Climate stress also enhances aflatoxin contamination, primarily caused by *Aspergillus flavus*, which thrives under high temperature and drought stress (Wu *et al*., 2014) [59]. The shifting distribution of these pathogens is evident across tropical and temperate regions, where outbreaks now occur in areas previously unaffected. Climate variability also affects host resistance durability and shortens latent periods, contributing to multiple infection cycles within a single season (Paterson & Lima, 2010) [44].

4.5 Pulses and Oilseeds

Pulses and oilseeds are highly sensitive to abiotic stress and are increasingly exposed to diseases such as wilt (*Fusarium* spp.), dry root rot (*Rhizoctonia bataticola*), and powdery mildew. Drought and heat stress predispose pulse crops like chickpea and pigeon pea to root rot and wilt diseases, especially in rainfed systems (Nene *et al*., 2012) [37]. Similarly, oilseed crops such as mustard and soybean face rising disease pressure under variable climates. For instance, white rust (*Albugo candida*) in mustard is favoured by increased humidity and altered winter temperatures (Meena *et al*., 2010) [32]. Soybean rust (*Phakopsora pachyrhizi*) also displays enhanced sporulation and dispersal under elevated CO_2 and warm, wet conditions.

5. Integrated Disease Management (IDM) in the Context of Climate Change

Integrated Disease Management (IDM) is a holistic approach combining multiple disease control strategies to minimize crop losses in an economically viable, environmentally sustainable, and socially acceptable manner. Climate change, by altering pathogen dynamics, vector populations, and host plant physiology, necessitates a re-evaluation and adaptation of IDM strategies. Under changing climate scenarios, IDM must become more climate-resilient, proactive, and technologically supported to ensure crop protection and food security.

5.1 Cultural and Agronomic Practices

Cultural and agronomic practices form a critical component of Integrated Disease Management (IDM) strategies. These practices aim to manipulate the cropping environment to create unfavorable conditions for pathogens and minimize disease incidence, thereby reducing the dependence on chemical controls. Implementation of such practices varies with crop type, agro-ecological conditions, and pathogen biology.

5.1.1 Crop Rotation

Crop rotation involves alternating different crops across seasons on the same field to interrupt the life cycle of soilborne pathogens. It is particularly effective against host-specific pathogens such as *Fusarium*, *Rhizoctonia*, and *Sclerotinia* spp. In wheat-based systems, rotating with non-host crops like legumes or oilseeds reduces the inoculum level of Fusarium head blight (*Fusarium graminearum*) (Dil-Macky & Jones, 2000) [14]. Potato growers rotate with cereals or maize to control *Phytophthora infestans* and *Verticillium dahliae* (Stevenson *et al.*, 2001) [52].

5.1.2 Sanitation and Residue Management

Sanitation involves removing diseased plant debris, volunteer crops, and infected pruning material, which serve as reservoirs for pathogens. In tomato cultivation, removal and destruction of infected plants help limit the spread of bacterial wilt (*Ralstonia solanacearum*). Burning or composting rice straw can significantly reduce the primary inoculum of Rhizoctonia solani, which causes sheath blight (Savary *et al.*, 2000) [47].

5.1.3 Adjusting Sowing Time and Plant Density

Altering sowing time can help crops escape critical infection periods by avoiding favorable environmental conditions for pathogen development. Early sowing of chickpea helps evade the peak activity of *Ascochyta rabiei* under humid conditions (Pande *et al.*, 2005) [42]. Wider plant spacing improves air circulation, reducing humidity and disease pressure from foliar pathogens such as Alternaria and Powdery mildew.

5.1.4 Use of Disease-Free Seed and Resistant Varieties

The use of certified, disease-free seed prevents the introduction of seedborne pathogens such as *Ustilago tritici* (loose smut of wheat) and *Xanthomonas oryzae* (bacterial blight of rice) Cultivation of blast-resistant rice varieties like 'IR64' and 'Tetep' has significantly reduced *Magnaporthe oryzae* incidence in Asia (Ou, 2021) [40]. Use of late blight-resistant varieties like 'Kufri Jyoti' in potato has proven effective under Indian conditions (Anon, 2019) [4].

5.1.5 Irrigation and Water Management

Moisture management is crucial in minimizing waterborne and root-infecting pathogens. Drip irrigation in tomato and chili reduces foliage wetness, thus lowering incidences of *Phytophthora capsici* and *Alternaria solani* (Granke & Hausbeck, 2010) [20]. Avoiding waterlogging helps prevent root rot caused by *Pythium* and *Fusarium* in crops like soybean and cotton.

5.1.6 Intercropping and Trap Cropping

Intercropping involves growing two or more crops simultaneously, which may reduce disease severity by hindering pathogen spread. Intercropping sorghum with cowpea or groundnut has been found to reduce downy mildew (*Peronosclerospora sorghi*) due to canopy modification and altered microclimate (Boudreau, 2013) [7]. Mustard is used as a trap crop to manage nematodes in vegetable crops by attracting and killing them before the main crop is planted.

5.1.7 Soil Amendments and Organic Inputs

Application of organic matter such as compost, farmyard manure, and green manure can suppress soilborne diseases by enhancing beneficial microbial activity. Incorporation of neem cake reduces *Macrophomina phaseolina* and *Sclerotium rolfsii* in chickpea and groundnut. Use of biofumigant crops like mustard and radish also suppresses soil pathogens due to release of glucosinolates.

5.2 Physical Control

Physical control practices constitute an essential component of Integrated Disease Management (IDM) and are widely adopted in sustainable agriculture to mitigate the incidence and severity of plant diseases. These methods involve the manipulation of environmental conditions and the direct use of mechanical or thermal means to eliminate or reduce the population of plant pathogens and their vectors. The major physical control strategies include heat treatment, soil solarization and use of protective barriers. These approaches are eco-friendly, cost-effective, and can be effectively combined with biological, chemical, and cultural controls to enhance disease suppression.

5.2.1 Soil Solarization

Soil solarization is the practice of covering moist soil with transparent polyethylene sheets during the hot summer months to trap solar radiation, thereby increasing the soil temperature to levels lethal to many soilborne pathogens, nematodes, and weed seeds. In tomato (*Solanum lycopersicum*), soil solarization for 4-6 weeks has been proven effective in reducing populations of *Fusarium oxysporum* f. sp. l*ycopersici* and *Ralstonia solanacearum*, the causal agents of wilt and bacterial wilt, respectively (Katan, 1981) [28].

5.2.2 Hot Water Treatment

Hot water treatment is used for seed and vegetative propagule disinfection. It kills pathogens present on or within seeds without adversely affecting germination when properly applied. Hot water treatment of seeds in paddy (*Oryza sativa*) at 52 °C for 10 minutes effectively controls *Xanthomonas oryzae* pv. *oryzae*, the causal organism of bacterial leaf blight (Mew & Gonzales, 2002) [34]. Hot water treatment at 50-55 °C for 20 minutes is used for banana suckers to control nematodes and *Fusarium oxysporum* f. sp. *cubense*.

5.2.3 Hot Air Treatment (HAT)

Hot Air Treatment has been widely recognized as an effective postharvest strategy to control fungal pathogens and extend shelf life in both horticultural and field crops. in bananas (*Musa* spp.), exposure to hot air at 45 °C for 45 minutes has been shown to significantly reduce surface fungal contamination while maintaining fruit quality. Cherry tomatoes treated with hot air at 38 °C for 12 hours exhibited reduced fungal incidence and delayed fruit softening, indicating protection against postharvest spoilage.

5.2.4 Use of Physical Barriers and Netting

Physical barriers such as net houses and screens help reduce vector-borne diseases by preventing vector access to crops.

In tomato and chili, growing seedlings in insect-proof net houses reduces transmission of Tomato leaf curl virus and Chilli leaf curl virus by whiteflies (*Bemisia tabaci*) (Sastry & Zitter, 2014) [47].

5.2.5 Flaming and Steam Treatment
Flaming and steam treatments are used to eliminate pathogen propagules from plant debris or soil surfaces, particularly in organic farming systems. In lettuce and carrot cultivation, flame weeding or soil steaming has been successfully applied for controlling *Sclerotinia sclerotiorum* and damping-off diseases caused by *Pythium* spp. and *Rhizoctonia solani* (Melander *et al*., 2005) [33].

5.3 Biological Control
Biological control involves the use of living organisms *viz*., predators, parasites, or antagonists to suppress plant pathogens. It is a critical component of IDM due to its ecological sustainability and minimal environmental impact. Example such as *Trichoderma harzianum* and *T. viride* have been effectively used to control sheath blight (*Rhizoctonia solani*) in rice and stalk rot in maize by mechanisms including mycoparasitism, antibiosis, and competition (Harman *et al*., 2004) [21]. *Bacillus subtilis* suppresses bacterial wilt in tomato (*Ralstonia solanacearum*) and root rot in chickpea (*Fusarium solani*) through the production of lipopeptides and induction of systemic resistance in host plants (Kloepper *et al*., 2004) [29]. Use of Predatory Insects in Cotton: The release of predators like *Chrysoperla carnea* and parasitoids such as *Trichogramma chilonis* is effective in managing sucking pests and bollworm complex, which also transmit plant pathogens (Romeis *et al*., 2008) [46].

5.4 Resistance
Host plant resistance (HPR) is a fundamental strategy within Integrated Disease Management (IDM), offering a sustainable, environmentally friendly, and economically viable method for managing plant diseases. It involves the genetic capacity of a crop to restrict or inhibit pathogen infection and disease progression. Resistance may be qualitative (controlled by a single major gene) or quantitative (controlled by multiple genes), each contributing differently to disease suppression (Parlevliet, 2002) [43]. Mechanisms of resistance can be passive, such as structural barriers and pre-formed chemicals, or active, involving induced defense responses like hypersensitive cell death and the production of phytoalexins upon pathogen detection (Dangl & Jones, 2001) [12]. Incorporating resistant cultivars in IDM significantly reduces the dependence on fungicides, lowers environmental risks, and maintains crop productivity.

For example, in rice (*Oryza sativa*), resistant varieties such as IR64 and CO 39 have shown effectiveness against *Magnaporthe oryzae*, the causative agent of rice blast, and are used alongside agronomic measures and judicious fungicide use (Skamnioti & Gurr, 2009) [51]. Wheat (*Triticum aestivum)* cultivars carrying resistance genes such as Sr24 and Sr31 have been instrumental in managing stem rust (*Puccinia graminis* f. sp. *tritici*), including the virulent Ug99 race (Singh *et al*., 2011) [50]. In potato (*Solanum tuberosum*), varieties like Sarpo Mira provide resistance to late blight (*Phytophthora infestans*), reducing the need for chemical sprays when combined with disease forecasting systems (Bradshaw *et al*., 2006) [8]. Similarly, tomato (*Solanum lycopersicum*) lines such as Hawaii 7996 are resistant to bacterial wilt (*Ralstonia solanacearum*) and perform well under integrated approaches involving soil solarization and raised-bed cultivation. Chickpea (*Cicer arietinum*) varieties like JG 62 and Annigeri 1 are widely adopted for their resistance to Fusarium wilt (*Fusarium oxysporum* f. sp. *ciceris*), often in conjunction with biocontrol seed treatments and soil health practices (Pande *et al*., 2013) [41]. Cotton (*Gossypium hirsutum*) varieties such as Fibermax 958 show moderate resistance to Verticillium wilt (*Verticillium dahliae*) and are integrated with crop rotation and soil sanitation (Zhang *et al*., 2016) [60]. While HPR offers long-term benefits, it is not without challenges. Pathogens may evolve to overcome resistance genes, especially when a narrow genetic base is used repeatedly (McDonald & Linde, 2002) [31]. To combat this, resistance gene pyramiding and periodic resistance monitoring are recommended strategies.

5.5 Chemical control
Recent advancements in chemical plant protection have led to the development of innovative and targeted formulations that enhance efficacy, reduce environmental risks, and mitigate resistance development in pathogens. One such innovation is the use of nano-formulated pesticides, which improve solubility, enhance stability, and ensure controlled release of active ingredients. For instance, copper-based nanoparticles have shown significant potential in suppressing bacterial and fungal pathogens such as *Xanthomonas* spp. and *Alternaria* spp. due to their high surface area and ion-releasing capacity (Kah *et al*., 2019) [26]. Another promising development is the use of plant defense inducers chemicals that activate the plant's innate immune responses rather than acting directly on the pathogens. Compounds like acibenzolar-S-methyl (ASM) and β-aminobutyric acid (BABA) have demonstrated efficacy against a range of diseases by enhancing systemic acquired resistance (Walters *et al*., 2013) [57]. Additionally, biodegradable and smart delivery systems, such as liposome-encapsulated fungicides and polymeric carriers, are being explored to improve site-specific delivery and minimize off-target effects. These delivery systems are particularly beneficial in minimizing fungicide leaching and prolonging field efficacy. Moreover, combination formulations that include multiple modes of action (e.g., mixing strobilurins with SDHI or triazole fungicides) are increasingly recommended to delay resistance buildup in high-risk pathogens like *Botrytis cinerea* and *Phytophthora infestans* (Oliver & Hewitt, 2014) [39]. Such innovations reflect a paradigm shift from conventional chemical use toward precision-targeted, environmentally safer chemical interventions aligned with sustainable disease management practices.

6. Role of Digital Tools and ICT in Climate-Smart IDM
Digital tools and Information and Communication Technologies (ICTs) have emerged as vital components in enabling Climate-Smart Integrated Disease Management (IDM) by improving disease forecasting, decision-making, and timely intervention. These tools facilitate real-time surveillance, spatial mapping of disease outbreaks, and early warning systems by integrating data from remote sensing, weather stations, and mobile-based reporting platforms. Precision agriculture technologies, such as drones, geographic information systems (GIS), and Internet of Things (IoT) devices, help monitor crop health and microclimatic conditions conducive to disease development, thereby

allowing for site-specific disease control strategies (Gebeyehu *et al*., 2023) [17]. Mobile applications and ICT platforms also play a significant role in knowledge dissemination by providing farmers with access to localized agro-advisories, fungicide recommendations, and integrated management practices in their local languages. For example, tools like PlantVillage Nuru and e-KrishiPathshala in India are increasingly being used to disseminate climate-informed IDM practices among smallholder farmers (Anon, 2021) [3]. Furthermore, digital decision support systems such as the CABI Pest Risk Information Service (PRISE) and EPIRICE provide climate-sensitive, data-driven disease prediction models that enhance the preparedness of stakeholders against outbreaks exacerbated by climate change (Anon, 2022) [2]. These innovations contribute to minimizing crop losses, optimizing pesticide usage, and ensuring environmental sustainability key pillars of climate-smart agriculture. However, digital literacy, data accessibility, and infrastructural challenges remain critical barriers to the widespread adoption of ICT in disease management, particularly in developing countries.

7. Challenges and Future Directions

Climate change continues to pose significant challenges to the effective management of crop diseases, as shifting weather patterns alter the biology, virulence, and distribution of pathogens and vectors. One of the primary challenges is the unpredictability of disease outbreaks due to increased climate variability, such as erratic rainfall, elevated temperatures, and extreme weather events, which disrupt existing disease forecasting models (Chakraborty & Newton, 2011) [10]. Another challenge is the breakdown of host resistance, as climate-induced stress can compromise plant immunity and lead to the resurgence of previously minor or geographically restricted pathogens (Bebber, 2022) [5]. Furthermore, over-reliance on chemical control in response to climate-driven disease pressure raises concerns about resistance development, non-target effects, and environmental degradation (Savary *et al*., 2019) [50]. Inadequate infrastructure, limited digital access, and low awareness among farmers, particularly in developing countries, hinder the implementation of climate-informed IDM practices (Gebeyehu *et al*., 2023) [17].

To address these issues, future directions must focus on the integration of real-time disease surveillance systems, AI-driven decision support tools, and climate-resilient crop varieties. Advancements in omics technologies, such as genomics and transcriptomics, hold potential for identifying climate-resilient genes for disease resistance. Additionally, strengthening farmer training through ICT-based agro-advisories, improving access to climate-smart inputs, and fostering international collaboration for disease monitoring and forecasting are essential strategies for future resilience. Building robust policy frameworks that prioritize sustainable, adaptive IDM strategies under changing climatic scenarios will be critical in safeguarding global food security.

8. Conclusion

Climate change is significantly reshaping the patterns and intensity of crop diseases, posing new challenges to traditional management practices. Changes in temperature, rainfall, and humidity have led to the emergence of new pathogens, increased survival rates of existing ones, and altered host-pathogen interactions. These shifts demand more adaptive and resilient Integrated Disease Management (IDM) strategies that can respond to unpredictable conditions. Incorporating climate-smart practices such as disease forecasting, resistant crop varieties, and precision agriculture tools is essential to protect field crops and ensure sustainable production. A holistic and forward-looking approach is necessary to address the growing threat of climate-induced disease pressures.

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