AGRICULTURAL AUTOMATION, CLIMATE CHANGE-ACTION AND FOOD SECURITY: GLOBAL ISSUES & LOCAL PERSPECTIVES

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Published By:

Society for Agriculture, Environmental Resources & Management (SAEREM)

First published 2026

SAEREM World

Nigeria

C 2026 Eteyen Nyong

Typeset in Times New Roman

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AGRICULTURAL AUTOMATION, CLIMATE CHANGE-ACTION AND FOOD SECURITY (GLOBAL ISSUES & LOCAL PERSPECTIVES)

SAEREM BOOK CHAPTERS First Published 2026 ISBN 978-978-60709-7-6

Printed at: SAEREM

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Preface

This book adopts an exegetical approach as well as a pedagogic model, making it attractive agriculture and environmental economics teachers, professional practitioners and scholars. It is eschews pedantry and lays bars the issues in such clarity that conduces to learning. The book elaborates on contemporaneous Agricultural Automation, Climate Change-Action and Food Security issues of global significance and at the same time, is mindful of local or national perspectives making it appealing both to international and national interests. The book explores the ways in which Agricultural Automation, Climate Change-Action and Food Security issues are and should be presented to increase the public's stock of knowledge, increase awareness about burning issues and empower the scholars and public to engage in the participatory dialogue Agricultural Automation, Climate Change-Action and Food Security necessary in policy making process that will stimulate increase in food production and environmental sustainability. Agricultural Automation, Climate Change-Action and Food Security: *Global Issues & Local Perspectives* is organized in three parts. Part One deals with The Concept of Agricultural Automation, Part Two is concerned with The Concept of Climate Change-Action and Part Three deals with the Concept of Food Security

Eteyen Nyong; October 2026

Chapter Two

Climate Change–Driven Shifts in Plant Pathogen Epidemiology

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Introduction

Climate change according to the United Nations Framework Convention on Climate Change (UNFCCC) is defined as “a change of climate which is attributed directly to human activities that alters the composition of the global atmosphere and which is in addition to natural variability observed over comparable time periods”. Climate change is no longer a distant projection for plant pathology. It is a present, tangible factor shifting ranges and changing the severity of crop diseases across international borders. Increased temperatures and humidity, together with variable rainfall and an increase in the frequency of extreme weather events, are impacting all the three components of the disease triangle: host, pathogen and environment, and simultaneously shifting them such that plants and crops face unexpected changes and

diseases in surprising ways; occurring at different times of the year, affecting new plants, or even manifesting themselves in geographical locations traditionally considered as safe.

The empirical record shows that this is no longer a matter of projection. The spread of the wheat stem rust race Ug99 from East Africa towards the Arabian Peninsula, the climate-linked expansion of the whitefly vector of cassava mosaic disease, the establishment of banana Fusarium wilt Tropical Race 4 in Mozambique, the intercontinental movement of wheat blast from South America to Bangladesh and Zambia, the emergence of maize lethal necrosis as a novel virus complex, and the coffee leaf rust epidemics of Colombia and Central America are all well documented (Avelino *et al*., 2015; Mahuku *et al*., 2015; Islam *et al*., 2016; Kriticos *et al*., 2020; Tembo *et al*., 2020; van Westerhoven *et al*., 2022). Although these cases involve different pathogens, hosts and mechanisms, taken together they indicate a consistent pattern: pathogens and vectors are moving into new regions, meeting new hosts and, in some cases, combining into new and more destructive disease complexes.

These developments carry particular weight for Nigeria and the wider African continent. Agriculture in the region is dominated by smallholder producers who have limited financial and institutional capacity to absorb new crop losses, and national plant health systems are thinly resourced relative to the scale of the production landscape (Omokaro, 2025). Rising temperatures, erratic rainfall and flood–drought sequences, such as those experienced across Nigeria in 2022, add further stress to crops that are already vulnerable. Many of the most economically important crops in the region, including cassava, maize, banana and wheat, are the same crops affected by the emerging epidemics described in this chapter.

The ability to detect and respond to these changes has not kept pace with the changes themselves. Surveillance networks in sub-Saharan Africa are sparse, confirmation of newly introduced pathogens depends on a small number of laboratories, and predictive models are often calibrated on data from other regions. At the same time, new tools are emerging, including climate-suitability and dispersal modelling, risk-based survey design (Ferris *et al*., 2024) and smartphone-based artificial intelligence diagnostics such as PlantVillage Nuru (Mrisho *et al*., 2020). Whether these tools can be developed, validated and deployed quickly enough, and whether they are matched by breeding, quarantine and management capacity, is one of the central questions for crop protection in the coming decades.

The central problem, therefore, is that climate change is altering the conditions under which plant diseases develop and spread faster than the systems designed to monitor and manage them can adapt. Surveillance programmes, breeding priorities and quarantine regulations in most countries remain organised around historically established disease distributions and assume that the epidemiological baseline is stable. The evidence reviewed in this chapter indicates that this assumption no longer holds: pathogens and vectors have established themselves hundreds of kilometres beyond their known ranges, resistance genes that

protected crops for decades have been overcome, and combinations of climatic stress have produced disease outcomes that cannot be predicted from any single factor. Soil-borne pathogens such as banana Fusarium wilt TR4 are effectively impossible to eradicate once established, so delayed detection translates directly into permanent loss.

The problem is compounded by gaps in the literature. Much of the available work addresses individual pathogens, individual climatic variables or regions outside Africa, and predictive models are frequently built on East African, Latin American or Asian data that may not transfer well to West African conditions. There is limited synthesis connecting climatic drivers, documented epidemic cases and the practical adaptation of surveillance, forecasting and crop protection. An integrated account is therefore needed, and this chapter responds to that need.

The chapter begins by outlining the principal climatic drivers of change and then documents the resulting range expansion of pathogens and vectors through six case studies. It considers novel disease emergence, host range shifts and altered virulence, and examines compound climatic stressors, including the 2022 flood–drought disease sequence in Nigeria. It then reviews the limitations of current detection and monitoring systems and the promise of predictive and AI-based forecasting, and closes with the implications for crop protection strategy, resistance breeding, quarantine policy and surveillance, followed by conclusions and recommendations.

1.0 Climatic Factors Driving Epidemiological Change

The four main interacting climatic factors contributing to the vast changes observed in plant diseases are temperature, precipitation and humidity levels, carbon dioxide levels within the atmosphere and the effects of extreme weather (Figure 1).

1.1 Temperature

Temperature is one of the most significantly documented factors influencing plant disease characteristics due to its direct effects on the growth rates, generation time and limits on survival ranges of the many plant pathogens (Shamuwa *et al*., 2025; Mohanapriya *et al*., 2025). Fungi, oomycetes, bacteria and viruses possess optimum ranges of temperatures required for growth, sporulation and pathogenesis. Any slight change on average temperatures will alter the number of pathogen life cycle (generation times) within a given transmission season. As the optimum range expands over the normal duration, the duration that epidemics can occur can become significantly longer. Insects on the other hand are heavily temperature-dependent. The generation time and number of life cycle per year are directly affected by varying average temperatures, which also increase the disease transmission rates for many viruses (Kriticos *et al*., 2020). In Nigeria, an observable rise in national average temperatures with fluctuating onset of rainy season has already been linked to a rising of insect pest damage to major food crops (Omokaro, 2025) and this has

profound implications when many of Nigeria's most damaging crop diseases, such as cassava mosaic disease, are transmitted by insects rather than directly by airborne spores.

1.2 Humidity, Precipitation and Leaf Wetness

The majority of oomycetes and fungal pathogens utilize high precipitation and high humidity levels in order to germinate and infect plant tissue. Changing precipitation patterns therefore have significant epidemiological consequences regardless of total annual rainfall amounts. Climate change can affect rainfall patterns in two different ways: drought occurs over extended periods stressing the plant, favouring drought resistant pathogens and intensive wet spells occur as individual, localized rain events resulting in prolonged leaf wetness duration, thereby favouring dispersal agents for splash and wind dispersed pathogens. Nigeria has experienced record instances of prolonged drought alternating with intensive rain, worsening stresses of flood-erosion-disease syndromes within single growing seasons (Omokaro, 2025).

1.3 Elevated CO_2 Levels in the Atmosphere

An increase in atmospheric CO_2 occurs indirectly through host physiology rather than direct action on the pathogen itself. Generally, an increase in CO_2 leads to a decrease in stomatal density and conductance thereby decreasing the point of entry for bacterial and many fungal pathogens entering plant tissue. In studies focusing on experimental increased CO_2 levels, research found a disease severity reduction in over 20-30%, linked by reduced stomatal conductance and change in leaf physiology causing a less palatable leaf to the pathogens. Not all such studies have discovered reduced pathogenicity when CO_2 levels were increased. Disease susceptibility may as well be increased in certain circumstances, with viruses in particular varying significantly depending upon their respective host and vector species. Temperature and elevated levels of atmospheric CO_2 further interact upon virus biology increasing the efficiency of movement throughout a plant as well as affecting vector behavior with varied responses depending on respective host, vector, and viral strains (Amari *et al*., 2021).

1.4 Extreme Weather Events

Storms, high wind and flooding possess the potential to transport pathogenic infections and effectively enhance disease spread beyond natural dispersal mechanisms. A good example was 2004-2005 hurricane season in Florida, were storm enhanced long-distance spread of *Xanthomonas citri*, the pathogen causing citrus canker, beyond the abilities of a simple splash dissemination process. It is noted in this instance that the rapid spread of disease was attributed to particular storm tracks that dictated the rate and extent of disease spread and these were mapped in particular predicting future epidemic centers. In West Africa, increased intensity of rainfall has had similar effect to splash and wind carried pathogens with high severity

exacerbated by flood-erosion-disease processes coupled with already depleted host resilience caused by the loss of soil nutrients (Omokaro, 2025).

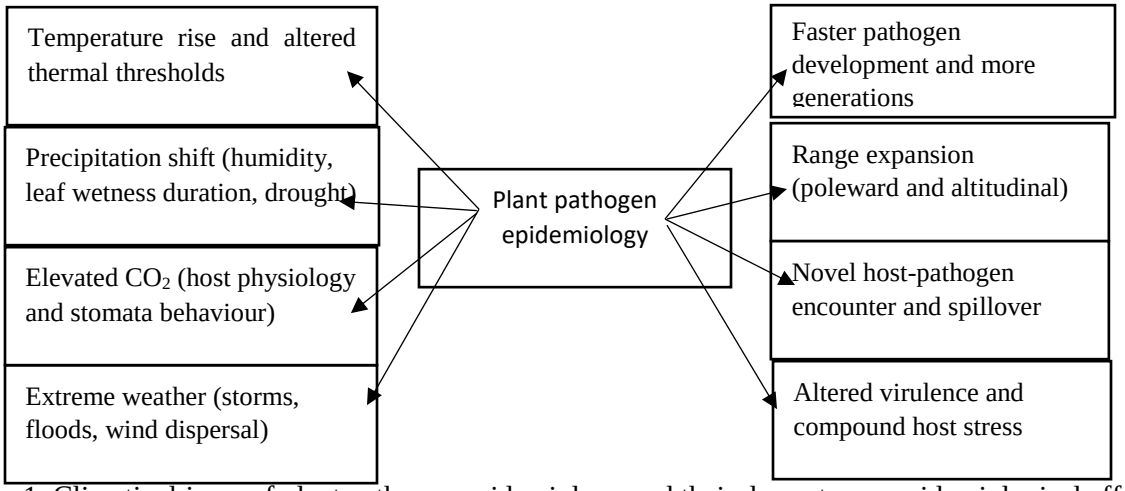


Figure 1: Climatic drivers of plant pathogen epidemiology and their downstream epidemiological effects.

2.0 Range Expansion of Plant Pathogens

The combined effect of these climatic changes is that plant pathogens and their vectors are also no longer restricted to their historical and geographically limited ranges. Indeed, they expand both north to south along a latitudinal axis, and west to east along an altitudinal axis, as they are tracked by isotherms and moisture regimes to which they are best physiologically adapted (Table 1). Six observed events are documented. These include:

2.1 Wheat rust (Ug99) - East Africa to the Arabian Peninsula

The clearest documented case of climate-influenced range expansion in a fungal pathogen is Ug99 of wheat stem rust (*Puccinia graminis* f. sp. Tritici), which was first described in Uganda in 1998 – 1999. It overcAme Sr31, a resistance gene protecting over 90% of wheat cultivars globally for over three decades, and spreading from the East African highlands through Kenya, Ethiopia, Sudan, and Yemen to finally appear in Iran in the shape of a stepwise journey consistent with spore transport via wind along existing

"rust tracks". Ethiopia has become something of a recognized epicenter of emergence of new races within the Ug99 group and is generally understood to be made much more permissive by the warmth and high rainfall characteristic of the Ethiopian highlands, in which wheat cultivation can be near continuous thereby supporting near continuous pathogen development (Meyer *et al*. 2017; Prank *et al*. 2019). Atmospheric dispersal models point to certain probable immigration routes bringing the disease into Ethiopia both from the East African and Arabian landmasses, and they are projected to be global mean climate niche modeling to 2100 for stem rust under business-as-usual warming, about 40% more urediniospores on average in infected fields under higher temperatures and lower humidity in most areas with a greater turbulence to promote atmospheric dispersal, suggesting that these are factors that favor pathogen transmission, both generally and along existing pathways.

2.2 Cassava Mosaic Disease and Whitefly Vector – Nigeria and East Africa

Cassava is one of Africa's most important food-security smallholder crop and Nigeria is the world's largest producer of it. Cassava mosaic disease (CMD) has therefore come to represent one of the continent's highest-priority vector-borne plant diseases. CMD is transmitted by *Bemisia tabaci*, whose numbers have expanded substantially across East and Central Africa since the late 1990s providing a "wave" that carried the associated CMD and Cassava Brown Streak Disease (CBSD) pandemics resulting in losses of up to 47%. Researchers used CLIMEX, a process-based climatic niche model which had been verified against thirteen years of field abundance data from Uganda, to show that the climatic conditions favourable to *Bemisia tabaci* had improved measurably over the 39-year historical period in the areas where pandemics subsequently appeared, while elsewhere these conditions had remained the same or had declined. This was the first instance in which historical climate change had been directly linked to the increased abundance of an insect vector responsible for a crop disease pandemic (Kriticos *et al*. 2020).

In Nigeria, where genetically distinct groups of *Bemisia tabaci* are identified through sampling throughout major cassava growing areas, and the SSA1 lineage (genetic group of *Bemisia tabaci* that is dominant in Sub-Saharan Africa) was found in four of the states to carry Ethiopian and East African strains of the cassava mosaic virus. Its presence is evidence of inter-regional spread initiated by the expanded distribution of an insect vector. This sort of novel pathogen-host overlap is the very essence of what a vector range shift made possible by climate change will produce, facilitating spread of existing pathogens between previously separated systems, transforming isolated occurrences into endemic disease and new pandemic events, as now observed across an expanded footprint across Central and East Africa.

2.3 Banana Fusarium wilt (Tropical Race 4): Mozambique and the wider region

Banana Fusarium Wilt (Tropical Race 4) TR4, a member of the same lineages that wiped out Central American Gros Michel monocultures in the past century, now threatens Cavendish bananas in both

commercial and smallholder production throughout Africa, as observed with TR4 in Mozambique starting in 2013. The disease entry and plant susceptibility was facilitated by unusual period of extreme drought and flooding and high precipitation during planting season, which created favourable conditions necessary to promote soil transmission that allows disease to invade the agricultural landscape beyond where it was planted. The outbreak spread from two infected plantations in northern Mozambique outward into many of the fields in smallholder production, including roadside planting, and whole genome sequencing showed the outbreak isolates in Mozambique to be a genetically distinct clonal population, different from all other introduced populations worldwide. Because it is soil born, it persists over decades and become incurable once established. The disease transmission spread outside the known endemic zones. This has been confirmed as an unhindered, developing crisis to the food security of the region, with an estimated 70 –100 million African currently depend upon bananas as a source of their livelihoods (van Westerhoven *et al*. 2022a, 2022b).

2.4 Wheat blast's intercontinental jump: South America to Asia to Africa

Wheat blast, caused by the fungus *Magnaporthe oryzae* pathotype Triticum (MoT), provides a clearer-than-usual example of how newly-introduced diseases establish themselves because each step of its propagation has been observed in real-time. The disease established itself in Brazil in 1985 and confined itself to South America for 30 years until February 2016, when it appeared, unannounced and widespread across 8 districts of Bangladesh, destroying wheat across 15,000 ha (16% of country's wheat area), caused yield losses of up to 100% (Islam *et al*., 2016). The phylogenomic analyses performed showed it was a South American strain, brought into the country presumably by contaminated grains/seeds rather than having independently evolved, thus became Bangladesh's first encounter with a crop pathogen lacking a local history and local resistant breed (Islam *et al*., 2016). Two years later, wheat blast reached a third continent. During the 2017–18 rainy season, symptoms were identified in a number of wheat fields in Muchinga Province of Zambia. Disease incidence at these individual farms varied from 50 –100% (with a mean of 84.8%) and this is the first documented occurrence of MoT anywhere on the continent of Africa (Tembo *et al*., 2020). While we have been unable to prove the definitive origin of this Zambian introduction (South America, or established population in Bangladesh), epidemiologically it is of little concern. If there are no existing breeding efforts to develop resistance, a non-evolved pathogen would successfully enter a large, rainfed farming landscape which would spread into bordering rainfed wheat susceptible farming environments (Tembo *et al*., 2020).

2.5 Maize Lethal Necrosis: A Disease Complex Borne from Co-infection

Another pathway, which is mechanistically distinct, to novel disease pressure is demonstrated by maize lethal necrosis (MLN) in East Africa. Maize lethal necrosis is not a novel pathogen per se but a novel disease complex by a virus new to the region in this case. Maize chlorotic mottle virus (MCMV) co-infects a plant already endemic for a potyvirus, typically Sugarcane Mosaic Virus (SCMV) and produced a novel synergic disease. Neither of the individually transmitted pathogens cause more than moderate disease severity, however co-infection produces a symptom complex-mottled leaves, stunted growth and rapid premature death new to East Africa which, following outbreaks documented in the Bomet region of Kenya in September 2011, become known as maize lethal necrosis (Mahuku *et al*., 2015). Even in the most affected Kenyan counties, yield losses reached 90-100% in 2013–2014 and Kenya alone sustained losses totaling 126,000 metric tons (valued around USD52 million) in 2012 (Mahuku *et al*., 2015). Within three years of its description in Kenya, disease incidence in Tanzania, Uganda, Rwanda, Democratic Republic of Congo, and Ethiopia have been confirmed tracing the distribution of MCMV and its vectors.

Maize lethal necrosis follows an alternative climate-disease transmission path than that of the single-pathogen jump of wheat blast. It involves an interaction between an introduced virus and an endemic virus at work on a maize-growing continuum being reconfigured by trends of increasing warmth and shifting precipitation, which have already contributed to an increase of insect pest load (Omokaro, 2025). The vectors of MCMV and of the viruses which infect and transmit other complexes of viruses and maize and cereal crop types are also climate-sensitive. An increase in ambient temperatures, expanding areas of occurrence for vector species spreading the viruses that affect cassava, is equally favorable to those elsewhere in the continent, just as it is for the vectors causing these diseases.

2.6 Coffee Leaf Rust: Origins, Epidemic, and Compounding Factors:

Coffee leaf rust (CLR), caused by the fungus *Hemileia vastatrix*, offers an important lesson because it did not originate in Latin America but rather is thought to have coevolved in tandem with coffee in East Africa prior to being introduced into virtually all current coffee growing areas around the globe, although it had previously caused relatively little threat to less than 5% of any region's output. Colombia had the most destructive outbreak of coffee leaf rust in history starting in 2008, moving to Central America and Mexico between 2012 and 2013. The proportion of infected coffee plants rose from less than 5% in Colombia before 2008 to more than 40% during the outbreaks. The output in Colombia dropped by an average of 31% during these periods compared to 2007, while output dropped by 16% in 2013 for Central America compared to 2011 and 2012 and the loss for all countries involved was estimated at $500 million in coffee crops (Avelino *et al*., 2015). Since most coffee production affected in the regions is smallholder (below 10 ha) and coffee serve as a major cash crop to purchase grains and other necessities, the situation

has moved from an agricultural epidemic into a regional food insecurity crisis (Avelino *et al*., 2015). The primary climatic factor that influenced the epidemics wasn't global warming per se, though rising temperatures are a part of it, but the shrinking interval between night time and day time minimum and maximum temperatures. Colombian and Central American farms recorded hotter nights and cooler days. On Guatemala's farms during the epidemic period, a roughly 0.9^{o}C and 1.2^{o}C swing lower for days was recorded compared to the long-term average. This shift seems to have reduced the time it took for the virus to become pathogenic to produce spore infections enabling more crop cycle infections per season and didn't necessitate a drastic overall temperature increase. Coffee leaf rust (CLR) infestations at altitude that previously affected up to1000 metres above sea level now occur at equivalent intensity from 400-1400 metres above sea level. This pattern of climate adaptation is reminiscent of those for Ug99 in Eastern Africa, but involves different hosts, continents, and pathogens. Furthermore, attributing the severity of this episode to climate solely is also unwise. According to Avelino *et al*. (2015) climate challenges interact with socio-economic issues to drive outbreaks of infection. Reduced spending on fertilizers and fungicides during a downturn in the prices of coffee and a subsequently weakened, vulnerable agricultural landscape, serve as examples of factors interacting in agricultural economies not dissimilar to Nigeria and all of Africa in which input costs, at the expense of global climate changes, and climate stressors combine and amplify each other.

Taken as a group, these cases suggest that pathogen/vector range expansion is no longer a risk to be modeled hypothetically as it is already a documented and ongoing phenomenon. Key pathogens have now been established hundreds of miles beyond their known ranges. This problem has become overwhelmingly concentrated in smallholder African systems, including Nigeria, which has insufficient financial and institutional capacity to absorb such new stresses, providing further justification for treating epidemiological baseline situations as a moving target rather than a fixed constant.

Pathogen / Disease	Type	Region(s)	Mechanism	Key Source(s)
Wheat stem rust (Ug99)	Fungus	East Africa → Arabian Peninsula	Poleward/altitudinal range expansion along wind-borne dispersal routes	Meyer *et al*., 2017; Prank *et al*., 2019
Cassava mosaic disease / whitefly vector	Virus / vector	Nigeria; East & Central Africa	Vector range expansion via improved climatic suitability	Kriticos *et al*., 2020; Efekemo *et al*., 2024
Banana Fusarium wilt (TR4)	Fungus	Mozambique	Introduction plus drought–flood sequence facilitating establishment	Viljoen *et al*., 2020; van Westerhoven *et al*., 2022a
Wheat blast (MoT)	Fungus	Brazil → Bangladesh → Zambia	Intercontinental introduction via contaminated seed/grain	Islam *et al*., 2016; Tembo *et al*., 2020
Maize lethal necrosis	Virus complex	Kenya; East Africa	Novel synergistic co-infection of introduced and endemic viruses	Mahuku et al., 2015
Coffee leaf rust	Fungus	Colombia; Central America	Reduced diurnal thermal amplitude shortening pathogen latency	Avelino *et al*., 2015

Table 1: Documented cases of climate-linked range expansion and novel disease emergence referenced in this chapter, illustrating that the pattern spans fungal, viral, and vector-borne pathogens across multiple crops and continents.

3.0 Novel Disease Emergence and Host Range Shifts

Many mechanisms mediated by the direct influence of climate change may drive significant changes in plant disease epidemiology: alterations to host and pathogen phenological synchrony; new host-pathogen interactions as species move beyond current range borders; changes in pathogen virulence and aggressiveness as climatic stresses mount; and compound stress interactions, whereby infection further increases host vulnerability to, for example, drought or heat stress. These mechanisms can also lead to the introduction of novel disease pressures as a result of pathogens crossing continental divides to enter new hosts, combining with previously established populations via mutation and form devastating disease complexes. Singh *et al*. (2023) have already identified integral components of this increased-risk pattern, which account for: pathogen dispersal, with particular focus on the global transport of seed, grain and planting material, thereby enabling introduction events to coincide with climatic regimes that is favorable for completion of the pathogen life cycle; and climate shifts creating new disease complexes at both the micro-scale (novel, weakly virulent lineages of plant pathogens) and the macro-scale (novel host-pathogen pairings at the species and genus level).

It is argued that although altered host infection rates under changing weather patterns are likely across all pathogen groups, fungal and oomycete pathogens possess a particularly enhanced capacity to exploit the current elevated risk. This is attributed primarily to their broad tolerance to environmental extremes and to ongoing selection for thermotolerant lineages capable of growth and infection across temperature ranges previously considered unfavorable — a process analogous to the emergence of thermotolerance in human fungal pathogens under a warming climate. This selection may also favor the emergence of novel, weakly virulent lineages of plant pathogens.

3.1 Host-Pathogen Synchrony Disruption

Many plant infections require a combination of susceptible host phenological phase and the presence of a critical load of inoculum at a specific juncture; any alteration or delay in one step relative to another has implications. Longer and warmer growing periods in many locations translate into changed opportunities of host and pathogen to complete life cycles. But species respond to temperature differently, which either synchronises different development phases to meet each other at precisely the wrong time or completely divorces them, and they never collide. Fusarium head blight of wheat, for instance, depends on pathogen spores being ready to infect exactly when the crop is flowering; a shift in either flowering time or spore maturation windows changes disease risk significantly. More broadly, Chaloner *et al*. (2021) modelled temperature-dependent infection risk for 80

fungal and oomycete crop pathogens against projected yield changes for twelve major crops, and found that while yields and infection risk are both projected to rise at high latitudes, the tropics where much of Africa's food production is concentrated face a combination of stagnant yield gains and shifting pathogen pressure, meaning the burden of crop protection is likely to grow even where productivity itself does not.

3.2 Novel Host–Pathogen Encounters and Spillover Risk

Spillover risk is a phenomenon whereby a pathogen encounters new species or variety of host to which it had not previously infected at scale. As temperature and rainfall belts shift, both crop species and their pathogens are moving into new geographical space and they are not always moving together and not always necessarily at the same pace and it is as a result of that that opportunities for the emergence of Spill-over can occur. One good illustration of spillover risk that is well known already are the Westward and Continental movement of *Fusarium oxysporum* f. sp. Cubense Tropical Race 4 (TR4) - the fungus that causes Fusarium wilt of banana that had been recorded in Africa for the first time in Northern Mozambique in 2013, and by 2019 it had moved into both Mayotte and the Comoros islands (Food and Agriculture Organization of the United Nations [FAO], 2025). The fungus produces durable chlamydospores that persist in the soil for hundreds if not thousands of years. So, once you have it there is no way to eradicate it, and its entry into a new country represents a near-permanent host-pathogen encounter, not a transient outbreak (International Plant Protection Convention Secretariat [IPPC], 2024).

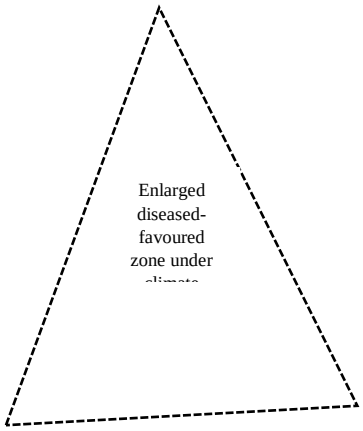
3.3 Altered Pathogen Virulence and Aggressiveness Under Climate Stress

Both temperature and humidity not only dictate survival site, they can also affect aggressiveness of a pathogen once successfully established. Warmer and more erratic temperatures have been associated with increased outbreak of novel, more virulent races of existing pathogens, (e.g. cereal rusts), where climate shift is believed to have allowed for the evolution and dispersal of strains that overcome previously robust host resistance genes.

3.4 Multiple/Compound Stress Interactions

Possibly the most practically relevant transformation is that diseases no longer act in isolation. Weaker physical and biochemical defenses due to heat and drought stresses and n potentially lengthened period of pest activity due to increasing global temperatures means that the true effects on a stressed field can exceed that which either stress alone would produce in isolation.

Susceptible/stressed host



Dashed line = historical (baseline) disease triangle. Solid line = climate expanded disease triangle

Figure 2. The classic plant-disease triangle, reshaped by climate change

The classic host–pathogen–environment disease triangle is not merely shifting position under climate change; the zone in which disease is favoured is expanding, as warming, altered rainfall, and host stress act together.

4.0 Compound climatic stressors and crop-specific cases

4.1 Compound climatic stressors

Factors like temperature, moisture, CO, and extremes weather are often discussed independently for their role in causing diseases. However, field conditions more often show that a single crop can experience many stresses at the same time, e.g., drought, heat, flood occurring alongside or successively in the same season. It is difficult to predict how diseases are affected simply by adding individual effects of such factors. Roussin-Lveille *et al*. (2024) put this into context using the classical plant disease triangle (host, pathogen, environment). Climate change should be understood simultaneously on the three edges of this triangle. Signaling modification of the host for immunity, virulence enhancement of the pathogen, and the formation of environment conducive for interaction between the host and pathogen resulting in disease are some of the interesting areas of research. It is hypothesized that climatic extreme events might have a different influence on these phenomena when compared with gradual climate changes. Heatwaves and persistent droughts suppress certain elements of plant immunity, weaken the disease-suppressive

actions of the plant microbiome, and induce pathogen virulence through processes distinct from even slow and long-term changes in the climate (Xiong *et al*. 2026).

4.2 Drought as a Context-Dependent Modulator

Predicting disease outcomes in the presence of multiple stressors can be difficult. The study of disease development under drought conditions by Choudhary and Senthil-Kumar (2024) indicates that drought has the potential to both suppress or stimulate disease development depending on the type of pathogen, the time of drought application relative to inoculation, and the host plant's response to drought. Their research provides support for the idea that water-stressed host tissue will be less suitable for pathogenic fungi that require free moisture, but can leave the host plant in a state where its immune signaling pathways are shut off and more susceptible to non-free moisture requiring pathogens. The effects of climate-driven epidemiology generally suggest that drought cannot be broadly classified as "protection imparting" or "risk increasing" as one would for conditions of increased humidity (generally more conducive for sporulation). The overall effects of drought are ultimately still pathogen-dependent and dependent on the life cycle stage in which the drought occurs.

4.3 Flooding-drought-disease Sequences: Nigeria 2022

A typical example of compound climate stress resulting in disease pressure occurs during the 2022 season in Nigeria. The 2022 season experienced a 30 - 80 per cent yield loss due to pest and disease pressure in some farms (NAERLS, 2023). This increased the physical damage to farms due to flood damage experienced in 34 out of the 36 states in Nigeria (including the Federal Capital Territory) with over 1.4 million people affected and 37,000+ homes destroyed. The estimated damage to agriculture alone was about 700 billion naira (NAERLS, 2023). In essence, prolonged flooding saturation produced the ideal environmental conditions for soil and splash dispersed pathogens and led to nutrient depletion and root damage, decreasing survivors' resistance to disease infection once water levels receded, creating a drought to flood to disease impact sequence rather than a single environmental shock. This is clearly an example of the effects of drought, flood and subsequent disease pressure as opposed to a single environmental stress. To solve this problem, therefore, a Flood Early Warning Systems and continued breeding of crop varieties capable of tolerating flood conditions and climate stress should be given due priority, while sustaining the flood and drought management for the Nigeria’s increasing pest and disease prevalence. A similar conclusion has emerged from other studied on the impact of climate change on sub-Saharan agriculture,

which note that changes cause an interactive network of stresses rather than individual ones (Omokaro, 2025).

5. 0 Detection & Monitoring Challenges

5.1 Gaps in Current Surveillance Systems for Tracking Emerging Disease Pressure

In sub-Saharan Africa and in Nigeria in particular, plant disease surveillance networks are scarce and cannot realistically cover smallholder production systems on the vast scale that is required. The capacity to formally confirm newly detected pathogen invasions beyond merely reporting farmer accounts of symptoms resides within a limited network of central and national laboratories, and so an entirely novel disease may spread widely before it has been officially characterised. The *Fusarium oxysporum* f. sp. Cubense Tropical Race 4 (TR4) story is also revealing of this dilemma, although suspected banana symptoms were first visually identified by farmers in the Comoros, only the following week did agricultural researchers at the National Agricultural Research Centre perform tests and confirm infection, after which a retrospectively survey was carried out to determine the extent of spread of the pathogen (FAO, 2025).

5.2 Need for Predictive Epidemiological Modelling Under Climate Scenarios

Reactive identification alone is now of limited value. Climate-driven predictive modelling, of the type applied by Prank *et al*. (2019) in their analyses of wheat stem rust and in the modelling for suitability of Cassava as described in 2.2 above, may indicate regions where a pathogen will first be climatically suitable prior to arrival and where quarantine or extension personnel may have the time to intervene, rather than wait until establishment. The real scientific issue is that plant-pathogen interactions are different in each region, climatic situation and cropping systems. It means a model trained for one area will not represent well for other regions, and this is problematic in Nigeria and West Africa because the source of epidemiological data used in most global models came from East African, Latin American or Asian systems.

5.4 Automation and AI-Based Forecasting

Artificial intelligence (AI) and Machine Learning are the applied future of plant disease forecasting and have begun to be implemented for these uses by integrating data from remote sensors, satellites, internet of things (IOT), climatic sensors and data on pathogen distribution in the environment to produce up-to-date location-specific early-warning systems that replace the survey-based method used today, which rely on manually generated data on relatively infrequent, spatially heterogeneous (or aggregated) surveys in nearly every national plant protection system currently in existence. Deep-learning based analysis has also

demonstrated good potential for diagnosis based on images. For example, a convolutional neural network (CNN), a machine-learning based system, has been trained to successfully identify Coffee leaf rust symptoms from low-quality field images. This diagnostic technique would be crucial for both smallholders driven contexts and those situations where laboratory access is costly or impractical. This section further expands upon and elaborates two such systems - forecasting the airborne dispersion of disease and the Plant Village Nuru diagnostic tool. Although the tools would never replace the need for ground-based truth and a trained plant pathology specialist.

6.0 Implications of Climate Change for Crop Protection Strategy and Surveillance

If climatic shifts are altering epidemiology at rates faster than traditional methods of surveillance and breeding can keep up, then crop protection should cease to be static and instead take on the shape of an adaptive technology. Some or all of these concurrent strategies are appearing across cases in this chapter: forecasting (using atmospheric or epidemic variables to pre-warn of outbreaks at stages before they can be physically observed); an AI that extends the power of specialized disease diagnostics beyond the reach of experienced experts; new methods of surveying based on the likelihood and speed of a climate-triggered introduction; and further upstream, the processes by which these tools detect faster spreading of disease and inform for more timely fungicide applications and better policy responses to achieve protection.

6.1 Rethinking Regional Resistance-Breeding Priorities

Since the highest priority threat to a region might not be the pathogen currently being focused on by breeders, we must aim broader than solely focusing on resistance targets for prevalent endemic pathogens. It is clear, from the story of Ug99, how difficult it can be for decades of global wheat improvement based on genes like Sr31, that a resistance bred against a certain lineage becomes easily outmaneuvered by a single newly emerging race of the pathogen, often, to the immediate effect of that race globally. In Nigeria and the rest of West Africa, in contrast, the story of Cassava Brown Streak Disease (CBSD) suggests that integrating CBSD resistance at the breeding program level, even in states not currently infected, is necessary for protection rather than reacting to local problems as they occur.

6.2 Policy and Quarantine Implications for Emerging Pathogen Ranges

Once a soil-borne pathogen like *Fusarium oxysporum* f. sp. Cubense Tropical Race 4 (Foc TR4) has been introduced, any attempt to remove it is practically impossible. Therefore, the burden of protection rests squarely upon the need to prevent introductions via clean planting material, management of farm machinery and soil, and coordinated cross-border quarantine managements (IPPC, 2024). FAO's training initiative

involving plant protection officials from fourteen African countries, including Nigeria demonstrates that quarantine capacity must be developed on a cooperative and precautionary basis, and not ad hoc basis after an organism already has crossed a border (FAO, 2025).

6.3 Breeding and Management as the Remaining Pillar

Surveillance and forecasting provide valuable time and enable better early detection. However, they cannot provide a replacement to resistant germplasm and appropriate management once the disease is already a major one. The continued existence of Ug99 races virulent to Sr31 and the current lack of a cure for the TR4-affected banana once introduced to soil and infected serve as examples that surveillance without coupled programs of breeding and disseminating resistance will only retard, and not stop ultimate loss of crop. Forecasting and diagnostic tools presented in this section thus are better viewed as necessary but not sufficient. They only generate a lead time during which resistance, quarantine, and/or targeted treatments may be effective as an intervention, but only prior to the invasion's becoming an effectively unrestrained pandemic.

6.4 Forecasting: From Atmospheric Dispersal Modelling to Climate Suitability

As discussed in the case of Ug99, this principle has already been applied. A climate suitability approach modelled from atmosphere dispersion modelling has been used to specify actual route of pathogen entry into Ethiopia via the Arabian Peninsula and East Africa and this information now drives the targeting of surveillance resources to specified points prior to an actual outbreak occurring (Meyer *et al*., 2017). Similarly, CLIMEX-based analysis has been used previously to link the appearance of the East African whitefly vectored cassava disease pandemics to a warming of climate suitable for *Bemisia tabaci*, over a period of 39 years, in the relevant regions and where the pandemics have ultimately manifested (Kriticos *et al*., 2020). This enables surveillance to be moved early into regions becoming suitable, rather than waiting for the pathogen or vector itself to turn up.

6.5 AI-Enabled Field Diagnostics: Plant Village Nuru

Whereas forecasting attempts to anticipate outbreaks at a regional scale, AI-diagnostic tools aim to alleviate the bottlenecks that occurs to a very local scale. Plant Village Nuru is a deep-learning object detection tool developed as a public good by Penn State, FAO, IITA, CIMMYT, and partners, designed to detect cassava

mosaic virus disease, cassava brown streak virus disease, and cassava green mite damage, from a picture on a smartphone camera without an internet connection (a critical function in most circumstances where cassava will be affected). Field evaluations of Nuru in East Africa showed its accuracy for diagnosing disease symptoms was better than the average agricultural extension officer (65% accuracy vs 40%-58% for officials and 18%-31% for farmers) and that accuracy increased when farmers scanned multiple leaves (74%-88% accuracy when scanning six leaves per plant vs one leaf per plant). Nuru therefore can be used by any extension agent or farmer with a smartphone to expand the reach of diagnostics, which could provide the kind of distributed surveillance the rapid spread of climate change-driven outbreaks necessitates.

6.6 Redesigning Survey Strategy for Climate-Linked Introduction Risk: Nigeria Case Study

A third approach that changes where and how surveys are run has been seen in the case of cassava brown streak virus disease (CBSD) detection in Nigeria. CBSD is prevalent in East Africa. Given its westward progress along with its vector, researchers modeled potential spread to determine how Nigeria could most effectively detect an introduction using combined field and landscape spread models. Ferris *et al*. (2024) observed that Nigeria's current uniform surveillance system surveys newly exposed states far less frequently than where the virus is probably most likely to be introduced. Redistributing surveys to target newly exposed states according to cassava planting density, Ferris *et al*. (2024) predicted, would result in detecting CBSD at earlier stages of outbreak, more often, and at an earlier time point within outbreak dynamics. Like earlier mentioned about Ug99, this demonstrates that a changing disease distribution may warrant changes in survey strategy if to continue to prevent the worst outcomes from its introduction. In Nigeria, this can translate to designing survey systems around the probability of introduction, determined by factors like host distribution and climatic suitability.

Tool / Approach	Function	Crop / Pathogen	Region	Source
Atmospheric dispersal modelling	Identifies likely pathogen incursion routes before outbreak confirmation	Wheat stem rust (Ug99)	East Africa	Meyer *et al*., (2017)
CLIMEX climatic niche modelling	Attributes historical vector abundance	Cassava whitefly (*B. tabaci*)	East Africa	Kriticos *et al*., (2020)

	increases to climate change			
PlantVillage Nuru (AI / deep learning)	Offline smartphone diagnosis of foliar disease symptoms	Cassava (CMD, CBSD)	East and West Africa	Mrisho *et al*., (2020)
Landscape-scale computational survey modelling	Optimizes survey allocation for early detection of introduction	Cassava brown streak disease	Nigeria	Ferris *et al*., (2024)

Table 2. Selected climate-adaptive surveillance and forecasting tools referenced in this chapter.

Conclusion

This chapter has examined how climate change is reshaping plant pathogen epidemiology, moving from the climatic drivers of change to their consequences for pathogen distribution, disease emergence and crop protection. Temperature, precipitation and humidity, atmospheric carbon dioxide and extreme weather each influence the host, the pathogen and the environment, and their effects interact rather than simply add up. The classical disease triangle is therefore not only shifting; the zone in which disease is favoured is widening.

The evidence for this is no longer hypothetical. The six cases reviewed here, namely wheat stem rust Ug99, cassava mosaic disease and its whitefly vector, banana Fusarium wilt TR4, wheat blast, maize lethal necrosis and coffee leaf rust, differ in pathogen type, host and mechanism, yet they point to the same conclusion: pathogens and vectors are establishing themselves far beyond their historical ranges, and new disease complexes are forming from organisms that were previously minor problems. Compound stresses, illustrated by the flood drought–disease sequence of Nigeria's 2022 season, can produce losses well beyond those expected from any single stress. Disease outcomes under such conditions are also context dependent, as the variable effects of drought showed.

At the same time, detection and response capacity has not kept pace. Surveillance in sub–Saharan Africa is sparse, new pathogens may spread widely before they are formally confirmed, and many predictive models rest on data from other regions. Forecasting, risk-based surveys and AI-assisted diagnostics such as PlantVillage Nuru can create valuable lead time, but they are necessary rather than sufficient. Without resistant germplasm, effective quarantine and sound crop management, early warning will only delay losses, not prevent them.

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For Nigeria and the wider African continent, where many of the most damaging cases are concentrated and where the capacity to absorb climate-driven crop losses remains limited, the central lesson is that the epidemiological baseline is a moving target. Crop protection must therefore become adaptive, anticipating where disease will be favoured next rather than responding only where it has already occurred.

Recommendations

Considering the above trends, the following recommendations are proffered:

i. Direct surveillance towards regions of anticipated risk: Surveillance investment should shift from historically known outbreak centres to areas where climatic suitability and host presence indicate that introduction is eminent.

ii. Plan resistance breeding around emerging threats: Breeding programmes should target pathogens likely to arrive, not only those currently endemic. The loss of Sr31 protection to Ug99, and the emergence of maize lethal necrosis from viruses that were individually mild, show that long-standing resistance can fail quickly. Resistance to threats such as cassava brown streak disease should be incorporated before the disease reaches a given region, and breeding for flood and climate-stress tolerance should be prioritised.

iii. Strengthen quarantine and phytosanitary cooperation: Because soil-borne pathogens such as banana Fusarium wilt TR4 cannot practically be eradicated once established, prevention must be the priority. This requires clean planting material, management of soil and farm machinery, and coordinated cross-border quarantine. Regional training of plant protection officials, such as the FAO initiative involving Nigeria and other African countries, should be sustained on a precautionary basis.

iv. Develop regionally calibrated forecasting models: Predictive models should be built and validated with West African epidemiological and climatic data so that they reflect local pathogens, crops and cropping systems, instead of relying on models trained elsewhere.

v. Deploy digital and AI tools alongside ground verification: Tools such as PlantVillage Nuru should be extended to extension agents and farmers to widen diagnostic reach, particularly where laboratory access is limited. Their outputs should be checked by trained plant pathologists and laboratory confirmation, since such tools complement and do not replace expert diagnosis.

vi. Build compound-stress early warning and management systems: Flood early warning systems, together with drought and flood management, should be integrated with pest and disease monitoring so that post-flood and post-drought disease pressure can be anticipated, as the 2022 experience in Nigeria shows.

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vii. Invest in institutional capacity: National plant protection organisations, diagnostic laboratories and research institutions need sustained funding and trained personnel so that new pathogens can be identified and characterised promptly, before they spread widely.

References

Amari, K., Huang, C. and Heinlein, M. (2021). Potential impact of global warming on virus propagation in infected plants and agricultural productivity. Frontiers in Plant Science, 12, Article 649768. https://doi.org/10.3389/fpls.2021.649768

Avelino, J., Cristancho, M., Georgiou, S., Imbach, P., Aguilar, L., Bornemann, G., Läderach, P., Anzueto, F., Hruska, A. J. and Morales, C. (2015). The coffee rust crises in Colombia and Central America (2008–2013): Impacts, plausible causes and proposed solutions. Food Security, 7(2), 303–321. https://doi.org/10.1007/s12571-015-0446-9

Chaloner, T. M., Gurr, S. J. and Bebber, D. P. (2021). Plant pathogen infection risk tracks global crop yields under climate change. Nature Climate Change, 11(8), 710–715. https://doi.org/10.1038/s41558-021-01104-8

SAEREM BOOK CHAPTERS First Published 2026 ISBN 978-978-60709-7-6

Choudhary, A. and Senthil-Kumar, M. (2024). Drought: A context-dependent damper and aggravator of plant diseases. Plant, Cell & Environment, 47(6), 2109–2126. https://doi.org/10.1111/pce.14863

Ferris, A. C., Stutt, R. O. J. H., Godding, D. S., Mohammed, I. U., Nkere, C. K., Eni, A. O., Pita, J. S. and Gilligan, C. A. (2024). Computational models for improving surveillance for the early detection of direct introduction of cassava brown streak disease in Nigeria. PLOS ONE, 19(8), Article e0304656. https://doi.org/10.1371/journal.pone.0304656

Food and Agriculture Organization of the United Nations. (2024). Strengthening Capacities to Contain and Manage Fusarium Oxysporum F.Sp. Cubense Tropical Race 4 on Bananas in Lebanon - TCP/LEB/3803. https://openknowledge.fao.org/server/api/core/bitstreams/49f598ed-9d95-4e65-b75c-e13ddad9598c/content

International Plant Protection Convention Secretariat. (2024). Global coordination response on *Fusarium oxysporum* f. sp. cubense Tropical Race 4 (TR4). https://www.ippc.int/en/core-activities/capacity-development/programmes/ippc-global-coordination-on-fusarium-oxysporum-f-sp-cubense-tropical-race-4-tr4/

Islam, M. T., Croll, D., Gladieux, P., Soanes, D. M., Persoons, A., Bhattacharjee, P., Hossain, S., Gupta, D. R., Rahman, M. M., Mahboob, M. G., Cook, N., Salam, M. U., Surovy, M. Z., Sancho, V. B., Maciel, J. L. N., NhaniJúnior, A., Castroagudín, V. L., Reges, J. T. de A., Ceresini, P. C., … Kamoun, S. (2016). Emergence of wheat blast in Bangladesh was caused by a South American lineage of *Magnaporthe oryzae*. BMC Biology, 14, Article 84. https://doi.org/10.1186/s12915-016-0309-7

Kriticos, D. J., Darnell, R. E., Yonow, T., Ota, N., Sutherst, R. W., Parry, H. R., Mugerwa, H., Maruthi, M. N., Seal, S. E., Colvin, J., Macfadyen, S., Kalyebi, A., Hulthen, A. D. and De Barro, P. J. (2020). Improving climate suitability for *Bemisia tabaci* in East Africa is correlated with increased prevalence of whiteflies and cassava diseases. Scientific Reports, 10, Article 22049. https://doi.org/10.1038/s41598-020-79149-6

Mahuku, G., Lockhart, B. E., Wanjala, B., Jones, M. W., Kimunye, J. N., Stewart, L. R., Cassone, B. J., Sevgan, S., Nyasani, J. O., Kusia, E., Kumar, P. L., Niblett, C. L., Kiggundu, A., Asea, G., Pappu, H. R., Wangai, A., Prasanna, B. M. and Redinbaugh, M. G. (2015). Maize lethal necrosis (MLN), an emerging threat to maize-based food security in sub-Saharan Africa. Phytopathology, 105(7), 956–965. https://doi.org/10.1094/PHYTO-12-14-0367-FI

Meyer, M., Burgin, L., Hort, M. C., Hodson, D. P. and Gilligan, C. A. (2017). Large-scale atmospheric dispersal simulations identify likely airborne incursion routes of wheat stem rust into Ethiopia. Phytopathology, 107(10), 1175–1186. https://doi.org/10.1094/PHYTO-01-17-0035-FI

Mohanapriya, S., Vanitha, S., Geethalakshmi, V., Pazhanivelan, S., Ragunath, K. P., Sendhilvel, V. and Vanitha, G. (2025). Plant health dynamics in accordance with climate change. Physiological and Molecular Plant Pathology, 138, Article 102655. https://doi.org/10.1016/j.pmpp.2025.102655

Mrisho, L. M., Mbilinyi, N. A., Ndalahwa, M., Ramcharan, A. M., Kehs, A. K., McCloskey, P. C., Murithi, H., Hughes, D. P. and Legg, J. P. (2020). Accuracy of a smartphone-based object detection model,

PlantVillage Nuru, in identifying the foliar symptoms of the viral diseases of cassava CMD and CBSD. Frontiers in Plant Science, 11, Article 590889. https://doi.org/10.3389/fpls.2020.590889

National Agricultural Extension and Research Liaison Services. (2023). The impact of flooding on agricultural activities in Nigeria. https://nairaproject.com/projects/5770-the-impact-of-flooding-on-agricultural-activities-in-nigeria.html

Omokaro, G. O. (2025). Multi-impacts of climate change and mitigation strategies in Nigeria: agricultural production and food security. Science in One Health 4 (2025) 100113 https://doi.org/10.1016/j.soh.2025.100113

Prank, M., Kenaley, S. C., Bergstrom, G. C., Acevedo, M. and Mahowald, N. M. (2019). Climate change impacts the spread potential of wheat stem rust, a significant crop disease. Environmental Research Letters, 14(12), Article 124053. https://doi.org/10.1088/1748-9326/ab57de

Roussin-Léveillée, C., Rossi, C. A. M., Castroverde, C. D. M. and Moffett, P. (2024). The plant disease triangle facing climate change: A molecular perspective. Trends in Plant Science, 29(8), 895–914. https://doi.org/10.1016/j.tplants.2024.03.004

Shamuwa, K., Abdullahi, N., Tahir, B. and Abubakar, I. (2025). Impact of climate change on plant disease dynamics. Dutse Journal of Pure and Applied Sciences (DUJOPAS), 11 (1d): 240-247 https//doi - 10.4314/dujopas.v11i1d.24

Singh, B. K., Delgado-Baquerizo, M., Egidi, E., Guirado, E., Leach, J. E., Liu, H. and Trivedi, P. (2023). Climate change impacts on plant pathogens, food security and paths forward. Nature Reviews Microbiology, 21(10), 640–656. https://doi.org/10.1038/s41579-023-00900-7

Tembo, B., Mulenga, R. M., Sichilima, S., M'siska, K. K., Mwale, M., Chikoti, P. C., Singh, P. K., He, X., Pedley, K. F., Peterson, G. L., Singh, R. P., and Braun, H. J. (2020). Detection and characterization of fungus (*Magnaporthe oryzae* pathotype Triticum) causing wheat blast disease on rain-fed grown wheat (*Triticum aestivum* L.) in Zambia. PLOS ONE, 15(9), Article e0238724. https://doi.org/10.1371/journal.pone.0238724

van Westerhoven, A. C., Meijer, H. J. G., Houdijk, J., Martínez de la Parte, E., Matabuana, E. L., Seidl, M. F. and Kema, G. H. J. (2022a). Dissemination of Fusarium wilt of banana in Mozambique caused by *Fusarium odoratissimum* Tropical Race 4. Plant Disease, 107(3), 628–632. https://doi.org/10.1094/PDIS-07-22-1576-SC

van Westerhoven, A. C., Meijer, H. J. G., Seidl, M. F. and Kema, G. H. J. (2022b). Uncontained spread of Fusarium wilt of banana threatens African food security. PLOS Pathogens, 18(9), Article e1010769. https://doi.org/10.1371/journal.ppat.1010769

Viljoen, A., Mostert, D., Chiconela, T., Beukes, I., Fraser, C., Dwyer, J., Murray, H., Amisse, J., Matabuana, E. L., Tazan, G., Amugoli, O. M., Mondjana, A., Vaz, A., Pretorius, A., Bothma, S., Rose, L. J., Beed, F., Dusunceli, F., Chao, C.-P. and Molina, A. (2020). Occurrence and spread of

the banana fungus Fusarium oxysporum f. sp. cubense TR4 in Mozambique. South African Journal of Science, 116(11/12). https://doi.org/10.17159/sajs.2020/8608

Xiong, C., Ge, A.-H., Gao, M. and Singh, B. K. (2026). Impacts of climate extremes on plant pathogens, microbiomes and plant health. Nature Reviews Microbiology, 24(9), 637–653. https://doi.org/10.1038/s41579-026-01290-2

SAEREM BOOK CHAPTERS First Published 2026 ISBN 978-978-60709-7-6