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Plant Disease Shifting Climate Change Related Landscapes: Host Vector Epidemiology Responses and Adaptive Management Solutions

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ABSTRACT: Plant disease dynamics are changing globally as a result of climate change which is radically changing the interactions between host plants, pathogens, insect vectors and their surrounding habitats. Plant defense mechanisms are being weakened by rising global temperatures, changing precipitation patterns, increased atmospheric carbon dioxide concentrations and an increase in the frequency of extreme weather events. Meanwhile pathogen survival, virulence, transmission efficiency and geographic expansion are being enhanced. These environmental factors have accelerated the spread of established infections into previously unaffected areas and contributed to the establishment of novel plant diseases. Concurrently the hazards of disease transmission in agricultural systems have grown due to climate induced changes in insect vector populations, such as greater population densities, extended periods of activity and expanded ranges. This main goal of this review is to assess adaptive and climate resilient management approaches while summarizing current developments in our knowledge of how climate change affects host vulnerability, pathogen behavior, vector ecology and plant disease epidemiology. Emerging diagnostic and monitoring technologies such as molecular diagnostics, remote sensing, unmanned aerial vehicles and artificial intelligence-based decision support systems that allow for early disease detection and better forecasting in dynamic climatic conditions are given special attention. The main finding of the reviewed literature is that integrated, climate smart frameworks that incorporate resistant crop varieties, sustainable cultural practices, biological control agents and sophisticated monitoring tools are necessary for effective plant disease management under present and future climate scenarios. To improve agro-ecosystem resilience, sustain agricultural yield and protect global food security in the face of accelerated climate change and these adaptive techniques must be strengthened.

KEYWORDS: Host-pathogen interactions; Climate-driven disease spread; Climate-smart agriculture; Crop resilience; Food security.

INTRODUCTION

One of the major problems facing agriculture worldwide is climate change which has clear adverse effects on plant health and disease transmission. Increased atmospheric carbon dioxide, changed rainfall patterns and an increase in extreme weather events are all contributing factors to the evolution and spread of plant diseases (Chaloner et al., 2021). Plant diseases are determined by the interactions of the environment, its host plant and the pathogen. Climate change directly affects this relationship by encouraging pathogen survival, propagation and modification. It also continuously affects plants defense systems and growth (Raza et al., 2022; Mubeen et al., 2025). As a result, some preexisting diseases expand into currently unoccupied areas and new plant diseases appear (Savary et al., 2022). Warmer temperatures hasten the life cycles of pathogens, including bacteria and fungi as well as disease-transmitting insects (Mubeen et al., 2024a). Increased production of infectious material and quicker disease development result from this (Garrett et al., 2022). Disease outbreaks can occur earlier in the time of year when winters are milder because infections and insect vectors can live longer (Benitez et al., 2023). Rainfall variations are particularly significant because prolonged leaf wetness encourages illnesses that infect leaves and facilitates the long-distance transfer of bacterial organisms and spores (Velásquez et al., 2024; Mubeen et al., 2015a). Increased atmospheric carbon dioxide levels also affect plant health by altering nutritional balance, pores activity and plant structure. These modifications can either raise or lower the severity of the disease depending on the particular plant pathogen interaction. Plant defense mechanisms are weakened by climate related stresses including heat and drought (Ristaino et al., 2021). Climate change is also having an influence on plant disease management, often making many of the present control methods less successful. The plants may lose their built-in resistance under the influence of fluctuations in pathogen populations dynamics, disease pressure and ultimately the crops that are resistant to diseases may no longer remains resistant (Lago et al., 2025; Mubeen et al., 2024b). Additionally, disease prediction models prepared earlier may lose accuracy as climatic conditions continue to change drastically. Resistant varieties against climate change and disease control techniques are vitally needed to protect agricultural productivity and food safety. By combining the most recent information on pathogen behavior, host plant responses, insect vector ecology and disease epidemiology under shifting climatic conditions this review thoroughly investigates the effects of climate change on plant disease dynamics. An examination of changes in pathogen dynamics, host resistance and vector populations brought on by climate change follows a discussion of the major climate drivers that affect disease development and dissemination. Then with a focus on precision agriculture and digital tools the study emphasizes current developments in disease detection, monitoring and forecasting technology. In order to find long term solutions for protecting crop health and global food security under future climatic scenarios, adaptive and climate resilient disease management strategies including cultural, biological, genetic and integrative approaches are critically assessed.

The Impact of Climate Change on Plant Disease Epidemiology: Pathogenic organisms, their hosts and the environment interact and have a long-lasting impact on the emergence and spread of plant diseases in a changing climate. (IPCC, 2021). Major factors included in climate change are changes in rainfall patterns, rising global temperatures and higher atmospheric carbon dioxide levels (Falloon et al., 2022). Temperature is one of the most important factors influencing diseases progression in the plants. Warmer weather speeds up the growth of infections or shortens the time of infection until symptoms become apparent and also permits the multiple disease cycles in a single growing season (Garrett et al., 2022). However, by interfering with regular plant processes and defensive mechanisms can reduce plant resilience and increase susceptibility to illness (Velásquez et al., 2024).The development and spread of plant diseases are significantly impacted by fluctuations in humidity and rainfall. Spores can germinate, infect plants and spread leaf diseases when there is more rainfall and longer periods of moisture on leaves (Abdullahi et al., 2025). Small local conditions which induce disease outbreaks can also be created by irregular rainfall. However, by lowering their natural defenses and increases their susceptibility to infections by opportunistic and soil borne pathogens (Chetanraj et al., 2024). By altering plant development, leaf cover and nutrient balance elevated airborne carbon dioxide levels also affect plant diseases. Increased CO_2 can upset plants' carbon nitrogen balance which depending on the pathogen can either increase or decrease the severity of the disease (Eastburn et al., 2024). Depending on the particular plant and pathogen involved these alterations in plant physiology may either decrease or accelerate the development of illness (Bradshaw et al., 2024). Sudden illness outbreaks are becoming more common as a result of extreme weather events including floods and storms. When taken as a whole, these studies show a steady trend toward faster disease cycles, wider geographic ranges and more unpredictable outbreaks as a result of climate change. While changed rainfall patterns exacerbate illnesses that depend on leaf moisture and promote long-distance dissemination, rising temperatures decrease the latent periods of pathogens. Severe weather conditions also serve as disruption triggers resulting in severe but sporadic illness epidemics. When taken as a whole these interrelated climate factors are changing conventional epidemiological trends and throwing doubt on the accuracy of past illness prediction models. They harm plants induce stress and facilitate the rapid invasion and spread of diseases (Jeske et al., 2025). It is essential to update disease prediction models and management strategies because these climate related factors collectively are altering current trends of disease incidence and spreading diseases to new locations (de Souza et al., 2024). These climate driven interactions among temperature, moisture and extreme events collectively alter disease initiation, development and spatial spread (Figure 1).

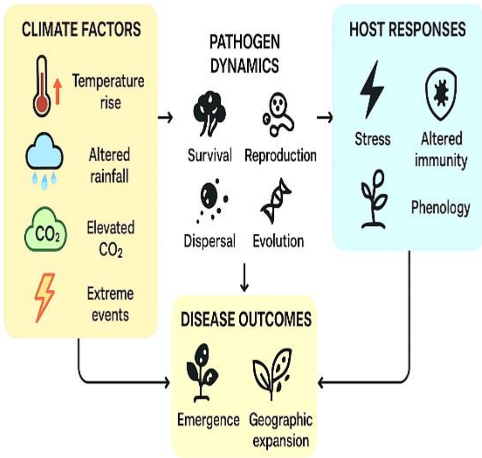

Figure 1: Climate change-driven shifts in plant disease epidemiology.

Global plant disease patterns are significantly shifting as a result of climate change profound effects on plant infection ability to survive, proliferate and disseminate (Chaloner et al., 2021). Increased temperatures accelerate the metabolism of pathogens which reduce the time until symptoms manifest and permit several disease cycles in a single growth season especially for bacteria and fungi (Velásquez et al., 2024). As a result, illnesses that were formerly uncommon are now widespread in many agricultural systems. When taken as a whole, our results imply that climate change exacerbates disease pressure in both yearly and perennial agricultural systems by increasing pathogen fitness and synchronizing pathogen life cycles with longer growing seasons. Fungal pathogens are especially vulnerable to variations in moisture and temperature. Higher humidity and erratic precipitation encourage germination and dissemination whereas warmer winter aid pathogens in surviving the season (Shabbiret al., 2025b). By affecting the insects that transmit viruses, viroid and climate change also has an indirect impact on these diseases. Diseases affecting plants spread more quickly due to increased insect mobility and reproduction brought on by elevated temperatures and longer growing periods (Arias et al., 2021). Stress from heat and drought weakens plants and exacerbates disease symptoms especially for phloem-based pathogens (Cimini et al., 2023). Plant diseases spreading to new areas is one of the main effects of climate change. Increased disease transmission is currently occurring in regions at higher temperatures and elevations where temperatures were previously inappropriate for numerous pathogens (Varma et al., 2025). These changes increase hazards in areas that are unprepared or depend on resistant crop types and lower the accuracy of current disease prediction algorithms. In general diseases of plants outbreaks are becoming more unpredictable and severe due to changes in pathogen behavior brought on by climate change. This emphasizes the critical necessity to implement adaptable and update disease forecasting methods (Garrett et al., 2022). The main climatic factors that affect pathogen survival, reproduction and dispersal including temperature rise, precipitation variability and extreme events (Figure 2). It also highlights the direct and indirect consequences of these factors on the onset and spread of illness.

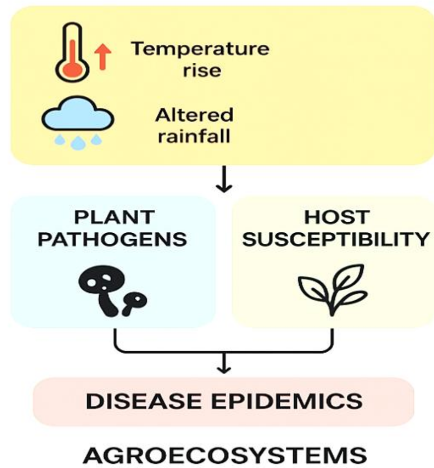

Figure 2: Main climatic factors that affect pathogen survival, reproduction and dispersal.

Climate Change Induced Alternation in Host Plant Responses: Plant development and the longevity of their resistance are also impacted by climate change along with to plant diseases. Plants are stressed by high temperatures, high atmospheric carbon dioxide levels and severe weather which makes it more difficult for them to fight against infections (Chaloner et al., 2021). For instance, heat stress can reduce the activation of resistance gene transcription and impair plant immunological responses including those regulated by signaling pathways including the chemicals salicylic acid and jasmonic acids (Huot et al., 2022). Additionally, higher temperatures can interfere with the plants ability to determine infections and disrupt resistance protein which enhances the development of diseases (Singh et al., 2023). According to studies when temperatures rise crops like wheat, rice and tomatoes may lose resistance to disease (Rodriguez et al., 2022). By reduced photosynthesis restricting nutrient intake and altering how leaves regulate water loss and drought stress increases a plants sensitivity. Plants are more vulnerable to vascular and opportunistic infections as a result of these changes which impair both local and whole plant defenses, including systemic acquired resistance (Baidya et al., 2022). Plants under drought stress frequently exhibit more severe wilt diseases and are more susceptible to phloem associated colonization by pathogens

(Ramegowda et al., 2024). Increased carbon dioxide levels can also alter the chemistry and growth of plant and carbon balance as well as the synthesis of protective chemicals. Increased CO_2 can promote plant growth but it can also change the structure of leaves or lower the concentration of defensive compounds which can make it simpler for viruses to infect plants (Smith et al., 2022). Depending on the particular plant pathogen system the overall impact of extra carbon dioxide on plant resistance varies with some crops exhibiting more severe disease and others less (Filonchyk et al., 2024). Severe weather circumstances including flooding and water logging impair root defenses, disrupt nutritional balance and cause low oxygen levels in roots. These stressors increase a plants susceptibility to bacteria and fungi that infect roots as well as soil borne diseases (Choudhary et al., 2022). In general, climate related stressors weaken plant resilience, alter the course of disease development and increase the likelihood of future and more severe disease outbreaks. In conclusion, abiotic challenges linked to climate change frequently decrease systemic defense mechanisms, disrupt immunological signaling and modify metabolic balance. All of which reduce the durability of plant resistance. When heat and drought stress are combined plants are more vulnerable to vascular, phloem associated and opportunistic diseases. The interconnected effects of temperature stress, drought and altered carbon metabolism on plant defense responses are depicted how climate stressors increase host vulnerability to disease (Figure 3).

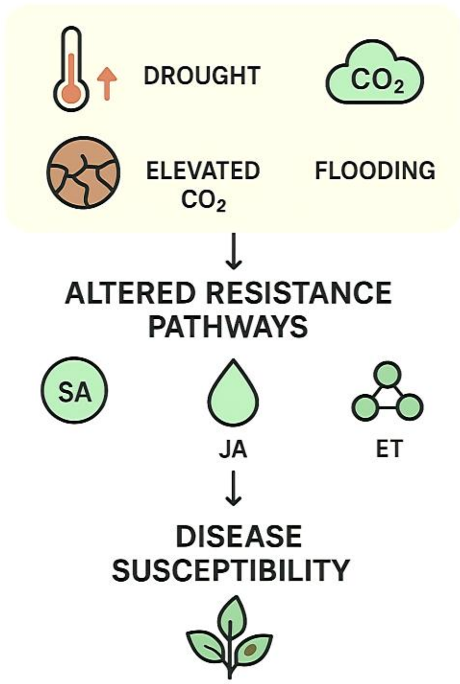

Figure 3: Relationship between climate stress and plant disease

Vector Dynamics under Climate Change: The location and population behavior of insect vectors that spread numerous commercially significant plant diseases are being significantly impacted by climate change. The survival, reproduction, mobility and feeding habits of vectors are directly impacted by rising temperatures, altered rainfall patterns and an increase in the frequency of extreme weather events. The transmission of plant diseases is also altered by these climate-associated variables (Varma et al., 2025). Insect vectors like aphids, whiteflies and psyllids can endure the winter thanks to warmer temperatures on average and milder winters. Because of this their activity starts earlier in the growing season and lasts more frequently which increases the amount of time that diseases can spread (Cantó et al., 2025). By promoting the quick expansion of vector communities, this extended activity raises the risk of disease acquisition and transmission within agricultural production systems (Clements et al., 2021). The way that infections react with their hosts is also impacted by variations in humidity and rainfall. While humidity and higher rainfall encourage the formation of leaf hopper and plant hopper populations which boost the spread of phytoplasmas and spiroplasmas which hot and dry circumstances frequently promote whitefly population outbreaks associated with begomovirus infections (Lago et al., 2024). Insect vectors can now spread into previously inappropriate regions such as higher temperatures and elevations. This propensity has also been demonstrated by psyllids that spread *Candidatus Liberibacter* species and aphids that spread cereal viruses, creating additional risks to temperate and subtropical farming practices (Narouei-Khandan et al., 2022). Furthermore, heat stress accelerates disease outbreaks by encouraging faster virus replication in insects and increasing their feeding activity (Bello-Rodríguez et al., 2023). Overall changes in vector ecology brought about by climate change are predicted to raise disease pressure and lessen the efficacy of existing management techniques. Creating climate resilient disease management and monitoring systems requires an understanding of how insect vectors react to climate conditions (Jeger et al., 2023). In general, a systematic change in vector ecology marked by longer activity periods, wider geographic ranges and improved transmission efficiency is being driven by climate change. The necessity for climate adaptive surveillance and control methods is highlighted by these changes which increase the transmission of pathogens while decreasing the efficacy of conventional vector management techniques.

Diagnosis and Monitoring of Plant Diseases under Climate Change: In addition to having an impact on pathogens and insect vectors in which climate change has a significant impact on the epidemiology of plant diseases by making disease surveillance and diagnosis more challenging. Because diseases can change in appearance due to variations in temperature, rainfall and CO_2 levels traditional symptom-based approaches that rely on visual monitoring of sick plants are becoming less dependable. Climate stressors like heat waves and drought can frequently create latent infections or postpone the onset of symptoms, underestimating the presence of pathogens. According to research early identification is further hampered by climate driven changes in the geographic distribution of diseases and their host plants because local diagnostic systems could not be ready for newly developing disease patterns (Eckardt et al., 2023). Molecular diagnostic technologies have grown in importance in plant pathology as a means of overcoming these obstacles. Because of their great sensitivity and capacity to detect infections before symptoms manifest PCR based tests are still regarded as the gold standard for pathogen identification (Yadav et al., 2024). Although its specificity may occasionally be low loop-mediated isothermal amplification has developed as a quick and field applicable alternative that may detect bacterial, viral and viroid infections in distant or resource limited places (Wang et al., 2023). Another significant development is next generation sequencing which enables thorough identification of both established and novel diseases and aids in monitoring pathogen evolution in response to shifting environmental circumstances (Lima et al., 2022). In the face of climate change widespread disease surveillance today relies on sensors and precision screening technologies in addition to laboratory-based techniques. Even before obvious symptoms appear unmanned aerial vehicles fitted with hyperspectral or multispectral sensors can identify early indicators of plant stress that are frequently connected to pathogen infection (Tran et al., 2023). Crop growth stages and previous disease records combined with statistical techniques allow more accurate predictions of disease epidemics (Choudhary et al., 2022). Precise and scalable disease detection under varied climatic conditions is made possible by combining laboratory based molecular techniques with field level remote sensing technology (Table 1). These technologies combined qualities enable practitioners to choose context appropriate diagnostic strategies depending on illness kind, spatial scale and resource availability, increasing surveillance effectiveness and enabling prompt disease management decisions. Such integrated diagnostic frameworks are particularly valuable in climate change scenarios where rapid disease emergence and symptom variability complicate traditional monitoring approaches.

Table 1: Plant disease monitoring and diagnostic techniques in the context of climate change.

Method	Target Pathogen	Strengths	Limitations	Reference
PCR	Bacteria, viroids	High sensitivity, quantitative, detects early infections	Requires laboratory setup	Patel et al., 2024
LAMP	Viruses, bacteria	Rapid & portable	Moderate specificity, limited multiplexing	Wang et al., 2023
NGS	Emerging pathogens	Detects known and unknown strains, tracks evolution	High cost, complex bioinformatics	Ribeiro et al., 2022
UAV	Foliar diseases	Large-area coverage, early detection of stress signals	Weather-dependent and expensive equipment	Eckardt et al., 2023

Management Strategies of Plant Diseases.: The growing unpredictability of climate conditions such as rising temperatures, higher CO_2 levels and more frequent droughts emphasize on the need to adapt latest disease management strategies. Climate change affects plant sensitivity, vector populations and pathogen behavior which ultimately needs to reassess traditional approaches of management (González et al., 2023). Integrated disease management which combines several strategies to protect the crop health has grown in importance (Naseer et al., 2025; Shabbir et al.,2025). Because stressed plants are more susceptible to diseases and cultural activities are particularly crucial in light of climate change. The risk of the disease can be reduced by the use of certified disease-free seeds for planting, crop rotation, pruning and other disease prevention strategies (Kim et al., 2023). Although crop rotation and planting with non-host species can reduce pathogen levels in the soil and contribute to more resilient agricultural systems, mulching and soil amendments improve soil health under harsh weather events. Strategies for chemical control require careful optimization as fungicides, bactericides and insecticides remain valuable and their excessive use can lead to pathogen resistance against these chemicals (Mubeen et al., 2015b). Climate change may worsen this issue by accelerating pathogen evolution and increasing the risk of resistance. Using chemicals cautiously in combination with predictive disease models reduces unnecessary use, improves effectiveness and enables more precise targeting (Patel et al., 2024; Anjum et al., 2021). Eco-friendly approaches are gaining more importance today (Usman et al., 2025) and use of different strategies like use of extracts (Shabbir et al., 2020; Saleem et al., 2021)and biological controls provided results against diseases. The use of biological controls for disease management has become more popular because it serves as an effective climate adaptation method. The soil health improvement and disease management benefits come from Trichoderma, Bacillus and mycorrhizal fungi which function as beneficial microorganisms. Research findings show that these biocontrol agents and rhizobacteria serve as environmentally friendly substitutes for synthetic pesticides which maintain their effectiveness when weather patterns change (Mansinhos et al., 2024; Sajid et al., 2025). The current environmental shift requires both host resistance and crop improvement as essential strategies for disease management. The development of crops which possess enduring wide-ranging defense mechanisms and their best possible life cycles will reduce the chances of disease occurrence. The development of gene editing and breeding and RNA interference techniques has established a fresh perspective which enables scientists to create improved disease management solutions (Ribeiro et al., 2023). Actively managing diseases is also essential. Climate monitoring and early warning systems, like UAV based sensors, forecasting modeling enable farmers to take immediate actions against diseases (Farooq et al., 2025; Iftikhar et al., 2024). Integrating these methods into regional health surveillance networks guarantees timely and effective responses under different situations caused by climate change (Kumar et al., 2022). By tackling disease risks proactively rather than reactively these management strategies collectively serve as the cornerstone of climate smart plant disease management. Host resistance provide long lasting defense against developing diseases, biological controls maintain ecological stability under changing climates and cultural practices lower baseline pathogen pressure and improve system resilience. These tactics allow for adaptive decision making that is sensitive to current meteorological and epidemiological conditions when paired with precision monitoring, early-warning systems and tailored chemical therapies. These integrated frameworks improve the long-term sustainability of crop protection under changing climatic scenarios, decrease environmental impacts and lessen reliance on chemical inputs.

Conclusion and Future Prospects: The interplay of vectors, host and infectious agents under diverse and changing climatic conditions is causing major modifications in plant disease patterns. Rising temperatures and extreme conditions have an impact on pathogen growth, development and virulence. Plants fighting against the disease are continuously challenged by the complex network of elements caused by environmental fluctuations. These elements or factors allow insects and other vectors to transmit infections into newer regions. Although biological modification and soil microbiological management can further improve plant durability, breeding initiatives aimed at producing resilient, multi pathogen resistant cultivars offer long term protection. Ecosystem based strategies like diversified agriculture, planting cover crops and improving soil health also increase the resilience of ecosystems. Future study and development should prioritize accessible, flexible and climate smart solutions. The agricultural community can anticipate new threats and efficiently respond to them. By combining information gained from data science, climatology and plant pathology, the agriculture sector can anticipate new threats, effectively respond to them and maintain crop productivity. A comprehensive approach combining breeding, biological and cultural methods is needed to protect global food safety and develop resilient growing crops systems within the face of climate change. Utilizing flexible, technologically advanced and proactive approaches is necessary to manage disease in plants in the context of climate change. Erratic rainfall, rising temperatures and frequent extreme weather events are expected to alter the geographic distribution, target range and virulence of many plant diseases while host plants are exposed to a mix of biotic and abiotic stresses. The management of plant diseases needs to shift from offensive to prevention. Climate smart strategies that tackle these problems by fusing state of the art technology with sustainable farming practices. Precision farming, digital intelligence driven disease monitoring and real time data from field sensors and hyperspectral imaging are some possible ways to identify early signs of pathogen stress before symptoms appear. When paired with machine learning and modeling approaches, these technologies can forecast disease outbreaks under a variety of climatic conditions, enabling farmers and regulators to take swift and targeted action. Developments in molecular biology and genetics also present revolutionary prospects for the treatment of illness. Rapid breeding methods, such as RNA interference and markers-assisted selection can create crops that are resistant to a variety of illnesses and can withstand abiotic conditions like heat and drought. Furthermore, pathogen population genetics can detect newly emerging virulent strains enabling the creation of resistant cultivars and customized management plans prior to epidemics. The importance of biological control and ecologically sustainable strategies is also expected to increase. For example, beneficial bacteria, such as soil microbiome enhancement, can increase plant capacity to resist climate stress by reducing reliance on synthetic pesticides. Sustainable agriculture techniques that lower pathogen stresses and improve ecosystem equilibrium include vegetative crops and soil health management. Regional and international collaboration will be necessary to coordinate disease surveillance and data exchange. Meteorological and socioeconomic data can enhance systems for early detection that enable prompt responses to emerging epidemics. The effective field implementation of these novel strategies will require investments in farmer information, agricultural extension services and involvement in monitoring initiatives. When taken as a whole, these innovations represent a major breakthrough in the control of climate resilient plant diseases, safeguarding food security and promoting ecologically sound farming in the face of worldwide warming.

DECLARATIONS

AI Usage Declaration

In line with COPE guidelines, AI-assisted tools were used only for language editing and formatting and did not contribute to scientific content, data, analysis, or conclusions. All responsibility for the manuscript rests with the authors.

Authors' Contributions

Muhammad Awais Fareed and Summia Iqbal: Writing of the original draft and preparation of figures. Muhammad Asif Shabbir: Conceptualization and finalization of the review. Saleha Sattar, Talha Shafique, Memoona Imdad, Muhammad Husnain, Awais Mutti, Rabbia Nasir, Hafiz Muhammad Talha Waleed and Iram Bilqees: Resources, project administration, collecting literature, visualization, validation, writing and editing. All authors have read and approved the final version of the manuscript.

Conflict Of Interest Statement

The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

Data sharing does not apply to this article as no new data were created or analyzed in this study.

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Ethical Statement

This article contains no studies regarding humans or animals.

Code Availability

Not applicable.

Consent To Participate

All authors participated in this research study.

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