OPEN ACCESS
International Journal of Agriculture & Sustainable Development
RESEARCH & INNOVATION DIVISION
IJASD
ISSN:2618-1193

Advancing Plant Health Management: Challenges, Strategies, and Implications for Global Agriculture

Shazia Hussain
University of Peshawar
*Correspondence: shaziahsn629@gmail.com

Citation | Hussain. S, "Advancing Plant Health Management: Challenges, Strategies, and Implications for Global Agriculture", IJASD, Vol. 6 Issue. 2 pp 73-89, April 2024
Received | Mar 19, 2024. **Revised |** April 04, 2024. **Accepted |** April 17, 2024. **Published |** April 21, 2024.

This review paper explores the intricate dynamics surrounding plant health management in the context of global agricultural sustainability and food security challenges. Beginning with an overview of the United Nations' designation of 2020 as the International Year of Plant Health and the projected increase in food demand by 2050, the paper delves into the critical role of cereals in African diets, emphasizing their nutritional significance and cultural importance. A historical perspective on plant disease management sets the stage for discussing modern approaches like integrated pest management and ecological strategies, emphasizing the need for interdisciplinary collaboration. The methodology section outlines a systematic review process, including database selection, formulation of review questions, and screening criteria for relevant studies. The paper then delves into specific plant pathogens affecting key crops like potatoes, grapes, bananas, and wheat, highlighting the economic and social impacts of diseases such as late blight, grey mold, banana Xanthomonas wilt, and wheat stem rust. The emergence of pesticide-resistant populations and novel pathogens adds complexity to disease management strategies, necessitating innovative solutions such as genetic engineering and ecological control measures. Key findings underscore the urgency of addressing emerging diseases and their socio-economic ramifications, particularly in vulnerable regions. The paper advocates for sustainable disease control practices, including early diagnosis techniques using next-generation sequencing, strict quarantine measures, and integrated pest management approaches. It also stresses the importance of socio-economic analyses in disease control programs and the integration of ecological perspectives for effective agricultural sustainability.

Keywords: Plant Health Management, Emerging Plant Pathogens, Integrated Disease Management, Ecological Approaches, Crop Yield Pest Resistance.

Introduction:

The United Nations has officially designated the year 2020 as the International Year of Plant Health. According to projections, a 60% increase in food production will be necessary to adequately nourish the estimated global population of 10 billion individuals by the year 2050. In order to meet the demand, it is necessary to increase production while simultaneously reducing food loss caused by pests, illnesses, and food waste. The global impact of agricultural pests and diseases on food crops is substantial, with average losses ranging from 21.5% (10.1 to 28.1%) to 30.3% (24.6 to 40.9%) for wheat, rice, maize, potatoes, and soybeans. 3 [1]. Smallholder farmers in different regions of the world may experience significant preharvest losses due to plant diseases. A survey conducted in Central America revealed that more than 50% of bean and maize farmers reported experiencing losses, while in South America, nearly 50% of potato farmers reported losses. Plant diseases are responsible for substantial declines in food crop productivity, resulting in negative impacts on human health, decreased yields, diminished species diversity, and increased expenses related to control measures [2].

The National Academy of Sciences has recently published a comprehensive research agenda for the field of agriculture, emphasizing the imperative of employing cutting-edge technologies to promptly and efficiently detect and treat plant illnesses. Emerging plant diseases encompass a category of diseases that have attained the following characteristics: 1) an increase in host range, geography, or incidence; 2) modified pathogenesis; 3) recent emergence; or 4) recent identification or recognition. The financial implications of emerging plant diseases and pest outbreaks in the agricultural sector are substantial, and they also have repercussions on human health, national security, and food security [3]. Due to climate change and increasing global trade, it is expected that pests and pathogens will alter their geographical ranges, resulting in a higher occurrence and intensity of emerging plant diseases. These diseases have already been more prevalent in recent decades. Plant diseases have a significant impact on various dimensions of food security, and effective management strategies can contribute to increased agricultural productivity and improved human health. This article examines the impact of recently identified plant diseases on food production and food security. It delves into the underlying mechanisms responsible for the emergence of plant pathogens and proposes a comprehensive research agenda that can be utilized by international science and development organizations to effectively curb the dissemination of newly identified plant diseases and improve mitigation strategies in the event of outbreaks [4].

The impact of plant diseases on food security

The increase in food prices during the global food crisis of 2007-2008 resulted in a significant number of individuals experiencing food insecurity. After the implementation of these price hikes, a series of food riots and political unrest ensued across the Middle East and Africa. Consequently, the former Secretary of State of the United States, John Kerry, expressed the view that ensuring access to food and agriculture should serve as the fundamental basis for development strategy. The climatic catastrophe is anticipated to lead to reduced agricultural yields and diminished food stockpiles inside nations. Additionally, it is projected to disrupt food supply networks and exacerbate plant diseases [5].

Plant diseases provide a significant worldwide challenge, exerting detrimental effects on both the yield of food crops and the social and political stability of nations. An exemplary instance is the Irish potato famine that occurred in the 19th century. The potato crop in Ireland was severely damaged by Phytophthora infestans in 1845, leading to the Irish famine that resulted in more than 2 million deaths and a significant migration from Ireland in the subsequent years. Upon the initial emergence of the pathogen in the United States in 1843, the impact was comparatively milder than in Ireland. In Ireland, the population faced severe food insecurity as a result of their dependence on a solitary food crop, a dearth of social and political determination, and a delay in the British government's response to the hunger crisis. The Bengal famine, compounded by conflict, poverty, and British occupation during World War II, led to the death of more than two million Bengalese individuals due to the spread of Cochliobolus miyabeanus, the bacteria responsible for rice production. The production of rice decreased by 25%, and the country's rice reserves were redirected to provide food for the armed forces. The recent occurrences of coffee rust outbreaks in Central America, caused by Hemileia vastatrix, provide an additional illustration of individuals being evacuated due to the emergence of an endemic plant disease and climate change. Certain regions in Central America had coffee yield reductions exceeding 50%, leading to the unemployment of over 400,000 workers in Honduras, El Salvador, and Guatemala. Consequently, this crisis has caused widespread hunger, poverty, and a significant increase in migration. The migration of coffee rust to higher altitudes in Central America can be attributed to various variables, including climate change, decreased coffee prices, and the cultivation of vulnerable coffee varieties. Growers in these regions were inadequately equipped and had limited availability of fungicides for disease treatment [6].

Plant diseases can emerge through many mechanisms. The transmission of illnesses through infected plant material can lead to an escalation in the occurrence, distribution, or range of a pathogen, as exemplified by the recent introduction of wheat blast into Bangladesh through infected seeds. The transmission of soybean rot from Brazil to the United States by Hurricane Ivan exemplifies the ability of severe meteorological phenomena, such as hurricanes, to disperse disease spores across different continents. The introduction of an insect vector, which happened several years after the initial detection of the citrus tristeza virus in South America, resulted in a more extensive geographical dissemination of the illness. When plant diseases are brought into novel environments, they possess the capability to alter their hosts and acquire the ability to infect more hosts. For example, it should be noted that CMV is not indigenous to cassava in South America. Instead, it was introduced into Africa's cassava crop from an unnamed host subsequent to the emergence of cassava as a prominent food crop in the region. The occurrence of a change in pathogenesis or virulence of an endemic strain can be observed through recent alarms regarding a new race of wheat stem rust pathogen in Ethiopia (race TTKTT) that possesses a significantly elevated combination of virulence genes. Additionally, a new race has emerged in Sicily that has the potential to overcome resistance in widely cultivated European wheat cultivars. The emergence of novel plant pathogenic species can be attributed to interspecific hybridization or mutations occurring within existing disease lineages. This phenomenon is shown by the cases of Phytophthora andina in South America and Phytophthora alni in the UK [7].

Cereals play a significant role in the dietary patterns of African populations, serving as valuable sources of essential vitamins, minerals, dietary fiber, and carbohydrates. As an example, sorghum exhibits a notable content of potassium and iron, while maize serves as a substantial provider of thiamine, niacin, and folate. In addition to rice, which is recognized as a significant dietary source of iron and B vitamins, millet holds considerable importance as a grain due to its high content of calcium, magnesium, and zinc. The diverse cultures and populations in Africa play a significant role in the global production and consumption of various grains, such as wheat, sorghum, millet, maize, and rice. These grains possess unique nutritional and gastronomic characteristics, rendering them highly suitable for various applications. Cereal grains in tropical Africa are pulverized and utilized to create dense porridges, which are referred to by various names throughout different continents. Fura, a variant of dense porridge, enjoys significant popularity in West Africa, namely in Nigeria, Ghana, and Burkina Faso. The cereal meal is a partially solid pouring cereal [8].

Maize (Zea mays), which is the most commonly cultivated cereal in Africa, is employed for a diverse range of purposes. In East and Southern Africa, maize serves as the primary staple grain and is consumed in many forms such as porridge, meal, and flour. In West Africa, maize is commonly consumed as a snack in the form of boiled or roasted maize cobs, despite its status as a staple food. Furthermore, maize plays a crucial role in the manufacturing of beer and other alcoholic beverages, as well as serving as a valuable source of animal feed. Sorghum (Sorghum bicolor) is the second most prevalent cereal in Africa, particularly in arid and semi-arid regions. Sorghum is utilized in both human and animal nutrition. Sorghum is primarily utilized in East Africa for the production of the customary alcoholic beverage called "chang'aa," and in West Africa for the production of the commonly consumed beer known as "dolo." Furthermore, sorghum is employed in the production of syrup and animal feed. Millet (Pennisetum glaucum) is a frequently farmed crop in Africa, particularly in the Sahel region. It is commonly consumed as porridge or as a side dish and is fed to both cattle and humans. In West Africa, there exists a traditional alcoholic beverage known as "tchapalo" which is derived from millet. Africa is a continent renowned for its abundant cultivation of rice (Oryza sativa), particularly in the region of West Africa. It is commonly consumed as a fundamental part of one's diet and is often served alongside a sauce or stew. Several traditional dishes, including paella, biryani, and jollof rice, are prepared using rice as a primary ingredient. Despite being cultivated in Africa, wheat (Triticum spp.) does not enjoy the same level of popularity as other cereal grains. Wheat is the main ingredient used in the production of bread, cakes, and other baked foods. It is also used to make bulgur, couscous, and pasta. Wheat straw is utilized as a raw material for animal feed. Despite its relatively lower popularity compared to other cereals, barley (Hordeum vulgare) is a grain that is cultivated across several regions of Africa. Barley is mostly utilized in the production of beer and other alcoholic beverages. Fonio (Digitaria exilis), a cereal of lesser recognition, originates from West Africa. Humans mostly utilize it as a dietary staple, often consuming it as a side dish or porridge [9].

Literature review

The history of plant disease management in agriculture can be divided into four significant phases. (i) Inadequate backing for traditional agricultural methods. (ii) The utilization of mechanical and temporal techniques for disease control, including roguing, plowing, and rotations. (iii) Regular utilization of insecticides and essential genes that provide resistance to diseases. The study examines the combined impact of integrated pest management and ecological management on populations, as well as the agricultural and natural environments. The objective of ecological plant disease management is to utilize evolutionary wisdom and principles in order to harness the regulating functions of nature. This approach strives to establish favorable conditions for the growth of healthy plants, ensuring consistent and abundant yields through the efficient utilization of natural resources. It does not merely promote reverting to ancient agricultural methods. One of the resources that contributes to high resistance to illnesses is the provision of an adverse environment for pathogens to grow, reproduce, spread, and progress. Furthermore, it is imperative to assess the immediate and enduring economic impacts of any plant disease management strategy. To accomplish sustainable control of plant diseases, a collaborative effort including various fields such as agronomy, breeding, plant pathology, soil science, economics, social science, and environmental science is necessary [10].

There are several factors that contribute to the heightened risk of both new and reemerging diseases. The primary causes are as follows: (a) new pathogens entering production systems; (b) more virulent strains entering a system or the emergence of a novel destructive strain in the region where the pathogen was discovered; (c) new vectors entering a production system that is proficient in spreading a pathogen; (d) altering farming practices that may favor some epidemic components of a categorical disease; (e) indiscriminate pesticide use, which results in the proliferation and development of pesticide-resistant strains; (f) intensification of agriculture to maximize yield and profit; (g) cultivar variation; and (h) steady short-term climate changes. Although certain factors are inherent to crop agriculture, there are also external effects that hold significance, such as trade, international exchange, and policy [11].

Host shifts, the absence of inherent host resistance, changes in climatic conditions, and trade movements have been linked to the emergence of novel diseases. Furthermore, it is widely recognized that these variables have an influence on the phenomenon of pathogen saturation in both crops and natural ecosystems. Climate, crop development, and disease modeling have been integrated in locations where infections are absent to highlight the importance of quarantine protocols, pathologist training, and the use of crop resistance measures to impede the introduction and establishment of pathogens in new countries.

The emergence and reemergence of phytopathogens pose a significant threat to crop resistance, necessitating ongoing breeding efforts to generate novel forms of resistance. The financial cost of this is shared by both seed firms and farmers. Upon the emergence of novel viruses, farmers are compelled to employ copious quantities of chemical pesticides in order to effectively manage and regulate the infections. These chemical pesticides cause significant damage to the water bodies and soil of the ecosystem. In addition, they exert influence on non-target organisms, including advantageous soil microbial flora and pollinators. Moreover, in lucrative markets, food products containing chemical residues that pose a risk to human health have to decline. Prolonged usage of chemical pesticides diminishes the efficacy of the protectant in the environment, hence requiring additional breeding efforts, which incur high costs. The emergence and reemergence of phytopathogens lead to a decrease in food output, resulting in increased food expenses and alterations in dietary patterns [12].

Pakistan is currently facing a significant demand and problem in augmenting wheat output due to its rapid population growth. The current wheat yield in Pakistan is twice as low as that of other developed nations. Pakistan exhibits a comparatively lower wheat yield per hectare in comparison to other highly developed nations, primarily because of a multitude of abiotic and biotic stressors. The most detrimental aphid species of wheat are Sito-bion avenae and Rhopalosiphum padi, which have the potential to significantly diminish wheat output by as much as 80% due to the spread of several viral and fungal illnesses. Biotic stressors exert a substantial influence on the growth of wheat plants, resulting in diminished yield and productivity. Reduced wheat production can also occur as a consequence of drought circumstances accompanied by significant rains throughout the reproductive and maturity stages. The presence of biotic elements, such as pests, has resulted in a reduction in crop output, hence exerting adverse effects on the national economy. The occurrence of insect pest outbreaks in agricultural systems is influenced by a multitude of factors that contribute to the growth and behavior of these pests. The population and diversity of pests are influenced by climatic changes, such as elevated temperatures and alterations in rainfall patterns [13]. The diverse array of dynamic pests resulting from climate fluctuations is a substantial obstacle in guaranteeing the stability and long-term viability of wheat and its associated commodities. Soil community members significantly disrupt the stability of the agricultural system, hence impacting the quality and productivity of the wheat harvest. Insect pests, such as grain aphids, cause harm to wheat crops. The diversity of aphids is influenced by climatic circumstances, which can have either a beneficial or negative impact on wheat productivity. The presence of aphids directly leads to a decrease in wheat yield due to sap-sucking, whereas indirect losses arise from the transfer of viral and fungal diseases. The extent of wheat production decline is contingent upon the specific stages of crop development and the severity of aphid infestation, resulting in varied levels of economic harm attributable to both biotic and abiotic factors. There are several tactics that can be employed to improve wheat production. These strategies include effective pest management, the utilization of biopesticides, the implementation of control measures such as delayed planting and crop rotation, and the optimization of natural enemies of pests while minimizing the use of pesticides.

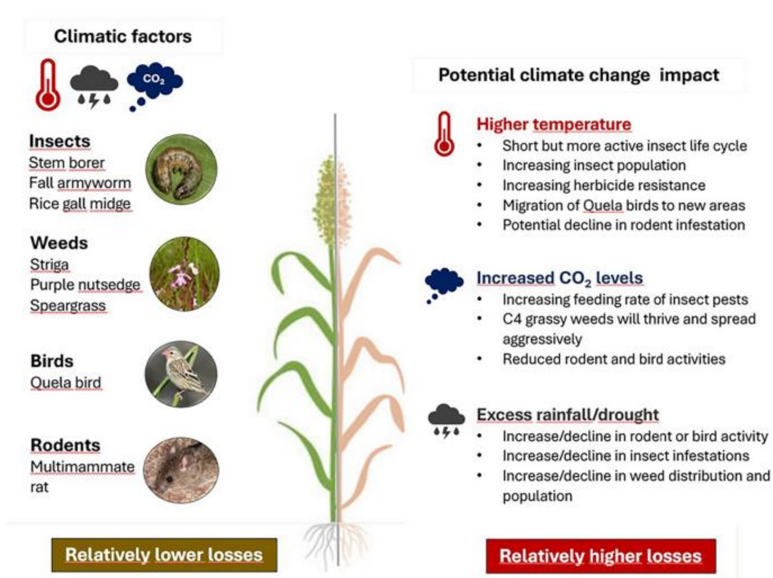

Figure 1: Climate change may significantly impact crop yields through its effects on insect pests, weeds, birds, and rodents [2].

Methodology

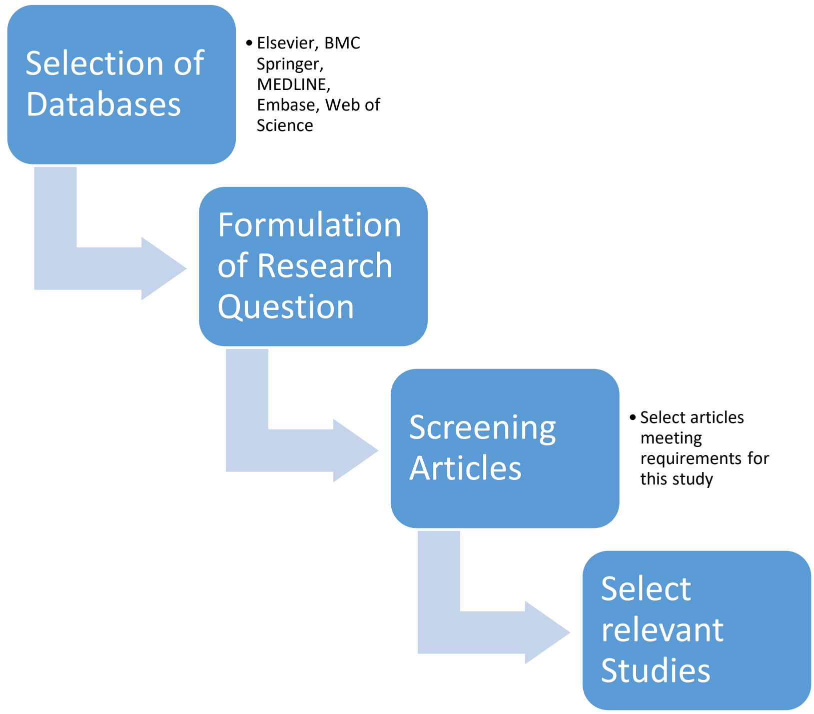

Figure 2: Flow of methodology

The methodology for finding unique studies provides data as follows:

Selection of Electronic Databases: A systematic review of electronic databases was conducted to identify relevant literature. Databases such as Elsevier, BMC Springer, MEDLINE, Embase, Web of Science, and Ovid were searched comprehensively. Additionally, Google Scholar was utilized to enhance the material. However, to ensure the validity of papers obtained through Google Scholar links to the active publishers were checked.

Formulation of Review Question and Screening Criterion: A review question was formulated to guide the search process. The review question focused on identifying primary studies related to emerging and reemerging plant pathogens affecting food crops globally, without geographical restrictions. Criteria for screening included evaluating only primary study abstracts and English research titles. Articles meeting the basic satisfactory requirement as determined by independent authors were selected for further evaluation.

Selection of Relevant Studies: Titles and abstracts that met the eligibility criteria were chosen for full paper evaluation. Independent authors assessed these articles to provide critical analytical data for the analysis. To minimize bias, the independence of authors in deciding whether to include or exclude articles was emphasized.

Plant Pathogens

Integrated disease management (IDM) is a viable approach for controlling potato late blight. However, the most efficacious technique to combat this disease lies in the development of resistant cultivars. The absence of a comparable Plant Pathology and Plant Breeding laboratory in Great Britain hinders the examination of potato germplasm. The occurrence of late blight poses a significant risk to all commercial cultivars. Despite the development of novel cultivars in various provinces of Pakistan, it remains imperative to conduct thorough examinations to ascertain the presence of genes conferring resistance against late blight disease. Despite their potential to lessen the occurrence of late blight, farmers in GB have a lack of access to fungicides. The use of fungicides can also contaminate the ecological system and diminish the variety of other species in the vicinity. [14] presented compelling evidence supporting the enduring presence of viruses responsible for late blight. P. infestans has become the most notorious plant pathogen of the potato crop due to the advent of new late blight disease strains that are more virulent and have a high intensity of emergence in new places. Furthermore, [14] incorporated up-to-date information pertaining to molecular genetic analysis and population biology in relation to late blight illness.

Grey mold-induced sickness

Fruits have a significant impact on the economy of the people. Different regions of Great Britain cultivate a diverse range of grape varietals that possess distinct characteristics. In recent times, viticulturists in GB have encountered difficulties due to illnesses affecting grapes. The recent increase in precipitation, which is linked to climate change, has contributed to the facilitation of disease transmission. The grey mold fungus (Botrytis cinerea) is a necrotrophic fungus that has been identified as a significant contributor to substantial losses in ripening grapes in Great Britain.

According to [15], almost 40% of grapefruits in Lahore and other areas of Pakistan have been documented to be affected by grey mold or Botrytis bunch rot disease. The fungus exhibits an asexual form, with the sexual form being hardly found. The gray mold fungus infects grape berries, resulting in reduced output and diminished fruit quality. Frequently, the fungus causes significant harm to grapes, rendering them unsuitable for human consumption. The occurrence of grape branch blight prior to fruit ripening is a potential consequence of the recent spring precipitation. The plant exhibits the growth of soft brown tissues in regions affected by disease. The infection of the leaf axils is responsible for the observed drooping or collapsing of the shoots.

The diseased berries may exhibit a reddish or brown coloration, contingent upon the specific cultivar. Epidermal fissures manifest in areas where the mycelium and spores of the fungus proliferate, owing to the presence of a gentle breeze and moderate temperature. The grape cluster had a consistent gray, smooth texture as a consequence. During the harvesting stage, the fungus develops robust and durable structures called sclerotia on the diseased grapefruit. In the subsequent season, when these berries descend to the ground or remain suspended on vines, they serve as a potential source of infection. The sclerotia undergo germination and then generate spores, which are distributed through various means such as wind, raindrop splashing, or irrigation water throughout the following season [16].

The transmission of this spore to individuals is facilitated by the availability of uncontaminated water and an optimal temperature. In the spring, spores enter the stigma by passing through the tip of the pedicel and infecting the flowers. Subsequently, the fungus enters a state of dormancy, awaiting the augmentation of the sugar content in the infected fruit at a later stage in the season. Subsequently, the berries undergo infection by the fungus, which proliferates swiftly within them. As the disease progresses, berries undergo shattering and splitting, hence creating an opportunity for the transmission of diseases to adjacent berries. Late infections are more severe in environments characterized by elevated relative humidity, ample free moisture, and moderate temperature. The viability of berries is compromised when they sustain damage from insects and avian predators. During the initial stages of fruit development, an ample supply of water and nutrients becomes accessible, facilitating the rapid dissemination of the fungus and subsequent induction of a lethal ailment. The management of this disease can be achieved through the implementation of eco-friendly biocontrol agents, cultural practices, and the cultivation of resistant varieties. The multifaceted nature of the infection pathways associated with the gray mold disease poses challenges in its therapy. Furthermore, it has the ability to persist for an extended duration as mycelia, conidia, and sclerotia on a diverse range of hosts. The rapid treatment of grape diseases poses challenges due to the inherent unpredictability and fluctuation of rainfall patterns. Furthermore, there is now no cultivar available that may be effectively employed to mitigate the financial losses resulting from the gray mold disease. Fungicides are characterized by their lack of environmental friendliness and high cost. The absence of marketing and storage infrastructure also plays a role in the escalation of postharvest costs [17].

Potato late blight

Phytophthora infestans (Montagne) de Bary is widely recognized as the most detrimental pathogen affecting potatoes and tomatoes, resulting in the occurrence of late blight (Plate 1) in solanaceous crops. The projected annual global losses of over $5 billion caused by late blight give rise to apprehensions about the disease's implications for food security. This disease is considered to be the most detrimental to potatoes, resulting in a significant decrease in crop production and incurring control costs of up to $10 billion USD. Approximately 25% of the Irish populace succumbed to the significant famine that occurred during the 19th century. This calamity was mostly caused by a sickness, resulting in the loss of 0.7 million lives throughout Europe and the displacement of an additional 1.5 million individuals. The disease existed prior to the establishment of plant pathology as a distinct scientific domain. However, the ongoing emergence of new disease strains with increased virulence and their spread into previously unaffected regions with heightened severity makes it a continuous public health concern. The completion of sexual reproduction is contingent upon the presence of mating types A1 and A2, as a result of the pathogen's heterothallism. The pathogen undergoes asexual reproduction, resulting in the formation of clonal lineages or populations, in regions where sexual reproduction is not possible. The intercontinental dissemination of pathogenic strains poses challenges to the management and control of late blight. The introduction of variants with increased virulence, improved fitness, and heightened resistance to fungicides has occurred as a result of the pathogen's spread across the continent. 32. Potato late blight poses significant economic consequences in Maine since it has the ability to cause the industry to fail and result in a 25% decrease in output. The exclusive utilization of fungicides incurs a cost of $80 million, with a concurrent increase in associated expenditures. According to a Delphi study, U.S. growers incurred a loss of $210.7 million in sales due to the expenses incurred for late-blight fungicides, which amounted to $77.1 million [18].

The management of P. infestans remains a significant challenge, particularly for small-scale farmers residing in the potato-producing areas of Kenya. Farmers mostly employ resistant cultivars and fungicides to battle late blight. The limited availability of resources is a huge challenge for small-scale farmers in efficiently managing diseases, resulting in substantial financial losses and, in several instances, catastrophic crop failure. Efficacious fungicides induce disease resistance, leading to the eventual loss of resistance in resistant strains. The diversification and expansion of P. infestans strains into novel regions have been observed. The resilience of Phytophthora infestans to late blight poses a significant economic risk to potato cultivation. The direct transfer of resistance genes from wild potato species to cultivars, facilitated by genetic engineering, has made it easier to pyramid multiple Rpi genes. This intervention has the potential to enhance the resistance of potatoes against rapidly emerging strains of P. infestans [19].

The presence of Xanthomonas Wilt (BXW) in bananas

Bananas (Musa spp.) is positioned as the fifth most prevalent staple food on a global scale, following rice, wheat, maize, and potatoes. The geographical valuation of the crop is in relation to its economic significance, as indicated by the fact that a mere 10% of the global annual production of around 100 million tons is sold for commercial purposes. Approximately one-third of global production is derived from this crop, which serves as the primary source of sustenance for over 100 million individuals residing in Sub-Saharan Africa. Banana

Xanthomonas Wilt (BXW) poses a significant danger to the banana crop in East and Central Africa, potentially leading to output reductions of up to 100% if not effectively managed. While the disease has a substantial effect on food security, there is a lack of comprehensive documentation regarding its economic implications for farmers and the whole economy. Some of the emerging research avenues for sustainable management include the development of resistant banana cultivars, exploration of endophytes as biological control agents, enhancement of cultural control approaches, and dissemination of information to farmers on BXW. The bacterial illness known as Banana Xanthomonas Wilt (Plate 2) is attributed to the pathogenic bacterium Xanthomonas campestris pv. musacearum. Banana crops are confronted with a multitude of hazards, including pathogenic and insect agents, infertile and impoverished soils, and various other challenges. This perilous bacteria has rapidly disseminated to all regions of Sub-Saharan Africa where banana cultivation takes place. Various cultivars display different levels of susceptibility to the disease, however none demonstrate absolute genetic resistance [20].

The sickness poses a significant threat to the means of subsistence and food security of numerous rural communities, leading to a complete loss of crops. The fruit undergoes rapid and premature ripening, resulting in the presence of brown stains within the fruit and decay in the bunch, rachis, and male flowers. The foliage undergoes a progressive process of withering and exhibits indications of chlorosis and necrosis. The plant ultimately undergoes desiccation and perishes as a whole. The onset of symptoms can occur rapidly, as early as 3-4 weeks after infection, depending on the pathogenic virulence, environmental variables, and cultivar susceptibility (known as the disease triangle). The germs are transported to the inflorescences by insect vectors such as fruit flies and stingless bees. Furthermore, mechanical transmission can occur through soilborne infection, the presence of infected plant debris, or the use of contaminated farm implements. In addition to the generation of contaminated plantlets, raindrops have the potential to transfer the infection to adjacent susceptible plants. Due to its rapid spread, the disease induces severe symptoms and ultimately leads to the complete destruction of the crop, including propagation materials, resulting in a concerning impact. Furthermore, due to the prolonged persistence of the virus in the soil, it is prudent to postpone the replantation of bananas in afflicted fields for a duration of six months. Once an infection has initiated, banana crops that have been affected are irreparable. Areas affected by the illness have experienced yield reductions of up to 60%, posing a threat to the food security and livelihoods of millions of individuals in the East African region [21]

Approximately 0.8 million metric tons (equivalent to US$ 0.28 billion) of bananas are lost on a yearly basis, resulting in a deprivation of food supply for approximately 35 million individuals in Africa. This estimate was derived from a 1% decrease in production by BXW in the banana industry. Numerous cultivators and vendors heavily depend on bananas as a primary source of income, hence rendering such a loss capable of inflicting severe economic repercussions on local communities. Creative strategies to battle the illness include the implementation of breeding programs aimed at developing resistant banana types, the enforcement of stringent quarantine restrictions to impede the transmission of Banana Xanthomonas Wilt (BXW), the utilization of PCR and LAMP techniques for early diagnosis, and the adoption of hygienic practices by farmers. The absence of resistance within the Musa germplasm and the sterile characteristics of the crop contribute to the sluggishness of conventional breeding methodologies. Genetic engineering has been employed as a means to tackle these issues, resulting in the development of transgenic bananas that demonstrate enhanced resistance to mixed species nematodes and complete resistance against X. campestris pv. Musacearum [22].

The Presence of Rust on Wheat and Black Stems

Wheat is rated #1 in terms of per capita calorie consumption, food availability, and the value of imports into Africa. The annual production of wheat on over 10 million acres of land across the continent amounts to approximately 26 million metric tons (MT). Every year, almost 41 million metric tons (MT) of wheat is imported, amounting to US$ 12 billion. This accounts for 25.4% of all wheat imports worldwide. The reason for this is that domestic wheat output is insufficient to meet the demand.

The causative agent of wheat stem rust is Puccinia graminis f. sp. tritici, commonly referred to as black rust because of the production of numerous glossy black asexual teliospores. Despite its historical prevalence in African nations, the disease is currently experiencing a resurgence in both Africa and Europe. It is a highly severe disease in numerous wheat-producing areas throughout. Without a doubt, a field that demonstrates strong kernel growth and fruition has the potential to rapidly deteriorate, resulting in a jumble of black straw and deteriorated, withering kernels, just a few weeks before harvesting. Effective breeding resistance attempts have decreased losses caused by pathogens and produced cultivars that are resistant. However, the resistance gradually diminishes, requiring more breeding efforts. Black stem rust, also known as wheat stem rust, exerts a significant detrimental impact on global wheat production, resulting in a reduction in yields ranging from 10% to 70%. Furthermore, this sickness leads to an escalation in the expenses associated with fungicides, monitoring fees, and potential trade restrictions. The potential for the emergence of novel, highly pathogenic strains exacerbates these risks, underscoring the critical significance of effectively managing and controlling wheat stem rust [23].

This rust is especially important for wheat crops that mature late or are planted late in the later stages of their growth. In warm and humid regions such as Sub-Saharan Africa, the illness has the ability to persist over multiple years by infecting wild grasses and plant debris. Most of the dissemination of P. graminis spores takes place in the atmosphere, where a significant quantity of spores disperse over short distances, leading to localized outbreaks. Nevertheless, only a minuscule proportion of spores possess the capacity to traverse significant distances prior to initiating and establishing novel infections.

In 1999, a highly contagious prototype strain called Ug99 originated in Uganda and resulted in significant epidemics in wheat-producing areas of East Africa. This prototype is rapidly changing, with over 13 races already discovered in Yemen, Iran, and Sub-Saharan Africa. Ug99 poses a significant threat to the majority of wheat cultivars in India and Pakistan. These two nations collectively account for around 20% of global wheat production. Moreover, given the ability of the rust fungus's spores to disperse across continents by wind, it is plausible that approximately 80% of wheat cultivars cultivated in Asia and Africa are susceptible to its infestation. Wheat, a prominent grain crop, is susceptible to rust diseases and several pests. These diseases can lead to a lack of access to food and result in significant reductions in crop production. It is crucial to identify and integrate valuable rust-resistant genes from different sources into pre-breeding lines and future wheat varieties in order to prevent this issue. The utilization of environmentally friendly genetic resistance can impede the progression of rust infections. The field of wheat genomics has experienced a significant transformation due to advancements in Next-Generation Sequencing (NGS) technology and bioinformatics tools. These advancements have facilitated the identification of potential genes, improved breeding values, and the establishment of marker-trait associations.

According to the findings by [24], and other researchers, it has been discovered that yield losses in Sub-Saharan Africa can reach up to 50% in some places and 100% in wheat fields that have suffered substantial damage. Furthermore, [25] reported an annual production loss of 8.9% in the aforementioned location. If production were to decrease by 1%, African nations engaged in wheat production could experience an annual loss of 0.26 million metric tons (or US$ 0.09 billion), resulting in a lack of staple food supply for 5.4 million individuals. According to [25], if the output losses reach 8.9%, there might be a loss of 2.3 million MT of wheat. This would result in a shortage of wheat for approximately 48.2 million consumers in Africa. This might lead to a 5.6% rise in wheat imports into Africa, potentially impacting global wheat prices.

Potential sources of recently identified pathogenic microorganisms

The emergence of bacterial and fungal pathogenic organisms, as well as common insect pests, has been associated with several theories. a) Despite the virus's potential nativeness and extensive distribution in crop areas, a novel host has just been found. b) After becoming indigenous and extensively dispersed, the fungus or bacteria acquire a detrimental nature as a result of heightened virulence or diminished defensive systems in the crop host. c) The bacteria or fungi may have been introduced to a previously unaffected region and crop, resulting in the illness posing a threat to rare crops such as chili peppers. Insect vectors that consume or exploit diverse plant species harbor harmful bacteria or fungi, thereby transmitting these organisms to following plants.

Numerous factors are believed to contribute to the onset of disease, including the interplay between various pathogenic bacteria and fungi, interactions between pathogens and plants, interactions between insects and pathogens and plants, and adverse environmental conditions such as extended periods of drought and unpredictable water patterns. According to several researchers, adverse dynamics have the potential to synergistically contribute to the development of complex illnesses. According to [26], climate dynamics can alter the nature of microorganisms, transforming them into opportunistic pathogens.

The impacts of emerging diseases and their unprecedented ramifications

In numerous scenarios, food crops are susceptible to infection by newly emerging pathogens, including viruses, fungi, bacteria, parasitic plants, noxious weeds, and insect pests. This infection leads to reduced crop yields and a subsequent decrease in the food supply accessible to human populations. These factors continue to pose the most significant challenges to food and agricultural growth in most developing countries. The emergence and reemergence of plant diseases possess the potential to significantly diminish agricultural yield due to the potential delay in the acquisition of resistance by crop plants. New diseases have the potential to lead to reduced food production or total crop failure. Crop failures have a substantial impact on the quantity of food accessible for human and animal consumption, hence serving as a direct catalyst for poverty and food insecurity. Furthermore, the introduction of novel pests such as insects can impede the growth of crops, resulting in reduced yields and posing a threat to food security. Like their predecessors, new pests have a negative effect on the marketing and sale of agricultural products, both within and outside of communities. They also reduce farmer earnings and hinder the eradication of poverty. To date, the management and control of plant pests have necessitated extensive utilization of synthetic pesticides, resulting in adverse consequences for both the environment and public health. This holds especially true for farmers with low income, as they may lack the financial means or ability to request personal protection equipment, pesticides with lower toxicity, or appropriate tools for application [27].

In many instances, the initial impacts of a newly identified plant disease or pest hold greater significance from a social and political perspective compared to its agricultural implications. Farmers commonly experience apprehension towards unfamiliar circumstances due to their uncertainty over the potential effects of the new disease on their crops and productivity. The feed industry would express apprehension regarding the potential deposition of lethal alkaloids or aflatoxins on cereal crops in the event of a novel fungal outbreak. Feed grain and seed exporters may have concerns about the potential closure of the export market. The farmers, feed, and seed business, researchers, and plant pathologists would be responsible for acquiring knowledge on how to prevent, manage, control, or coexist with the new ailment.

Climate change presents a significant peril to the human population, resulting in an annual global economic burden exceeding US$ 1.2 trillion and causing around 0.4 million deaths each year. Two indicators that demonstrate the impact of climate change on agriculture are the average global temperature increase of 0.74 °C over the past century and the escalation of atmospheric CO2 concentration from 280 ppm in 1750 to 400 ppm in 2013. Modifications of this nature will exert a substantial influence on the cultivation and production of the diverse array of crops on our planet. These modifications also have a simultaneous impact on the intensity, dissemination, and propagation of several plant diseases, posing a threat to our food security. The Ug99 race of stem rust, caused by Puccinia graminis f. Sp. climate change-related tritici, poses an additional threat to the resistance to stem rust induced by Sr31. The potential risks associated with increasing temperatures and CO2 levels are believed to be heightened by notable rice diseases, including sheath blight (Rhizoctonia solani), blast (Pyricularia oryzae), and late blight (Phytophthora infestans) of the potato. The disease landscape has undergone alterations as a result of climate change, underscoring the necessity for further investigation into models capable of forecasting the magnitude of significant infections in crucial crops within actual field environments. Moreover, given the dynamic nature of the environment, it is imperative to incorporate innovative approaches for achieving sustainable food production alongside disease control measures [28].

Impact of Pathogens on the health of Host plant

Healthy soils have a crucial role in the maintenance of agriculture and the management of plant diseases due to their influence on pathogen densities, particularly those responsible for soil-borne diseases. The presence of healthy soils has a significant impact on the accessibility of essential nutrients necessary for the growth and development of plants, as well as the composition of crucial microbial communities. Industrial emissions, air pollution, water contamination from agricultural waste, and the negligent application of synthetic pesticides for weed and insect control and crop cultivation have resulted in a multitude of significant and perhaps irreversible alterations throughout time. The quality of agriculture is diminished as a result of soil compaction, reduced organic matter, imbalances in mineral nutrition, pesticide residues, and heavy metal contamination. Moreover, the deterioration of agricultural quality has the potential to exacerbate the vulnerability of host plants to pathogen invasion and infection. The implementation of agronomic management strategies can exert a substantial influence on soil quality, thereby affecting the occurrence of diseases.

Consequently, many efforts to improve soil quality by increasing the diversity of microorganisms and beneficial microorganisms in agricultural regions, such as the addition of organic matter replenishment, also help avoid the occurrence of multiple diseases. The practice of crop rotation has been widely recognized for its ability to enhance the soil's physical, chemical, and nutritional equilibrium, while also promoting the diversity of the microbial community. On the other hand, the danger of disease incidence and epidemics is heightened by production techniques and field management practices, such as monocultures and continuous cropping of a single crop or variety, due to the allowance for diseases to accumulate in substantial inoculum loads. This assertion holds particular validity in the context of soil-borne diseases, however, it also extends to several diseases that adversely affect crops cultivated above the earth. The implementation of restricted pesticides and the introduction of resistance genes, driven by enhanced selection pressures on pathogenic microorganisms, expedite the cessation of disease management approaches. This phenomenon is attributed to the reduced diversity of the host crop, along with the excessive and negligent application of synthetic pesticides that possess stringent mechanisms of action.

The excessive utilization of pesticides, the adoption of monoculture agricultural methods, and the insufficient implementation of crop rotation schemes due to limited land resources collectively modify the ecological balance and create favorable circumstances that promote the rapid and effortless spread of diseases. Furthermore, the inherent immunity of crops is impaired, along with their ability to resist diseases. These factors contribute to the occurrence of new infections, especially in areas with vulnerable crops, favorable weather conditions, and extremely active pathogen strains. The interaction between these three components is commonly known as the "disease triangle." The study examined three monoculture crops, including banana, wheat, and potato, which increase the probability of new infections, particularly those caused by BXW, black stem rust, and late blight, respectively [29].

Approaches for static management

The regulation of pathogens poses significant challenges due to their rapid spatiotemporal dynamics and rapid growth. This management issue is helped by short generation times and enormous genetic diversity, which enables infections to circumvent the most effective disease management measures that rely on industrial pesticides and resistance through big R genes. The IPM techniques, which have gained recent support, seek to effectively address plant diseases by employing a combination of several measures tailored to individual illnesses, geographical locations, and temporal factors. Nevertheless, the utilization of synthetic pesticides has emerged as the predominant and sole IPM approach, particularly for crops that do not possess the R major gene for resistance. Research indicates that the reckless use of synthetic fertilizers and pesticides has not resulted in a recent increase in food production. This implies that the utilization of synthetic pesticides for the management of plant diseases is both economically less advantageous and less efficacious. Typically, pesticides are administered in accordance with a predetermined protocol encompassing a specified type, timing, dosage, and frequency of application. Irrespective of the pathogen's chemical sensitivity, the resistance status of particular crop plants, or the environmental conditions. The inflexible and unchanging approach to pesticide application diminishes the efficiency of management, increases production expenses, and leads to various unnecessary adverse environmental and social consequences, including ecological deterioration and harm to humans and livestock.

Chemical pesticide sprays continue to be the predominant method employed in the primary potato-producing regions across the globe for the purpose of mitigating the occurrence of potato late blight. An instance of static plant disease management can be observed in the application of chemical pesticides for the treatment of potato late blight. In Europe, about 36 fungicides and fungicidal combinations have been officially approved for the specific objective of managing potato late blight. While routine chemical pesticide treatment has proven to be beneficial in mitigating potato late blight, there has been a growing concern regarding the environmental and economic hazards connected with this practice. Hence, it is unsurprising that in specific geographical areas, the expenses associated with pesticides may constitute a range of 10% to 25% of the commercial worth of the potato crop. In certain potato-producing regions, a maximum of twenty rounds of pesticide spraying are necessary per season for efficient management [30].

The occurrence of pesticide-resistant populations of P. infestans has been documented on a global scale, primarily attributed to the excessive utilization of pesticides. As a consequence, the efficacy of chemical management for potato late blight has diminished, resulting in a heightened need for pesticide treatment in terms of dosage and frequency, so perpetuating a detrimental cycle. The implementation of IPM is recommended as a means to mitigate this issue. To mitigate the potential transmission and occurrence of epidemic breakouts in the future, it is imperative to adopt suitable crop rotation strategies, employ biological management methodologies, eliminate alternative hosts, eliminate any plant debris that may serve as a reservoir for pathogen spores, and completely eradicate all afflicted crops. Furthermore, the adoption of cultivars exhibiting enhanced tolerance and/or resistance to both abiotic and biotic stressors, the implementation of efficient quarantine systems, the utilization of consistent tools for disease epidemic prediction, the adoption of cropping systems encompassing a diverse array of crop species, the adjustment of planting dates, and the utilization of a combination of various pesticides with distinct modes of action have all been suggested as potential strategies.

Strategies for managing and isolating new phytopathogens

All the disorders mentioned in this review originate from the infections that occur during quarantine. The management and prevention of diseases caused by quarantine pathogens can be achieved by the utilization of rapid, effective, and cost-effective diagnostic techniques that enable early diagnosis and the implementation of corrective actions. There is a significant demand for comprehensive diagnostic tools that can diagnose diseases and simultaneously determine the quantitative pathogen genotypes. Such approaches are highly desirable as they enable timely interventions to effectively terminate or restrict infections. This could potentially reduce the duration of quarantine for items during transportation. The utilization of NGS strategies shows significant potential due to their ability to detect infections with high sensitivity and provide the genomic sequence data required for quantitative confirmation of genotype-specific identification, including the identification of new genetic variants. Illumina sequencing necessitates the use of specialized laboratory equipment and skilled workers to accurately discover and identify specific fungal subspecies. The Oxford Nanopore Technologies (ONT) MinION device is cost-effective and easily transportable, enabling broader use in the field while providing the same benefits as other NGS devices. Moreover, through the differentiation of single-nucleotide changes, it is possible to differentiate several isolates, strains, and subspecies.

Various governments and ministries of agriculture worldwide are enforcing stringent standards and regulations to mitigate the spread of invasive pests and phytopathogens. Sufficient financial resources are being allocated by governments towards the detection and accurate identification of invading phytopathogens. The purpose of this is to streamline the utilization of High-Throughput sequencing (HTS) methods, which are presently in the initial phases of investigation and advancement. These methods are advised for the detection of phytopathogens that have not been previously identified or are subject to regulation. HTS technologies enable the screening of plants and plant products with greater speed and accuracy compared to conventional diagnostic approaches. Regrettably, the efficacy of these technologies is hindered by inadequate funding, particularly in underdeveloped countries [31].

Management of plant disease outbreaks

To ensure the sustainable management of plant disease epidemics, it is imperative to comprehensively evaluate the impacts of management measures on financial, ecological, and sociological aspects from many perspectives. This necessitates a comprehensive understanding of the mechanisms that underlie disease epidemics, the operation of productive agroecosystems, and the roles that policies, both individual and collective, play in the management of disease epidemics. Plant disease control programs have the dual objective of safeguarding the natural environment and natural resources, while also striving to enhance food quality and productivity within the agricultural sector. In order to attain this goal, future studies in the ecological control of plant diseases should prioritize the following areas: The study examines the fundamentals of agronomic production and the evolutionary and epidemic patterns of plant diseases in various ecological systems. Agronomic productivity and crop health are significantly influenced by ecological concerns. (c) Analyzing the occurrence and control of plant disease outbreaks via a socio-economic lens. The integration of ecological perspectives with the control of significant agricultural diseases has been facilitated by technological advancements.

Conclusion

Gaining insight into the impact of climate change on agriculture is of utmost importance, particularly in terms of the occurrence and intensity of diseases and pests, as these elements significantly influence food security. Climate change has a significant influence on the quality and productivity of food crops, as well as the establishment and resurgence of new pests and diseases. Pests and emerging diseases have a deleterious impact on the social and political aspects of society. The understanding of the impacts of climate change on the emergence of new diseases and plant health remains limited. It is anticipated that climate change will exert an influence on the proliferation and maturation of infections, alter the resilience of host crops, and modify the physiological dynamics between pathogens and hosts. These effects may indirectly contribute to the escalation of plant disease severity. The reckless utilization of synthetic pesticides is indirectly facilitating the emergence of a novel cohort of resistant diseases and pests.

References:

[1] M. Sezonlin et al., "Phylogeography and population genetics of the maize stalk borer Busseola fusca (Lepidoptera, Noctuidae) in sub-Saharan Africa," Mol Ecol, vol. 15, no. 2, pp. 407–420, Feb. 2006, doi: 10.1111/j.1365-294x.2005.02761.x.

[2] J. Benjamin et al., "Cereal production in Africa: the threat of certain pests and weeds in a changing climate—a review," Agric. Food Secur. 2024 131, vol. 13, no. 1, pp. 1–16, Apr. 2024, doi: 10.1186/S40066-024-00470-8.

[3] M. K. Dhillon and D. P. Chaudhary, "Biochemical interactions for antibiosis mechanism of resistance to Chilo partellus (Swinhoe) in different maize types," Arthropod-Plant Interact, vol. 9, no. 4, pp. 373–382, Aug. 2015, doi: 10.1007/s11829-015-9374-z.

[4] P. A. Calatayud, B. P. Le Ru, J. van den Berg, and F. Schulthess, "Ecology of the African maize stalk borer, Busseola fusca (Lepidoptera: Noctuidae) with special reference to insect–plant interactions," Insects, vol. 5, no. 3, pp. 539–563, 2014, doi: 10.3390/insects5030539.

[5] R. Day et al., "Fall armyworm: impacts and implications for Africa," Outlooks Pest Manag, vol. 28, no. 5, pp. 196–201, Oct. 2017, doi: 10.1564/v28_oct_02.

[6] M. Snyman, A. K. Gupta, C. C. Bezuidenhout, S. Claassens, and J. van den Berg, "Gut microbiota of Busseola fusca (Lepidoptera: Noctuidae)," World J Microbiol Biotechnol, vol. 32, no. 7, p. 115, Jul. 2016, doi: 10.1007/s11274-016-2066-8.

[7] R. Kfir, W. A. Overholt, Z. R. Khan, and A. Polaszek, "Biology and management of economically important lepidopteran cereal stem borers in Africa," Annu Rev Entomol, vol. 47, no. 1, pp. 701–731, 2002, doi: 10.1146/annurev.ento.47.091201.145254.

[8] ákos Mesterházy, J. Oláh, and J. Popp, "Losses in the Grain Supply Chain: Causes and Solutions," Sustain. 2020, Vol. 12, Page 2342, vol. 12, no. 6, p. 2342, Mar. 2020, doi: 10.3390/SU12062342.

[9] T. Tufail et al., "Wheat straw: a natural remedy against different maladies," Food Sci Nutr, vol. 9, no. 4, pp. 2335–2344, Apr. 2021, doi: 10.1002/fsn3.2030.

[10] A. Dabija, M. E. Ciocan, A. Chetrariu, and G. G. Codină, "Maize and sorghum as raw materials for brewing, a review," Appl Sci, vol. 11, no. 7, p. 3139, Apr. 2021, doi: 10.3390/app11073139.

[11] C. Mbosso et al., "Fonio and Bambara groundnut value chains in Mali: issues, needs, and opportunities for their sustainable promotion," Sustainability, vol. 12, no. 11, p. 4766, Jun. 2020, doi: 10.3390/su12114766.

[12] S. Sharma, R. Kooner, and R. Arora, "Insect pests and crop losses," Breed. Insect Resist. Crop. Sustain. Agric., pp. 45–66, Oct. 2017, doi: 10.1007/978-981-10-6056-4_2.
[13] S. Fahad et al., "Bio-based integrated pest management in rice: An agro-ecosystems friendly approach for agricultural sustainability," J. Saudi Soc. Agric. Sci., vol. 20, no. 2, pp. 94–102, Feb. 2021, doi: 10.1016/J.JSSAS.2020.12.004.
[14] V. Pallas and J. A. García, "How do plant viruses induce disease? Interactions and interference with host components," J Gen Virol, vol. 92, no. 12, pp. 2691–2705, Dec. 2011, doi: 10.1099/vir.0.034603-0.
[15] Y. J. H. Galani, C. Orfila, and Y. Y. Gong, "A review of micronutrient deficiencies and analysis of maize contribution to nutrient requirements of women and children in Eastern and Southern Africa," Crit Rev Food Sci Nutr, vol. 62, no. 6, pp. 1568–1591, 2022, doi: 10.1080/10408398.2020.1844636.
[16] O. Ekpa, N. Palacios-Rojas, G. Kruseman, V. Fogliano, and A. R. Linnemann, "Sub-Saharan African maize-based foods—processing practices, challenges and opportunities," Food Rev Int, vol. 35, no. 7, pp. 609–639, Oct. 2019, doi: 10.1080/87559129.2019.1588290.
[17] M. Ronald, M. Charles, M. Stanford, and M. Eddie, "Predictions of the Striga scourge under new climate in southern Africa: a perspective," J Biol Sci, vol. 17, no. 5, pp. 194–201, 2017, doi: 10.3923/jbs.2017.194.201.
[18] Z. M. Hassan, N. A. Sebola, and M. Mabelebele, "The nutritional use of millet grain for food and feed: a review," Agric Food Secur, vol. 10, no. 1, p. 16, Dec. 2021, doi: 10.1186/s40066-020-00282-6.
[19] K. Ramesh, A. Matloob, F. Aslam, S. K. Florentine, and B. S. Chauhan, "Weeds in a changing climate: Vulnerabilities, consequences, and implications for future weed management," Front. Plant Sci., vol. 8, p. 95, Feb. 2017, doi: 10.3389/FPLS.2017.00095/BIBTEX.
[20] D. Ouattara, S. Nacro, K. Latévi, A. Coulibaly, and I. Somda, "Ecology of the African rice gall midge, Orseolia oryzivora (Diptera: Cecidomyiidae) in Western Burkina Faso, West Africa," Adv Entomol, vol. 08, no. 01, pp. 1–14, 2020, doi: 10.4236/ae.2020.81001.
[21] A. Galati, F. A. Oguntoyinbo, G. Moschetti, M. Crescimanno, and L. Settanni, "The cereal market and the role of fermentation in cereal-based food production in Africa," Food Rev Int, vol. 30, no. 4, pp. 317–337, 2014, doi: 10.1080/87559129.2014.929143.
[22] A. F. Lum, D. Chikoye, and S. O. Adesiyan, "Control of Imperata cylindrica (L.) Raeuschel (speargrass) with nicosulfuron and its effects on the growth, grain yield and food components of maize," Crop Prot, vol. 24, no. 1, pp. 41–47, Jan. 2005, doi: 10.1016/j.cropro.2004.06.006.
[23] L. H. Swanepoel et al., "A systematic review of rodent pest research in Afro-Malagasy small-holder farming systems: are we asking the right questions?," PLoS One, vol. 12, no. 3, Mar. 2017, doi: 10.1371/journal.pone.0174554.
[24] E. O. Ogah, J. A. Odebiyi, F. K. Ewete, A. A. Omoloye, and F. E. Nwilene, "Biology of the African rice gall midge Orseolia oryzivora (Diptera: Cecidomyiidae) and its incidence on wet-season rice in Nigeria," Int J Trop Insect Sci, vol. 30, no. 01, p. 32, Mar. 2010, doi: 10.1017/s1742758410000044.
[25] V. Sardana, G. Mahajan, K. Jabran, and B. S. Chauhan, "Role of competition in managing weeds: an introduction to the special issue," Crop Prot, vol. 95, pp. 1–7, May 2017, doi: 10.1016/j.cropro.2016.09.011.
[26] P. A. J. van Oort, F. Gou, T. J. Stomph, and W. van der Werf, "Effects of strip width on yields in relay-strip intercropping: a simulation study," Eur J Agron, vol. 112, Jan. 2020, doi: 10.1016/j.eja.2019.125936.
[27] F. E. Nwilene, K. F. Nwanze, and A. Youdeowei, "Impact of integrated pest

management on food and horticultural crops in Africa," Entomol Exp Appl, vol. 128, no. 3, pp. 355–363, Sep. 2008, doi: 10.1111/j.1570-7458.2008.00744.x.
[28] H. De Groote et al., "The potential of a herbicide resistant maize technology for Striga control in Africa," Agric Syst, vol. 97, no. 1–2, pp. 83–94, Apr. 2008, doi: 10.1016/j.agsy.2007.12.003.
[29] S. Skendžić, M. Zovko, I. P. Živković, V. Lešić, and D. Lemić, "The impact of climate change on agricultural insect pests," Insects, vol. 12, no. 5, p. 440, May 2021, doi: 10.3390/insects12050440.
[30] K. S. Poutanen et al., "Grains—a major source of sustainable protein for health," Nutr Rev, vol. 80, no. 6, pp. 1648–1663, Jun. 2022, doi: 10.1093/nutrit/nuab084.
[31] F. Shah and W. Wu, "Soil and Crop Management Strategies to Ensure Higher Crop Productivity within Sustainable Environments," Sustainability, vol. 11, no. 5, p. 1485, Mar. 2019, doi: 10.3390/SU11051485.