Review Article

Adapting Plant Protection Strategies to Meet the Challenges Posed by Climate Change on Plant Diseases-A review

Abstract

Climate change poses a significant challenge to global agriculture, with profound implications for plant disease dynamics and plant protection strategies. This review aims to synthesize current research on the impact of climate change on plant diseases, particularly focusing on how these changes affect pathogen life cycles, host resistance, and disease distribution. Emphasizing the Indian context, this paper explores the adaptation of plant protection strategies in response to these challenges, including the integration of traditional methods and advanced scientific approaches. It provides a comprehensive overview of the key aspects of climate change relevant to agriculture, including changes in temperature, precipitation patterns, and atmospheric CO_2 levels. It delves into the direct and indirect impacts of these climatic changes on plant diseases, highlighting how altered environmental conditions influence pathogen virulence and the susceptibility of host plants. This section also discusses the shifted patterns in pest and disease distribution due to climate change, with a focus on the Indian agricultural scenario. Then it examines the current challenges in plant protection, assessing the limitations of traditional methods like chemical, biological, and cultural control in the context of a changing climate. It identifies critical areas such as increased disease incidence, pathogen resistance development, and the necessity for sustainable and adaptable plant protection strategies. Further it explores various adaptive strategies, including Integrated Disease Management (IDM), advances in breeding for disease resistance, biotechnological approaches, and climate-smart agricultural practices. It outlines how IDM principles and practices are being adapted to new climate scenarios, the role of genetic engineering and traditional breeding in developing disease-resistant varieties, the development of biopesticides and biocontrol agents, and the application of climate forecasts in disease management.Case studies and practical applications from different regions of India provide real-world examples of effective adaptation strategies, drawing lessons and best practices. The review concludes by identifying research gaps, advocating for multidisciplinary collaborations between plant pathology, climatology, and agronomy, and emphasizing the critical role of policy in supporting adaptive strategies. This comprehensive synthesis and analysis aim to contribute to the broader understanding of plant protection in the era of climate change and guide future research and policy-making in this vital field.

Keywords:*Climate Change, Plant Diseases, Adaptation, Pathogens, Resilience, Biotechnology*

I. Introduction

Climate change, a global phenomenon marked by significant alterations in weather patterns, has profound implications for agriculture, a sector inherently dependent on climatic conditions. The relationship between agriculture and climate change is bidirectional; while agriculture contributes to climate change through greenhouse gas emissions, it is also highly susceptible to its impacts [1]. The rise in average temperatures, changes in precipitation patterns, and increased frequency of extreme weather events, such as droughts and floods, have already begun to affect crop yields, agricultural practices, and the prevalence and distribution of pests and diseases.Increased temperatures can accelerate crop maturation, reducing the growing period and potentially diminishing yields [2]. On the other hand, in some regions, warmer conditions may extend the growing season, though this benefit is often offset by other climatic stresses. Changes in precipitation patterns, including both prolonged droughts and excessive rainfall, can lead to water scarcity or waterlogging, impacting crop health and productivity [3]. Climate change is closely linked to the increased volatility of agricultural production. For example, the frequency and severity of extreme weather events such as heatwaves, storms, and frosts have a direct and often devastating impact on crop yields. This volatility not only affects food security but also has significant economic implications for farmers and the global agricultural market [4].

Climate change significantly affects the prevalence and spread of plant diseases. The alteration in climate conditions can create more favorable environments for many pathogens, leading to increased disease incidence and new disease emergence [5]. Temperature and moisture are critical factors in the development and spread of plant diseases. Rising temperatures can accelerate the life cycles of many pathogens, increase their overwintering ranges, and facilitate their expansion into previously unsuitable areas [6].Additionally, changes in humidity and precipitation patterns influence the proliferation of fungal and bacterial diseases. Increased humidity can promote the growth and spread of fungi, while an alteration in rainfall patterns can affect the dispersal of pathogens. Moreover, extreme weather events like flooding and heavy rains can facilitate the spread of soil-borne diseases and create conditions conducive to outbreaks of water-borne pathogens [7].It is also important to consider the indirect effects of climate change on plant diseases. For instance, plants stressed by drought, heat, or other climatic factors are often more susceptible to diseases. Climate change can also affect the range and behavior of insect vectors that transmit diseases, potentially leading to new disease dynamics [8].

The primary goal of this review is to collate and synthesize the existing body of research concerning the impact of climate change on plant diseases. This synthesis encompass a broad range of studies, encompassing various aspects such as the direct effects of climatic factors on pathogens and the indirect effects on host plants and ecosystems [9]. By consolidating current knowledge, this review aims to provide a comprehensive understanding of how changing climate conditions are influencing plant disease dynamics, contributing to both the academic discourse and practical applications in agriculture and plant protection.In addition to understanding the impact of climate change on plant diseases, this review seeks to explore and critically evaluate the various strategies that are being developed and implemented to adapt plant protection practices to these changing conditions. These strategies range from traditional methods like breeding for disease resistance to innovative approaches such as the use of biotechnology and integrated disease management practices. The effectiveness, feasibility, and sustainability of these strategies scrutinized to provide insights into the future of plant protection in the context of ongoing climate change.The methodology for literature selection was involve a systematic search of academic databases, including PubMed, Scopus, and Web of Science, among others. Criteria for inclusion was consist of the relevance to climate change and plant diseases, the significance of the study in advancing understanding or practice, and the rigor of the research methodology. Both peer-reviewed articles and significant gray literature, such as reports from governmental and international agencies, considered. The analysis was involved a critical evaluation of the findings, methodologies, and conclusions of the selected literature, aiming to identify trends, consensus, and gaps in the current body of knowledge.

II. Climate Change and Its Impacts on Plant Diseases

Climate change encompasses significant shifts in long-term weather patterns, primarily attributed to human activities, particularly the emission of greenhouse gases. In the context of agriculture, three key aspects of climate change are critically important: temperature, precipitation, and carbon dioxide (CO_2) levels.Global temperatures have been rising steadily, with the last few decades witnessing unprecedented warming [10]. This increase affects agriculture in several ways. Warmer temperatures can accelerate crop development, reducing the time for biomass accumulation and potentially decreasing yields [11]. However, in some cooler regions, a warmer climate may initially benefit certain crops by extending the growing season.Climate change also alters precipitation patterns, leading to more frequent and intense droughts and floods [12]. These changes impact soil moisture levels, water availability for irrigation, and the risk of both water deficit and excess, all of which are critical for agricultural productivity.Elevated atmospheric CO_2 concentrations can stimulate photosynthesis and plant growth, a phenomenon known as the CO_2 fertilization effect [13]. This benefit is often constrained by other factors like nutrient availability and may be offset by the negative impacts of increased temperatures and altered precipitation.

Climate change significantly influences the life cycles and virulence of plant pathogens. Warmer temperatures can increase the growth rate and reproductive capacity of many pathogens, potentially leading to more frequent and severe disease outbreaks [14]. For example, fungal pathogens like *Puccinia* spp., which cause rust diseases in cereals, demonstrate increased development rates under warmer conditions [15].Changes in temperature and humidity also affect the survival and dispersal of pathogens. Some pathogens may benefit from milder winters, leading to higher survival rates and earlier onset of disease in the growing season. Moreover, increased humidity and wetter conditions favor the proliferation of many fungal and bacterial diseases.

Climate change can alter the resistance and susceptibility of plants to diseases. Stress conditions induced by climate change, such as heat stress, drought, or waterlogging, can weaken plant defenses, making them more susceptible to infections [16]. For instance, drought stress has been shown to reduce the effectiveness of plant defense mechanisms against pathogens like *Fusarium* spp., which cause wilts and rots in various crops.Conversely, in some cases, increased CO_2 levels and higher temperatures might enhance certain aspects of plant defense, potentially reducing disease severity. This response, however, is highly variable and depends on the specific plant-pathogen interaction.Climate change is leading to shifts in the geographic distribution of pests and diseases. As temperatures rise, many pathogens and insect vectors are expanding their range poleward and to higher elevations [17]. This shift not only increases the risk of disease in areas previously unaffected but also introduces new challenges in managing diseases in these regions.Changes in climate can lead to the emergence of new diseases or the re-emergence of old ones. The altered environmental conditions may allow previously minor pathogens to become more significant threats. Additionally, the changing climate can disrupt the synchrony between pests, their natural enemies, and host plants, potentially leading to uncontrolled pest populations.

III. Current Challenges in Plant Protection

A. Traditional Plant Protection Strategies

Traditional plant protection strategies, fundamental to agriculture for decades, primarily comprise chemical, biological, and cultural control methods. Chemical control, utilizing a range of synthetic pesticides like herbicides, insecticides, fungicides, and nematicides, has been a mainstay due to its effectiveness and rapid action, despite growing environmental and health concerns [18]. Biological control, alternatively, employs living organisms such as beneficial insects, mites, or microorganisms to manage pest populations, offering a more environmentally sustainable option, though its effectiveness can vary greatly depending on specific conditions [19]. Cultural control, involving modifications to farming practices like crop rotation, intercropping, and the use of resistant varieties, is designed to create unfavorable conditions for pests and promote beneficial organisms, forming a core component of integrated pest management (IPM) strategies [20].These traditional methods face new challenges in the context of changing climate conditions. The efficacy of chemical pesticides can be undermined by increased temperatures and altered precipitation patterns, affecting their persistence, volatilization, and overall effectiveness [21]. Similarly, climate change disrupts the ecological balance essential for biological control, as shifts in temperature and humidity can impact the reproduction and survival of biological control agents, and pest migration to new areas might outpace the establishment of natural enemies [22]. Furthermore, cultural control practices such as crop rotation and the use of resistant varieties may need reevaluation in response to shifting pest and disease patterns, while extreme weather events like flooding and droughts can jeopardize the effectiveness of these strategies [23].

Table 1: Traditional Plant Protection Strategies[24,25].

Strategy	**Description**	**Examples**	**Advantages**	**Limitations**
Chemical Control	Use of synthetic substances like herbicides, insecticides, fungicides, and nematicides to control pests and diseases.	Insecticides for controlling aphids; Fungicides for powdery mildew.	Quick and effective; Wide range of options.	Environmental impact; Pesticide resistance; Health concerns.
Biological Control	Utilization of living organisms such as beneficial insects, mites, or microorganisms to manage pest populations.	Ladybugs to control aphids; Bacillus thuringiensis (Bt) for caterpillar control.	Environmentally friendly; Target-specific.	Variable effectiveness; Requires careful management.
Cultural Control	Modifying farming practices to reduce pest and disease risk.	Crop rotation to prevent soil-borne diseases; Sanitation to remove infected plant material.	Sustainable; Reduces chemical dependency.	Requires more planning and knowledge; Less immediate results.

B. Emerging Challenges

Climate change significantly exacerbates the incidence and severity of plant diseases, with warmer temperatures and higher humidity levels creating ideal conditions for the proliferation of fungal and bacterial pathogens [26]. This shift in climatic patterns is not only intensifying existing plant diseases but also paving the way for the emergence of new pathogens and the spread of familiar ones to previously unaffected regions. Compounding this issue is the growing development of resistance among pathogens to chemical pesticides, a consequence of their continuous and often indiscriminate use [27]. This resistance diminishes the effectiveness of existing pesticides and drives a costly, environmentally taxing cycle of developing new chemical solutions. Consequently, there is an escalating need for sustainable and adaptable plant protection strategies. Modern agriculture is increasingly seeking methods that are not only effective against current threats but can also adjust to evolving climatic conditions. This demand underscores the importance of developing resilient crop varieties, incorporating advanced technologies such as precision agriculture and genetic modification, and embracing holistic approaches like integrated pest management (IPM), which synergistically combine various control methods to maintain sustainability and adaptability in plant protection [28].

IV. Adapting Plant Protection Strategies

A. Integrated Disease Management (IDM)

Integrated Disease Management (IDM) represents a comprehensive, multi-faceted approach to plant protection, strategically combining various methods to manage plant diseases in an economically viable and environmentally responsible manner. The foundational principles of IDM revolve around a deep understanding of disease biology, vigilant monitoring of disease levels, utilization of disease forecasting models, and the implementation of an array of control methods including cultural, biological, chemical, and physical strategies [29]. Central to IDM is the emphasis on preventative measures like crop rotation and the use of disease-resistant crop varieties, coupled with judicious application of chemical controls, aiming not for outright eradication of disease but for effective management to reduce dependency on chemical pesticides and minimize environmental impacts. In the context of evolving climate scenarios, IDM necessitates adaptive modifications to meet emerging challenges. These adaptations include updating disease risk assessment models to factor in climate change projections, developing and deploying climate-resilient crop varieties, and enhancing the efficacy of biological control agents under varied climatic conditions [30]. Additionally, IDM adaptation involves improving irrigation and drainage systems to address water-related disease challenges and integrating advanced technologies such as remote sensing and Geographic Information Systems (GIS) for more precise disease monitoring and management, ensuring that plant protection strategies remain robust and effective in the face of changing environmental conditions.

B. Advances in Breeding for Disease Resistance

The advancement in breeding for disease resistance, incorporating both traditional methods and genetic engineering, has been pivotal in developing plant varieties capable of withstanding disease pressures. Traditional breeding has long utilized the introduction of resistance traits from wild relatives or other cultivars into commercial varieties, a practice that has fortified crops against a range of diseases [31]. In parallel, the advent of genetic engineering has opened new avenues for enhancing disease resistance. Modern techniques, particularly gene editing, enable the precise introduction or overexpression of specific resistance genes in crops, offering targeted protection against particular pathogens [32]. This dual approach is exemplified in several case studies demonstrating the successful development of resistant varieties. Notably, the creation of wheat varieties resistant to the 'UG99' strain of stem rust represents a significant breakthrough in safeguarding global wheat production against this formidable disease [33]. Similarly, the introduction of late blight-resistant genes into potato varieties has markedly mitigated the impacts of this historically devastating disease, showcasing the effectiveness of these advanced breeding strategies [34]. These examples underscore the critical role of both traditional breeding and genetic engineering in developing resilient crop varieties, thus fortifying global food security against the backdrop of emerging and evolving plant diseases.

Table 2: Advances in Breeding for Disease Resistance [35,36]

Aspect	**Description**	**Examples**	**Techniques**	**Benefits**
Traditional Breeding	Involves crossing different varieties or species to introduce disease-resistant traits.	Developing wheat varieties resistant to stem rust by crossing with resistant wild relatives.	Selective breeding, backcrossing, hybridization.	Utilizes natural genetic diversity; Well-established techniques.
Genetic Engineering	Direct manipulation of an organism's DNA to enhance disease resistance.	Bt cotton resistant to bollworms.	Transgenic approaches, gene insertion.	Precise introduction of traits; Can overcome limitations of traditional breeding.
Gene Editing (CRISPR/Cas9)	A precise tool for modifying an organism's genetic material to enhance specific traits, including disease resistance.	Developing rice varieties resistant to bacterial blight.	CRISPR/Cas9, TALENs, ZFNs.	High precision; Faster development; Can target specific genes.

C. Biotechnological Approaches

The advent of biotechnological approaches in agriculture has significantly advanced the development of biopesticides and biocontrol agents, presenting more sustainable alternatives to traditional chemical pesticides. Biopesticides, derived from natural sources such as microorganisms, plant extracts, and minerals, offer the advantage of having a reduced environmental footprint and being highly target-specific, thus minimizing unintended effects on non-target species [37]. In tandem, biocontrol agents, including beneficial bacteria and fungi, play a pivotal role in suppressing disease-causing pathogens. They achieve this through a variety of mechanisms such as competition, parasitism, and the induction of plant defense responses, thereby contributing to a more holistic and environmentally friendly approach to disease management. Complementing these developments, the application of CRISPR and other gene-editing technologies has ushered in a new era in plant breeding and protection. These technologies allow for precise, targeted modifications of plant genomes, facilitating the rapid development of disease-resistant crop varieties with greater accuracy than conventional breeding methods [38]. The use of CRISPR, in particular, has shown significant promise, enhancing resistance against a wide spectrum of viruses, fungi, and bacteria in various crops. This illustrates the immense potential of gene-editing technologies as powerful tools in the realm of plant protection, enabling the cultivation of more resilient crops that can better withstand the challenges posed by pests and diseases.

D. Climate-Smart Agricultural Practices

In the realm of adapting plant protection strategies to the challenges posed by climate change, climate-smart agricultural practices such as diversification and rotation strategies play a pivotal role. Diversification, the practice of cultivating a variety of crops, effectively reduces the risk of disease outbreaks by not allowing any single pathogen to dominate. Similarly, crop rotation disrupts the life cycles of pathogens and pests, thereby curtailing their accumulation in the soil, a fundamental principle in sustainable agriculture [39]. Complementing these strategies, effective soil and water management techniques have emerged as critical components in disease control, especially under changing climatic conditions. Practices such as conservation tillage, optimized irrigation scheduling, and improved drainage systems are instrumental in mitigating the prevalence of both water-borne and soil-borne diseases [40]. Additionally, the integration of climate forecasts and modeling into disease management strategies has gained considerable importance. Utilizing predictive models that incorporate climatic data enables the forecasting of disease outbreaks, thus allowing for more timely and targeted interventions. This approach not only enhances the effectiveness of plant protection measures but also empowers farmers to align their strategies with anticipated climatic conditions and associated disease risks, thereby optimizing agricultural outputs while mitigating potential losses due to pests and diseases [41]. These combined strategies underscore a comprehensive approach to plant protection, aligning agricultural practices with ecological principles and technological advancements to combat the multifaceted challenges posed by a changing climate.

V. Case Studies and Practical Applications

A. Success Stories

Examples of Effective Adaptation Strategies in Various Regions

In India, a diverse and climatically varied country, several successful adaptation strategies in agriculture have been implemented. For instance, in the semi-arid tropics of central and southern India, farmers have successfully adopted drought-tolerant crop varieties, developed through both traditional breeding and biotechnological approaches, to combat the increasing frequency and severity of droughts [42]. These varieties have not only improved yields in drought conditions but also offered greater resilience against pest outbreaks associated with climate stress.Another example is the use of Integrated Pest Management (IPM) practices in the cotton-growing regions of Punjab and Maharashtra. Farmers have adopted a combination of biopesticides, pheromone traps, and resistant varieties to combat the widespread issue of pest resistance to chemical pesticides, notably in the case of the cotton bollworm [43]. This approach has significantly reduced pesticide use and increased yields, while also mitigating the environmental impact of cotton farming.

Title 3: Innovative Global Projects and Trials for Adapting Plant Protection Strategies in the Context of Climate Change [44,45].

Project/Trial	Location	Focus Area	Strategies/Technologies Used	Outcomes/Goals
Drought-Tolerant Crop	Sub-Saharan	Developing crops resistant to drought	Traditional and molecular breeding techniques.	Enhanced crop resilience to drought, ensuring food security in

Development	Africa	stress.		arid regions.
Heat-Resistant Wheat Varieties	Australia, India	Breeding wheat that can tolerate high temperatures.	Genetic engineering, marker-assisted selection.	Creation of wheat varieties that maintain yields under heat stress.
Flood-Tolerant Rice (Sub1 Gene)	Southeast Asia	Developing rice varieties resilient to flooding.	Marker-assisted breeding incorporating the Sub1 gene.	Improved rice survival and yield in flood-prone areas.
Precision Agriculture for Disease Management	Europe, North America	Using technology for efficient disease control.	Remote sensing, AI, IoT-based solutions.	Optimized use of inputs, early disease detection, and management.
CRISPR for Disease Resistance	Global	Enhancing crop resistance to various diseases.	CRISPR/Cas9 gene-editing technology.	Development of crop varieties with enhanced resistance to viruses, fungi, bacteria.
Integrated Pest Management (IPM) Programs	Asia, Africa	Sustainable pest and disease control.	Combination of biological, cultural, and chemical methods.	Reduced reliance on chemical pesticides, sustainable crop protection.
Agroforestry for Climate Adaptation	Central and South America	Combining agriculture and forestry practices.	Diversification with trees and crops.	Improved biodiversity, soil health, and resilience to climate extremes.
Soil Health Improvement Initiatives	United States, Europe	Enhancing soil quality and resilience.	Organic farming, conservation tillage, cover cropping.	Increased soil organic matter, better crop health, and disease resistance.

B. Ongoing Research and Experimental Approaches

1. Innovative Projects and Trials Worldwide

In the Indian context, several innovative research projects and trials are underway to address the challenges posed by climate change in agriculture. One significant area of research is the development of heat-tolerant wheat and rice varieties. The Indian Agricultural Research Institute (IARI) has been at the forefront of this research, developing varieties that can withstand higher temperatures and shorter growing seasons [46].Another area of focus is the development and application of precision agriculture technologies. Remote sensing, drone technology, and IoT-based solutions are being tested for their efficacy in monitoring crop health, optimizing water use, and predicting pest and disease outbreaks [47]. These technologies have the potential to revolutionize farm management by providing real-time data and predictive analytics for more efficient and sustainable farming practices.

2. Potential Breakthroughs and Future Directions

Looking towards the future, the potential breakthroughs in Indian agriculture in the context of climate change adaptation are numerous. One promising direction is the use of gene-editing techniques, such as CRISPR/Cas9, to develop crops with enhanced resistance to diseases and pests, and better tolerance to abiotic stresses like drought and salinity [48]. Another future direction lies in the integration of artificial intelligence and machine learning in agricultural practices, which could lead to more precise disease forecasting models and automated pest management systems.Additionally, the development of sustainable and climate-resilient agricultural systems, such as agroforestry and organic farming, is gaining traction. These systems not only help in adapting to climate change but also contribute to mitigation by enhancing carbon sequestration and biodiversity [49].

VI. Challenges and Opportunities for Future Research

A. Identifying Research Gaps

In the Indian context, several research gaps need to be addressed to effectively combat the challenges posed by climate change to agriculture. One critical area is the understanding of the interaction between climate change and plant disease dynamics. While significant strides have been made, there is still a need for more localized studies to understand how regional climatic variations influence disease patterns in specific crops [50].Another area needing further exploration is the impact of climate change on soil health and its subsequent effect on plant health and crop yields. Studies focusing on the long-term impacts of altered precipitation patterns, increased temperatures, and CO_2 levels on soil microbiota and nutrient dynamics are crucial [51]. There is a pressing need for more research on the development of climate-resilient crop varieties, especially for crops that are staple to the Indian diet, like rice and wheat. This includes understanding the genetic basis of resilience traits and employing advanced breeding techniques to develop varieties adapted to the changing climate [52].

B. Integrating Multidisciplinary Approaches

Addressing the challenges posed by climate change to agriculture requires a multidisciplinary approach. Collaboration between plant pathology, climatology, and agronomy is essential to develop comprehensive strategies for crop protection and management [53]. For example, integrating climatological data with plant disease models can improve the accuracy of disease forecasts and help in developing effective disease management strategies [54].Additionally, agronomic research that incorporates climate models can aid in developing agricultural practices that are both resilient to climate variability and sustainable. This includes research on water-efficient farming practices, soil conservation techniques, and the development of integrated pest and disease management strategies that are tailored to local climatic conditions [55].

C. Policy Implications and Recommendations

The role of government and international agencies is pivotal in supporting adaptive strategies for climate-resilient agriculture. Policy measures are needed to promote research and development in key areas such as climate-resilient crops, sustainable farming practices, and advanced pest and disease management techniques [56].One important aspect is the funding and support for research initiatives that address the specific challenges of Indian agriculture in the context of climate change. This includes supporting collaborative research programs that bring together experts from different fields and facilitating the translation of research findings into practical solutions for farmers [57].Additionally, government policies should aim at building the capacity of farmers to adapt to climate change. This can be achieved through extension services that provide farmers with the latest information and technologies related to climate-resilient farming practices, pest and disease management, and soil and water conservation techniques [58]. International agencies play a crucial role in facilitating the exchange of knowledge and technologies between countries and in supporting developing countries like India in their efforts to adapt to climate change. This can involve funding research projects, providing technical expertise, and supporting the implementation of climate-resilient agricultural practices at the grassroots level [59].

VII. Conclusion

Adapting plant protection strategies to the challenges posed by climate change is a multifaceted endeavor, especially in the diverse and climatically varied landscape of India. The synthesis of current research underscores the urgent need for integrated approaches, encompassing traditional and innovative strategies. Integrated Disease Management, advances in breeding for disease resistance, biotechnological innovations, and climate-smart agricultural practices offer promising pathways. However, the effectiveness of these strategies hinges on addressing existing research gaps, fostering multidisciplinary collaborations, and robust policy support. Lessons learned from successful case studies provide valuable insights into best practices and adaptable solutions. As climate change continues to impact agriculture, ongoing research and adaptive strategies, supported by government and international agencies, will be crucial in ensuring sustainable food security and the resilience of agricultural systems in India and beyond.

References

1. Agovino, M., Casaccia, M., Ciommi, M., Ferrara, M., & Marchesano, K. (2019). Agriculture, climate change and sustainability: The case of EU-28. *Ecological Indicators*, *105*, 525-543.

2. Hatfield, J. L., Boote, K. J., Kimball, B. A., Ziska, L. H., Izaurralde, R. C., Ort, D., ... & Wolfe, D. (2011). Climate impacts on agriculture: implications for crop production. *Agronomy journal*, *103*(2), 351-370.

3. Kaur, G., Singh, G., Motavalli, P. P., Nelson, K. A., Orlowski, J. M., & Golden, B. R. (2020). Impacts and management strategies for crop production in waterlogged or flooded soils: A review. *Agronomy Journal*, *112*(3), 1475-1501.

4. Naylor, R. L., & Falcon, W. P. (2010). Food security in an era of economic volatility. *Population and development review*, *36*(4), 693-723.

5. Elad, Y., &Pertot, I. (2014). Climate change impacts on plant pathogens and plant diseases. *Journal of Crop Improvement*, *28*(1), 99-139.

6. Hunjan, M. S., & Lore, J. S. (2020). Climate change: Impact on plant pathogens, diseases, and their management. *Crop protection under changing climate*, 85-100.

7. Nieder, R., Benbi, D. K., Reichl, F. X., Nieder, R., Benbi, D. K., & Reichl, F. X. (2018). Soil as a transmitter of human pathogens. *Soil components and human health*, 723-827.

8. Jones, R. A., &Barbetti, M. J. (2012). Influence of climate change on plant disease infections and epidemics caused by viruses and bacteria. *CABI Reviews*, (2012), 1-33.

9. Chapman, J. W., Reynolds, D. R., & Wilson, K. (2015). Long- range seasonal migration in insects: mechanisms, evolutionary drivers and ecological consequences. *Ecology letters*, *18*(3), 287-302.

10. Yiou, P., Vautard, R., Naveau, P., &Cassou, C. (2007). Inconsistency between atmospheric dynamics and temperatures during the exceptional 2006/2007 fall/winter and recent warming in Europe. *Geophysical Research Letters*, *34*(21).

11. Hatfield, J. L., Boote, K. J., Kimball, B. A., Ziska, L. H., Izaurralde, R. C., Ort, D., ... & Wolfe, D. (2011). Climate impacts on agriculture: implications for crop production. *Agronomy journal*, *103*(2), 351-370.

12. Mall, R. K., Gupta, A., & Sonkar, G. (2017). Effect of climate change on agricultural crops. In *Current developments in biotechnology and bioengineering* (pp. 23-46). Elsevier.

13. Wang, S., Zhang, Y., Ju, W., Chen, J. M., Ciais, P., Cescatti, A., ... &Peñuelas, J. (2020). Recent global decline of CO2 fertilization effects on vegetation photosynthesis. *Science*, *370*(6522), 1295-1300.

14. Baker, R. E., Mahmud, A. S., Miller, I. F., Rajeev, M., Rasambainarivo, F., Rice, B. L., ... & Metcalf, C. J. E. (2022). Infectious disease in an era of global change. *Nature Reviews Microbiology*, *20*(4), 193-205.

15. Chen, X. (2020). Pathogens which threaten food security: Puccinia striiformis, the wheat stripe rust pathogen. *Food Security*, *12*(2), 239-251.

16. Lamalakshmi Devi, E., Kumar, S., Basanta Singh, T., Sharma, S. K., Beemrote, A., Devi, C. P., ... & Wani, S. H. (2017). Adaptation strategies and defence mechanisms of plants during environmental stress. *Medicinal plants and environmental challenges*, 359-413.

17. Bebber, D. P. (2015). Range-expanding pests and pathogens in a warming world. *Annual review of phytopathology*, *53*, 335-356.

18. Khursheed, A., Rather, M. A., Jain, V., Rasool, S., Nazir, R., Malik, N. A., & Majid, S. A. (2022). Plant based natural products as potential ecofriendly and safer biopesticides: A comprehensive overview of their advantages over conventional pesticides, limitations and regulatory aspects. *Microbial Pathogenesis*, 105854.

19. Sindhu, S. S., Sehrawat, A., Sharma, R., & Khandelwal, A. (2017). Biological control of insect pests for sustainable agriculture. *Advances in Soil Microbiology: Recent Trends and Future Prospects: Volume 2: Soil-Microbe-Plant Interaction*, 189-218.

20. Deguine, J. P., Aubertot, J. N., Flor, R. J., Lescourret, F., Wyckhuys, K. A., &Ratnadass, A. (2021). Integrated pest management: good intentions, hard realities. A review. *Agronomy for Sustainable Development*, *41*(3), 38.

21. Gatto, M. P., Cabella, R., & Gherardi, M. (2016). Climate change: the potential impact on occupational exposure to pesticides. *Annali dell'Istitutosuperiore di sanita*, *52*(3), 374-385.

22. Schowalter, T. D. (2022). *Insect ecology: an ecosystem approach*. Academic press.

23. Venkateswarlu, B., & Shanker, A. K. (2011). Dryland agriculture: bringing resilience to crop production under changing climate. In *Crop stress and its management: Perspectives and strategies* (pp. 19-44). Dordrecht: Springer Netherlands.

24. Kumar, A. (2007). Traditional plant protection management practices of Rajasthan. *Leisa India*, *9*, 29-30.

25. Abate, T., van Huis, A., & Ampofo, J. K. O. (2000). Pest management strategies in traditional agriculture: an African perspective. *Annual review of entomology*, *45*(1), 631-659.

26. Elad, Y., &Pertot, I. (2014). Climate change impacts on plant pathogens and plant diseases. *Journal of Crop Improvement*, *28*(1), 99-139.

27. Karunamoorthi, K., & Sabesan, S. (2013). Insecticide resistance in insect vectors of disease with special reference to mosquitoes: a potential threat to global public health.

28. Barzman, M., Bàrberi, P., Birch, A. N. E., Boonekamp, P., Dachbrodt-Saaydeh, S., Graf, B., ... &Sattin, M. (2015). Eight principles of integrated pest management. *Agronomy for sustainable development*, *35*, 1199-1215.

29. Hampel, H., Toschi, N., Babiloni, C., Baldacci, F., Black, K. L., Bokde, A. L., ... & Alzheimer Precision Medicine Initiative. (2018). Revolution of Alzheimer precision neurology. Passageway of systems biology and neurophysiology. *Journal of Alzheimer's Disease*, *64*(s1), S47-S105.

30. Ahmad, Z., Ahmad, T., Abbasi, A., Waraich, E. A., Hina, A., Ishfaq, T., ... & Jameel, J. (2023). Climate Change and Global Crop Production. In *Climate-Resilient Agriculture, Vol 1: Crop Responses and Agroecological Perspectives* (pp. 27-56). Cham: Springer International Publishing.

31. Bohra, A., Kilian, B., Sivasankar, S., Caccamo, M., Mba, C., McCouch, S. R., & Varshney, R. K. (2022). Reap the crop wild relatives for breeding future crops. *Trends in Biotechnology*, *40*(4), 412-431.

32. Rato, C., Carvalho, M. F., Azevedo, C., &Oblessuc, P. R. (2021). Genome editing for resistance against plant pests and pathogens. *Transgenic Research*, *30*(4), 427-459.

33. Bhavani, S., Hodson, D. P., Huerta-Espino, J., Randhawa, M. S., & Singh, R. P. (2019). Progress in breeding for resistance to Ug99 and other races of the stem rust fungus in CIMMYT wheat germplasm.

34. Tiwari, J. K., Challam, C., Chakrabarti, S. K., & Feingold, S. E. (2020). Climate-smart potato: an integrated breeding, genomics, and phenomics approach. *Genomic Designing of Climate-Smart Vegetable Crops*, 1-46.

35. Sánchez-Martín, J., & Keller, B. (2019). Contribution of recent technological advances to future resistance breeding. *Theoretical and Applied Genetics*, *132*(3), 713-732.

36. Hoyos-Villegas, V., Chen, J., Mastrangelo, A. M., & Raman, H. (2022). Advances in breeding for quantitative disease resistance. *Frontiers in Plant Science*, *13*, 890002.

37. Lengai, G. M., & Muthomi, J. W. (2018). Biopesticides and their role in sustainable agricultural production. *Journal of Biosciences and Medicines*, *6*(06), 7.

38. Ali, Q., Yu, C., Hussain, A., Ali, M., Ahmar, S., Sohail, M. A., ... & Zhou, L. (2022). Genome engineering technology for durable disease resistance: Recent progress and future outlooks for sustainable agriculture. *Frontiers in Plant Science*, *13*, 860281.

39. Kumar, S., Meena, R. S., Datta, R., Verma, S. K., Yadav, G. S., Pradhan, G., ... & Mashuk, H. A. (2020). Legumes for carbon and nitrogen cycling: an organic approach. *Carbon and nitrogen cycling in soil*, 337-375.

40. Hamedi, A., & Hasan, F. (2021). UTILIZATION AND EVALUATION OF TREATED WASTEWATER ON THE PRODUCTION TECHNOLOGY OF WHEAT (TRITICUM AESTIVUM L.) UNDER DIFFERENT MODES OF CULTIVATION.

41. Warra, A. A., & Prasad, M. N. V. (2020). African perspective of chemical usage in agriculture and horticulture—their impact on human health and environment. In *Agrochemicals detection, treatment and remediation* (pp. 401-436). Butterworth-Heinemann.

42. Yahaya, M. A., & Shimelis, H. (2022). Drought stress in sorghum: Mitigation strategies, breeding methods and technologies—A review. *Journal of Agronomy and Crop Science*, *208*(2), 127-142.

43. Malinga, L. N. (2022). *Study on the use of biopesticides against cotton insect pests under field conditions and their cost benefits* (Doctoral dissertation).

44. Adenle, A. A., Azadi, H., & Arbiol, J. (2015). Global assessment of technological innovation for climate change adaptation and mitigation in developing world. *Journal of environmental management*, *161*, 261-275.

45. Smithers, J., & Blay-Palmer, A. (2001). Technology innovation as a strategy for climate adaptation in agriculture. *Applied Geography*, *21*(2), 175-197.

46. Pathak, H. (2019). Agricultural research and development: policy and program priorities in India. *Agricultural Policy and Program Framework: Priority Areas for Research & Development in South Asia*, 93.

47. Panday, U. S., Pratihast, A. K., Aryal, J., & Kayastha, R. B. (2020). A review on drone-based data solutions for cereal crops. *Drones*, *4*(3), 41.

48. Rasheed, A., Gill, R. A., Hassan, M. U., Mahmood, A., Qari, S., Zaman, Q. U., ... & Wu, Z. (2021). A critical review: recent advancements in the use of CRISPR/Cas9 technology to enhance crops and alleviate global food crises. *Current Issues in Molecular Biology*, *43*(3), 1950-1976.

49. Lal, R., Delgado, J. A., Groffman, P. M., Millar, N., Dell, C., & Rotz, A. (2011). Management to mitigate and adapt to climate change. *Journal of Soil and Water Conservation*, *66*(4), 276-285.

50. Ryan, J., Rashid, A., Torrent, J., Yau, S. K., Ibrikci, H., Sommer, R., &Erenoglu, E. B. (2013). Micronutrient constraints to crop production in the Middle East–West Asia region: significance, research, and management. *Advances in Agronomy*, *122*, 1-84.

51. Jansson, J. K., & Hofmockel, K. S. (2020). Soil microbiomes and climate change. *Nature Reviews Microbiology*, *18*(1), 35-46.

52. Kole, C., Muthamilarasan, M., Henry, R., Edwards, D., Sharma, R., Abberton, M., ... & Prasad, M. (2015). Application of genomics-assisted breeding for generation of climate resilient crops: progress and prospects. *Frontiers in plant science*, *6*, 563.

53. Eigenbrode, S. D., Binns, W. P., & Huggins, D. R. (2018). Confronting climate change challenges to dryland cereal production: A call for collaborative, transdisciplinary research, and producer engagement. *Frontiers in Ecology and Evolution*, *5*, 164.

54. Damos, P. (2015). Modular structure of web-based decision support systems for integrated pest management. A review. *Agronomy for sustainable development*, *35*(4), 1347-1372.

55. Raza, A., Friedel, J. K., & Bodner, G. (2012). Improving water use efficiency for sustainable agriculture. *Agroecology and strategies for climate change*, 167-211.

56. Selvaraju, R., Gommes, R., & Bernardi, M. (2011). Climate science in support of sustainable agriculture and food security. *Climate Research*, *47*(1-2), 95-110.

57. Hoffmann, V., Probst, K., &Christinck, A. (2007). Farmers and researchers: How can collaborative advantages be created in participatory research and technology development?. *Agriculture and human values*, *24*, 355-368.

58. Srivastav, A. L., Dhyani, R., Ranjan, M., Madhav, S., & Sillanpää, M. (2021). Climate-resilient strategies for sustainable management of water resources and agriculture. *Environmental Science and Pollution Research*, *28*(31), 41576-41595.

59. Dey, A., Gupta, A. K., & Singh, G. (2019). Innovation, investment and enterprise: Climate resilient entrepreneurial pathways for overcoming poverty. *Agricultural Systems*, *172*, 83-90.