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Harnessing Medicinal Plants and Their By-products to Combat Fungal Pathogens in the Face of Climate Change: Implications for Global Food Security

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ABSTRACT

This study investigates the impacts of climate change (CC) on the emergence and proliferation of fungal pathogens, with a particular focus on global food security and the potential of medicinal plants and their by-products as sustainable mitigation strategies. Through a systematic literature review of articles published up to 2024, we analyze how CC exacerbates the spread and severity of fungal diseases in crops, leading to significant agricultural losses and threats to food availability. The findings highlight that, alongside conventional approaches such as genetic resistance and precision farming, bioactive compounds derived from medicinal plants and their by-products offer promising, eco-friendly alternatives for the management of fungal pathogens. Recent advances in the application of plant extracts, essential oils, and other natural products demonstrate their efficacy in suppressing fungal infections and enhancing crop resilience under changing climatic conditions. Furthermore, the integration of these natural solutions into sustainable agricultural practices can reduce reliance on synthetic fungicides, thereby supporting ecosystem preservation. Policy recommendations are proposed to promote research, development, and adoption of medicinal plant-based interventions as part of comprehensive strategies to safeguard food security in the context of CC. The study underscores the urgent need for interdisciplinary and innovative approaches, including the utilization of medicinal plants and their derivatives, to address the rising challenges posed by fungal pathogens in a warming world.

Keywords: By-products, Climate change, Food security, Fungal pathogens, Medicinal plants, Sustainable agriculture

INTRODUCTION

The rising tide of fungal pathogens in an era of climate change (CC) poses a significant and multifaceted threat to global food security. The severity and scope of fungal diseases affecting crops have been rising, resulting in substantial losses in crop production worldwide. These fungal infections damage not only vital calorie crops such as rice, wheat, maize, and soybeans, but also economically important commodity crops like bananas, coffee, and barley. Despite extensive efforts to manage these infections with synthetic antifungals, a sizeable portion of crops are lost each year to fungal diseases, both before and after harvest. The problem is further exacerbated by the adaptability of fungi, their capacity to survive in soil for long periods, and the rapid emergence of antifungal resistance [1].

Recent outbreaks, such as Fusarium wilt Tropical Race 4 (TR4) devastating banana plantations in Southeast Asia and Latin America, coffee leaf rust (*Hemileia vastatrix*) causing billions of dollars in losses in Central America, and rice blast (*Magnaporthe oryzae*) threatening harvests in sub-Saharan Africa, illustrate the scale and specificity of the fungal threat. These examples demonstrate how fungal pathogens, intensified by CC, are already disrupting food systems across diverse regions [2-4].

CC, driven by both natural and anthropogenic factors such as greenhouse gas emissions and ozone depletion, has led to a measurable rise in global temperatures—about 0.6°C in the twentieth century and projected increases of 0.1–2°C per decade in the future. Such shifts are expected to significantly impact biodiversity, agricultural output, and food security. Changes in temperature, humidity, precipitation, and seasonal patterns directly influence the distribution, incidence, and severity of fungal diseases. Fungal pathogens are increasingly moving toward the poles as global warming accelerates, exposing new regions to severe crop losses [5, 6].

With 10–23% of world crops lost to fungal diseases annually, and an additional 10–20% lost post-harvest, fungal pathogens represent a serious danger to global food security [7]. Airborne spores can travel across borders and persist in soil for decades, making eradication extremely challenging. The overuse of single-target fungicides, monoculture cultivation, and changes in food systems have further heightened the risks by promoting the spread of resistant fungal strains [8].

Given the limitations of current chemical control methods and the urgent need for sustainable solutions, medicinal plants and their by-products have emerged as promising resources for the development of novel antifungal strategies. Bioactive compounds derived from medicinal plants—including essential oils, extracts, and secondary metabolites—have demonstrated significant antifungal properties against a wide spectrum of phytopathogenic fungi. These natural products offer eco-friendly alternatives to synthetic fungicides, with the potential to reduce environmental impact, mitigate the spread of resistance, and support ecosystem health [9, 10].

The integration of medicinal plant-based solutions into crop protection strategies aligns with the principles of sustainable agriculture and ecosystem preservation. Recent advances in biotechnology and phytochemistry have enabled the identification and application of potent antifungal agents from medicinal plants, which can be incorporated into integrated disease management frameworks. For instance, plant extracts and essential oils from species such as *Allium sativum* (garlic) [11], *Thymus vulgaris* (thyme) [12], and *Azadirachta indica* (neem) [13] have shown efficacy in suppressing major crop pathogens.

Furthermore, the use of medicinal plants and their by-products can contribute to the resilience of agroecosystems under CC by enhancing crop resistance, reducing reliance on chemical inputs, and promoting biodiversity. This approach is particularly relevant as CC continues to alter the epidemiology of fungal diseases, necessitating adaptive and innovative management strategies.

Therefore, this study systematically reviews the impacts of CC on fungal pathogens and global food security, with a particular emphasis on the role of medicinal plants and their by-products as sustainable mitigation strategies. By synthesizing evidence from recent literature, the study aims to inform future research directions and policy development for the integration of plant-based solutions into comprehensive fungal disease management, ultimately contributing to the safeguarding of food security and ecosystem health in a changing climate.

MATERIAL AND METHODS

A systematic literature search was conducted using specific keywords, including "fungal pathogens," "climate change," "global food security," and "ecosystem preservation." Boolean operators (AND, OR) were applied to combine these terms, ensuring a focused and comprehensive retrieval of relevant studies. The search was limited to articles published in English between 2005 and 2024 to capture the most current and pertinent data. The databases Scopus, Web of Science, and PubMed were selected due to their extensive coverage of multidisciplinary scientific literature.

To provide practical insights, selected case studies illustrating the impact of fungal pathogens on food security and ecosystem stability across various regions and species were included. These case studies highlight crop losses, economic consequences, and social implications associated with fungal diseases influenced by CC. The collected data were critically evaluated with emphasis on the role of CC in modulating fungal pathogen dynamics.

Inclusion and Exclusion Criteria

Specific criteria were established to ensure the selection of relevant and high-quality articles. Inclusion criteria required that studies address the relationships among fungal pathogens, CC, food security, and ecosystem preservation. Only peer-reviewed articles published in scientific journals were considered to guarantee the credibility of the sources.

Exclusion criteria encompassed articles that did not directly pertain to the study objectives, such as those focusing exclusively on fungal pathogens outside agricultural or ecological contexts or those lacking consideration of CC. Furthermore, articles published in languages other than English were excluded due to resource limitations.

Climate and Ecological Models

Modeling and simulation techniques were employed to assess the potential spread of fungal pathogens under various CC scenarios. Climate models, biosphere models, and climate projections incorporating historical data and relevant parameters were utilized to generate robust and insightful results. This approach enabled the evaluation of potential risks posed by fungal pathogens to food security and biodiversity in the context of changing climatic conditions.

Mitigation Strategy Assessment

CC necessitates the development of novel genetic and biological approaches to prevent the emergence of harmful fungal mutations. This study reviewed key strategies, including genetic resistance, biocontrol, precision agriculture, ecological restoration, and sustainable farming practices, to evaluate their potential effectiveness in mitigating the impact of fungal diseases. The assessment aimed to identify approaches that could sustainably reduce crop losses and preserve ecosystem health under changing environmental conditions.

Peer Review Process

Policy recommendations were formulated based on the comprehensive review and analysis presented in this study. These recommendations focus on addressing fungal disease challenges in the context of CC, including the promotion of sustainable agricultural practices, enhancement of biodiversity conservation programs, and ensuring global food security amid the emergence of fungal pathogens. The findings and recommendations were subjected to a rigorous peer review process involving experts in the relevant fields. Feedback from reviewers was incorporated to improve the accuracy, reliability, and scientific rigor of the study, thereby ensuring that the conclusions are evidence-based and robust.

Emission Scenarios

Well-established scientific literature and widely accepted CC projections formed the basis for selecting emission scenarios used to estimate future impacts. These scenarios were chosen to represent a range of potential future climatic conditions and their associated effects on food security and the prevalence of fungal diseases.

RESULTS AND DISCUSSION

Climate Change Overview

CC and environmental degradation present interconnected threats to the planet's future. These challenges have largely arisen from the increasing demands of a growing global population, often driven by rapid development that overlooks abrupt shifts in natural systems and their consequences. Climate is commonly defined as the long-term average of meteorological variables—such as temperature, precipitation, and wind—over a period of approximately 30 years, including statistical measures like means, variances, and the likelihood of extreme events [14].

Climate variability refers to natural fluctuations in climate parameters over time, despite the absence of a universally accepted definition. It is typically characterized by deviations in meteorological data from long-term averages during specific intervals (e.g., months, seasons, or years). Meteorologists and climatologists generally interpret climate variability as annual or shorter-term fluctuations around a mean climatic state. Importantly, human activities and climate variability often interact, amplifying environmental impacts. For example, the scale and persistence of wildfires during El Niño events in southern Sumatra, Kalimantan, and Brazil's peat-swamp forests demonstrate this complex interplay [15].

In 2022, the global average temperature was approximately 0.86°C higher than the 20th-century average of 13.9°C. Notably, global temperatures have exceeded this average for 46 consecutive years since 1977 (Fig. 1). Additionally, significant shifts in global precipitation patterns have been observed. The effects of CC are increasingly evident worldwide through extreme weather events and related disasters, including wildfires in Australia and the United States, accelerated melting of polar ice sheets, rising sea levels, altered river flow regimes, intense rainfall in China, droughts in South Africa, and species extinctions [16].

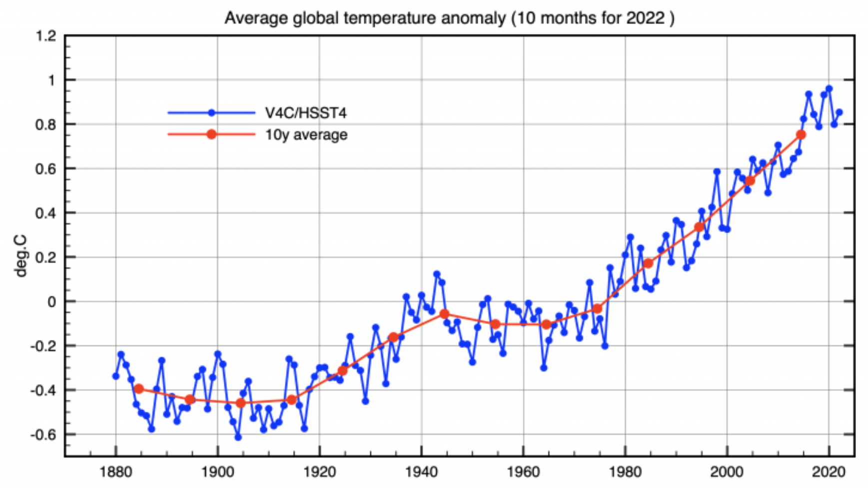

Fig. 1 Average global temperature anomaly (10 months for 2022)

Impact of Climate Warming on Pathogen Population Dynamics

Climate warming significantly influences the population dynamics of pathogens, affecting factors such as overwintering survival, population growth rates, and the number of generations in polycyclic species. For example, lower diurnal temperatures can shorten the latency period of *H. vastatrix*, the causal agent of coffee rust, thereby accelerating rust epidemics in Central America. Elevated temperatures reduce the pathogen's incubation time, leading to increased abundance during the growing season [5].

Higher temperatures and humidity levels have been linked to increased severity of diseases such as oilseed rape phoma stem canker and potato late blight caused by *Phytophthora infestans*. Furthermore, elevated average winter temperatures have contributed to a greater incidence of *Phytophthora* spp. infections in American chestnut trees, resulting in widespread mortality across North America.

Fluctuations in global temperatures can markedly affect the prevalence of pathogens in both natural and agricultural ecosystems, increasing the risk of exposure to novel pests and diseases. Many soil-borne fungal diseases are projected to become more widespread due to global warming, with significant implications for primary productivity. Additionally, viruses currently limited by overwintering constraints may expand their range as temperatures rise [17] (Table 1 and Fig. 2).

Table 1 Examples of pathogens impacted by climate change

Pathogen	Geographic range shift	Transmission dynamics	Seasonality shift
Mosquito-borne diseases (e.g., Dengue fever, Malaria)	Expanding to higher latitudes	Increased transmission due to longer breeding seasons	Longer transmission seasons
Waterborne diseases (e.g., Cholera, *Escherichia coli*)	Increased risk due to flooding and extreme weather events	Contamination of water sources	Year-round outbreaks
Tick-borne diseases (e.g., Lyme disease)	Expanding geographic range of ticks	Increased tick activity due to warmer temperatures	Longer transmission seasons
Fusarium spp.	Expanding into crops as temperatures and moisture levels change	Enhanced growth and mycotoxin production in warmer and wetter conditions	Extended disease development periods and increased crop susceptibility
Batrachochytrium dendrobatidis	Shifting to higher elevations and cooler habitats due to rising temperatures	Altered pathogen-host interactions and increased amphibian mortality	Changes in breeding and hibernation patterns of amphibians

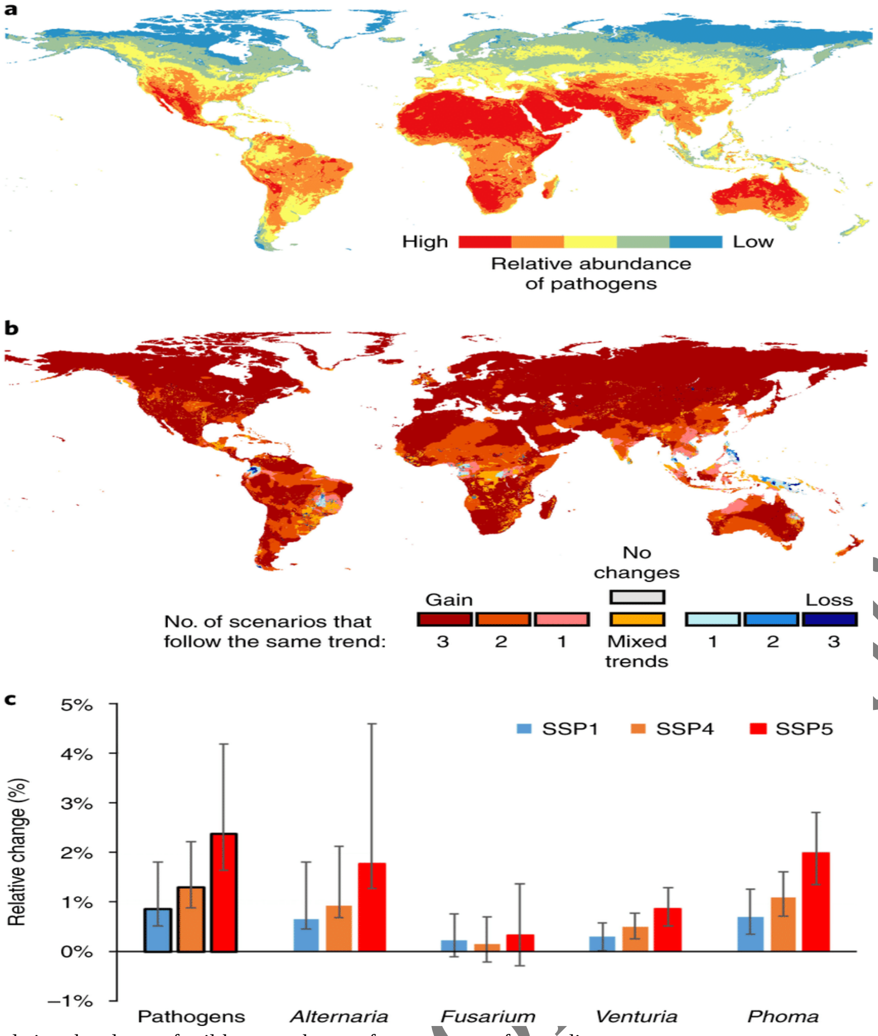

Fig. 2 Projected shifts in relative abundance of soil-borne pathogens from current to future climates.

Influence of Land Use and Greenhouse Gas Emissions

Human activities, such as urbanization and deforestation, have altered land use and the Earth's surface albedo, affecting heat absorption. Vegetated areas absorb more solar energy than bare soil or urban surfaces, contributing to warming. Moreover, anthropogenic emissions of greenhouse gases (GHGs)—including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), hydrochlorofluorocarbons (HCFCs), and chlorofluorocarbons (CFCs)—trap longwave radiation, leading to global temperature increases. While natural processes like chemical weathering have historically regulated atmospheric CO_2 over millions of years, current concentrations have surged to 417.2 ppm in 2022, representing a 51% increase over pre-industrial levels [18].

Effects of Elevated CO_2 on Plant-Pathogen Interactions

Elevated CO_2 levels have complex, host- and pathogen-dependent effects on plant diseases. Without significant reductions in carbon emissions, global temperatures and the impacts of CC are expected to worsen. Fungal pathogens are likely to maintain or expand their influence on crops and native plants through range shifts and long-distance dispersal. For instance, increased CO_2 has been shown to exacerbate head blight and blotch in wheat, as well as powdery mildew on cucurbits, while reducing downy mildew susceptibility in soybeans. Changes in leaf surface properties have decreased brown spot disease in maple trees but increased rust disease in aspen [19].

Atmospheric CO_2 also modulates plant-pathogen interactions by influencing hormone levels and immune responses. Enhanced basal expression of jasmonic acid-responsive genes improves pathogen resistance, whereas reduced expression diminishes it. Complex biotic interactions, such as those involving wheat, barley yellow dwarf virus (BYDV), and its aphid vector *Rhopalosiphum padi*, are similarly affected by elevated CO_2. However, a comprehensive framework to predict and understand these multifaceted impacts remains lacking (Fig. 3).

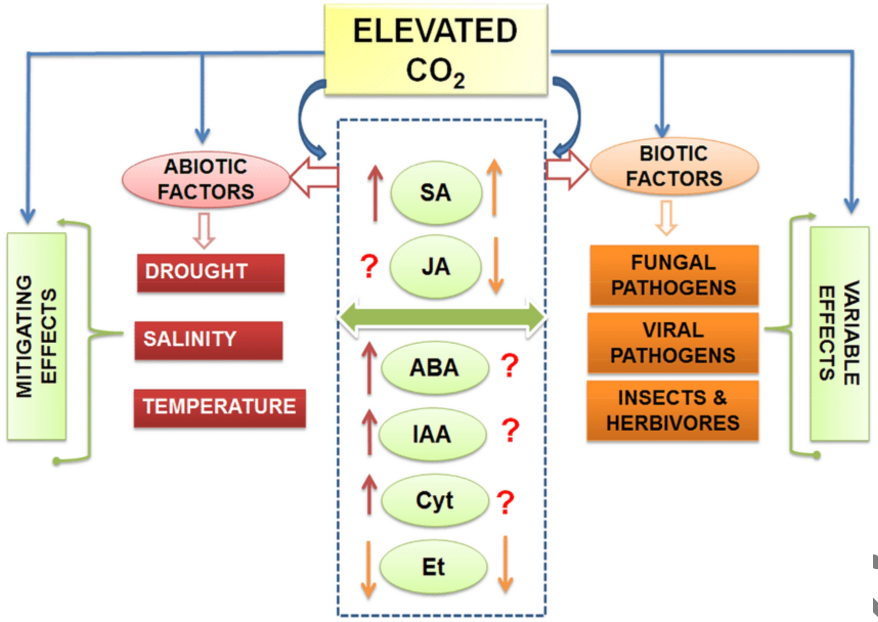

Fig. 3 The interaction between increased CO_2 levels, climate change, and pathogen behavior.

Climate Change Impacts on Species and Ecosystems

CC affects species and ecosystem composition both directly—through increased temperatures, altered precipitation patterns, water temperature changes, and sea-level rise—and indirectly, by modifying the frequency and extent of disturbances such as wildfires. Species in terrestrial and marine environments are vulnerable to these changes, often facing local extinction and migration to new habitats. For example, over the past 50 years, habitat degradation, loss, and fragmentation have increased the vulnerability of high-diversity ecosystems in the Melanesian Islands, which harbor over half of the world's coral species and many unique terrestrial ecosystems. Furthermore, CC and land-use practices have altered the type, severity, and frequency of disturbances, including blowdowns, fires, and droughts [20]. These changes significantly impact species composition and ecosystem productivity, especially in high-latitude and high-elevation regions.

Climate Change and the Emergence of Fungal Pathogens

The rise of fungal diseases is closely linked to CC and represents a serious threat to public health and global food security. As temperatures increase, fungi adapt by becoming more heat-tolerant and potentially more virulent. This adaptation facilitates their geographic expansion and infection of new hosts, leading to the emergence of fungal diseases in previously unaffected regions. CC influences fungal infections by expanding pathogen ranges, accelerating disease spread to non-endemic areas, and triggering outbreaks following natural disasters. Beyond crops, some fungi have evolved to overcome mammalian thermal barriers, posing risks to human and animal health in warmer climates [21].

Environmental instability caused by CC has intensified fungal pathogen severity. Altered rainfall patterns lead to droughts and floods, while increased frequency and intensity of tropical cyclones and tornadoes have far-reaching health impacts. The link between fungal diseases and natural disasters is increasingly recognized; Benedict and Park [22] provide a comprehensive review of this relationship. Displaced fungal species can cause infections in atypical regions, as exemplified by the 1977 dust storm in California's San Joaquin Valley, which dispersed Coccidioides immitis from Bakersfield to Sacramento, causing over 100 cases of coccidioidomycosis.

Climate models predict that the range of Coccidioides may expand from 12 to 17 U.S. states, with a 50% increase in infections. Following the 2011 Joplin, Missouri storm, a cluster of mucormycosis cases was linked to the thermotolerant saprotroph *Apophysomyces trapeziformis*, a rare pathogen [22]. CC-related disruptions may also increase the prevalence or range of other soil-borne fungal diseases, including Talaromyces marneffei, Blastomyces, Histoplasma, and Paracoccidioides, which are challenging to diagnose and treat outside their typical ranges.

Several fungal species have emerged or increased in prominence due to CC, including Candida auris, *Batrachochytrium dendrobatidis*, *Cryptococcus deuterogattii*, *Puccinia striiformis* (rust fungus), Fusarium head blight, and *Fusarium graminearum*. Since its discovery in 2009 from an ear infection in Japan, Candida auris has been reported worldwide and is considered the first novel fungal pathogen potentially linked to CC. Alternative hypotheses suggest its emergence relates to aquaculture expansion and environmental fungicide pollution [23].

B. dendrobatidis is responsible for the greatest recorded loss of amphibian diversity, devastating populations across Australia, the Americas, and Africa since 1998. IPCC projections indicate further spread, especially in northern hemisphere high-latitude regions. The fungus *C. deuterogattii* (formerly *Cryptococcus gattii* VGII) has caused hundreds of infections in humans and animals in temperate western Canada and the Pacific Northwest, with its expansion linked to human activities and CC [24].

P. striiformis, the rust fungus, causes one of the most destructive wheat diseases globally. Since 2000, more aggressive and thermotolerant strains (Pst1, Pst2, and "Warrier") have emerged, causing significant outbreaks in Australia and the south-central United States. Members of the *F. graminearum* species complex cause Fusarium head blight (FHB), a severe disease of wheat and cereals that can reduce yields by up to 75%, especially in warm, humid years [25].

FHB poses a serious threat to cereal production and food security. Over the past two decades, *F. graminearum*, which favors warmer, humid conditions, has displaced *Fusarium culmorum*, associated with cooler, wetter climates, in some temperate regions. The increasing aggressiveness and mycotoxin production of *F. graminearum* are expected to exacerbate FHB severity and its adverse effects on human and animal health [26].

The Fungal Challenge to Global Food Security

Since the mid-20th century, fungal crop diseases have become more severe and widespread, posing a significant threat to global food security. Plant-fungal infections adversely affect ecosystems and agriculture worldwide, often causing substantial yield losses and economic damage [27]. Pathogens such as *Phytophthora* spp., powdery mildew, and rusts infect a wide range of crops, reducing quality and productivity, thereby threatening the livelihoods of millions and undermining food security [28].

In natural ecosystems, fungal diseases disrupt ecological balance and cause declines in native plant populations. CC and globalization are expected to increase the prevalence and impact of these diseases, altering pathogen assemblages and shifting species distributions, particularly in high-latitude regions of China, Europe, and the United States [29, 30].

The "disease triangle" concept highlights the interaction between susceptible hosts, virulent pathogens, and conducive environments necessary for disease development [31]. Environmental factors such as temperature, humidity, sunlight, soil fertility, and atmospheric gases (e.g., CO_2, methane, ozone) significantly influence disease dynamics [32].

Certain fungi, such as *M. oryzae* (rice blast pathogen), can cause yield losses up to 100% [33]. Mycotoxin contamination from fungal-infected animal feed reduces milk production and directly affects livestock health [34]. Globally, phytopathogenic fungi cause economic losses estimated in the hundreds of billions of US dollars annually [35].

Post-harvest losses due to fungi exceed 10%, affecting a wide range of foods, including fruits, dairy products, and beverages [36]. Some spoilage yeasts exhibit resistance to preservatives and can survive harsh storage conditions, posing ongoing challenges. Additionally, mycotoxin-producing fungi threaten human health through contaminated food [37].

Modern agricultural practices, including monoculture cropping and reliance on single-target fungicides and limited resistance genes, have accelerated the emergence of virulent and fungicide-resistant fungal strains [36]. The rapid life cycles and genetic plasticity of fungi facilitate their adaptation and evolution, intensifying the challenge to crop protection [7] (Table 2).

Table 2 Impact of climate change on fungal diseases and crop losses

Climate changes	Fungal diseases	Crop losses
Increased temperature	Fones *et al.* [7] discovered that higher temperatures have caused a strong surge in the range of Mycosphaerella graminicola, a loss-contaminating pathogen, resulting in severe and devastating losses in wheat production. Elevated temperature awakens and promotes the host *Fusarium graminearum* fungal pathogen, resulting in greater mycotoxin infestation in corn [38].	As temperatures rise, the occurrence and intensity of some fungal diseases are increasing (e.g., rusts, powdery mildews, and downy mildews [39]).
Changes in precipitation	With higher temperatures, different rainfall patterns can also promote the spread of the frog's fungal pathogen, *Phytophthora cinnamomi* [16]. The results showed that an increase in rainfall and long intervals of saturation created the perfect settings for those pathogens to thrive and attain high incidence rates in already vulnerable plants.	Gunawardena *et al*. [40] demonstrated that heavy rainfall and waterlogging can lead to root rot and other soil-borne fungal diseases, consequently resulting in substantial cereal yield losses exceeding previously recorded levels.
Changes in CO_2 levels	Keswani *et al*. [41] had studied experimentally how increased CO_2 levels heightened the rice blast severity brought about by the fungal agent *Magnaporthe oryzae*. They learned that higher CO_2 levels favored the development and sporulation of disease, which grew into high plant disease rates and more crop losses.	According to Sanchez-Lucas *et al.* [42], oak seedlings (*Quercus robur*) grown under elevated CO_2 (~1000 ppm) conditions exhibited increased susceptibility to powdery mildew caused by *Erysiphe alphitoides*, compared to those grown at ambient CO_2 (~400 ppm).
Extreme weather events	West *et al*. [43] studied the extent to which the attack of severe storms throws the wheat pathogen *Zymoseptoria tritici* into the air, thus destroying the genetic diversity of the disease. The researchers determined that storm activity was the pathogen's natural dispersal channel and a powerful force driving disease transmission, resulting in crop damage.	Guche *et al.* [44] studied the impact of heatwaves on grapevine powdery mildew caused by *Erysiphe necator*. They discovered that heatwaves made disease worse and reduced grape yield, highlighting how vulnerable vineyards are to extreme temperatures.

Potential Mitigation Strategies

Several strategies have been proposed in the literature to mitigate fungal infections across diverse environments. Table 3 provides a summary of the principal mitigation approaches reported in recent studies.

Table 3 Mitigation strategies of fungal infections and their outcomes

Mitigation strategy	literature	Outcomes
Crop rotation	Turkington and Xi [45]	Crop rotation reduced the incidence and severity of wheat leaf rust (*Puccinia triticina*) by disrupting the disease cycle and reducing inoculum buildup.
	Bekele and Dawit [46]	Crop rotation with non-host crops reduced the severity and spread of Fusarium head blight (*Fusarium graminearum*) in wheat, resulting in decreased mycotoxin contamination.

Fungicide application	Bonfada *et al.* [47]	Fungicide treatments successfully controlled Fusarium head blight (*Fusarium graminearum*) in wheat, resulting in reduced mycotoxin contamination and improved grain quality.
	Klocke *et al.* [48]	Fungicide applications effectively controlled powdery mildew (*Blumeria graminis* f. sp. *tritici*) in wheat, resulting in reduced disease severity and improved yield.
Natural product inhibitors and their sources (NPs)	Alin *et al.* [49]	The garlic extract exhibited strong antifungal activity against *Fusarium oxysporum*, *Rhizoctonia solani*, and other plant pathogenic fungi. It showed potential as a natural alternative to synthetic fungicides.
	Ahmed *et al.* [50]	The essential oil exhibited strong antifungal activity against various plant pathogenic fungi, including *Fusarium oxysporum* and *Alternaria solani*. It showed potential as a natural fungicide for disease control.
Biological control	Sood *et al*. [51]	Trichoderma-based biocontrol agents effectively suppressed the growth and development of Fusarium wilt (*Fusarium oxysporum*) in tomato plants, leading to reduced disease incidence and improved plant health.
	Jaisani and Gohel [52]	Pseudomonas fluorescens-based biocontrol formulations effectively controlled charcoal rot (*Macrophomina phaseolina*) in soybean, reducing disease incidence and promoting plant growth.
Cultural practices	Kruidhof and Elmer [53]	Adjusting plant spacing in cucumber cultivation effectively reduced the incidence and severity of powdery mildew (*Podosphaera xanthii*) by improving air circulation and reducing humidity levels, resulting in improved disease management.
	Gramaje *et al.* [54]	Pruning grapevines during the dormant season (winter) reduced the incidence and severity of grapevine trunk diseases (e.g., Esca) by minimizing the access points for fungal infection, leading to improved disease management.

Fungicides and the Way Forward

Fungi represent one of the most serious biotic threats to global food security. Fungicides remain the most potent and immediate tool to combat this challenge. However, the increasing development of fungicide resistance underscores the urgent need for discovering and developing new antifungal agents. Enhancing disease durability is essential for achieving sustainability within the food production system. Current disease management strategies include the cultivation of crops with inbred resistance genes and the widespread application of antifungals [55]. Additionally, there is growing interest in genetically modified disease-resistant cultivars, RNA interference (RNAi)-based control methods, and microbial biological control agents (MBCAs) to protect crops from fungal infections [56].

According to Kohl *et al.* [56], MBCAs suppress disease by acting as live antagonists to plant pathogens, producing antimicrobial compounds, or by stimulating plant defense mechanisms. Nevertheless, fungicides continue to be the cornerstone of effective crop disease control.

An economic evaluation of fungicide use against *Septoria tritici* blotch (STB) in wheat, caused by *Zymoseptoria tritici*, in the United Kingdom highlights their value. Without fungicide treatment, STB can cause yield losses of approximately 20%. Implementation of control measures reduces losses to 5–10% [57]. Although fungicide applications incur costs, their benefits translate into increased wheat yields of up to 2.5 tons per hectare. The global fungicide market, valued at approximately 13.4 billion USD in 2019, is projected to grow at an annual rate of 4.7% over the next seven years, reflecting heavy reliance on these chemicals [58].

The use of fungicide combinations is widely recommended [59]. For example, most commercial formulations from Bayer and Syngenta combine two fungicides with different modes of action, working synergistically to inhibit fungal growth. Such combinations allow for lower doses of each fungicide, potentially reducing costs and environmental impacts. Given the continued importance of chemical fungicides in crop protection [60], exploiting fungicide synergies is a promising strategy to reduce chemical inputs while maintaining efficacy. However, this approach requires caution, as resistance to one component can compromise the effectiveness of the entire mixture if the other is applied at suboptimal concentrations.

Fungicides typically target key fungal processes such as plasma membrane integrity, microtubule cytoskeleton dynamics, and mitochondrial respiration. Azole fungicides, the most common single-target site agents, inhibit ergosterol biosynthesis, disrupting membrane function. Strobilurins and succinate dehydrogenase inhibitors (SDHIs) interfere with mitochondrial electron transport. Together, azoles, strobilurins, and SDHIs constitute approximately 77% of the fungicide market [55]. While single-site fungicides are effective, their specificity renders them vulnerable to resistance development, often due to point mutations in target enzymes after several years of use.

The emergence of drug-resistant strains of Aspergillus fumigatus illustrates the crossover of resistance from agricultural to clinical settings, posing challenges for both crop protection and human health [36]. Continuous innovation in antifungal development is essential to outpace fungal adaptation. Ideal new fungicides should: (i) be effective against a broad spectrum of key pathogens; (ii) target multiple essential fungal processes to reduce resistance risk; (iii) exhibit low toxicity to non-target organisms, including humans and beneficial species; and (iv) activate plant defense pathways to prime resistance [61]. Agrochemical companies have played a pivotal role in fungicide development, often optimizing lead compounds to enhance efficacy and durability [62].

RNA-based fungicides offer a novel, fungi-specific approach that addresses environmental and toxicity concerns associated with chemical fungicides. RNA interference (RNAi) enables the production of double-stranded RNAs (dsRNAs) or small RNAs (sRNAs) that specifically silence virulence-related genes in fungal pathogens [31]. Delivery methods include direct application of dsRNAs or sRNAs to plants or transgenic expression, though the latter raises regulatory and public acceptance challenges. Spray-induced gene silencing has demonstrated efficacy against pathogens such as *F. graminearum*, *Botrytis cinerea*, and *Sclerotinia sclerotiorum* [63]. Evidence suggests that these RNAs can be absorbed directly by fungal cells or accumulate within plant tissues prior to uptake.

Natural Product Inhibitors and Their Sources

Natural products (NPs) provide valuable opportunities for discovering novel fungal inhibitors, with several advantages discussed later in this article. NPs with inherent fungicidal properties have been isolated from diverse sources, including marine organisms, plants, and mammals [64]. Chemical modification of promising NPs can enhance their efficacy, although such derivatives may require regulatory registration and evaluation. For example, Luotonin A, a quinoline alkaloid extracted from plants, has demonstrated inhibitory activity against various fungal phytopathogens. Recent studies on synthesized analogues of Luotonin A revealed antifungal activity comparable to that of the widely used fungicide azoxystrobin [65].

Another promising approach involves biofumigation, which utilizes bioactive compounds released during the decomposition of freshly harvested cover crops incorporated into the soil. This process generates isothiocyanates and glucosinolate compounds that effectively sanitize the soil and exert antifungal effects. Mulch treatments composed of cover crops such as white mustard, Indian mustard, and berseem clover have been shown to reduce infection rates, lower mycotoxin contamination, and increase grain yield in wheat by controlling the pathogen *F. graminearum* through biofumigation [66].

Modern Agriculture, Pathogens, and Future Mitigation Strategies for Sustainable Land Management

Pathogens are highly sensitive to land management practices. For example, fertilization with nitrogen and phosphate in grassland soils across four continents has been shown to consistently favor harmful fungi over beneficial mutualistic species. Traditional disease management relies heavily on chemical fungicides and the deployment of disease-resistant cultivars to suppress pathogens. However, these strategies may have reached their limits, as evidenced by the increasing resistance of soil-borne fungal pathogens to fungicides. Currently, effective chemical controls are lacking for many diseases caused by common soil-borne pathogens such as *Fusarium* and *Verticillium* spp. [67].

Moreover, the widespread use of chemical controls is becoming increasingly unacceptable due to their adverse effects on biodiversity—including beneficial microorganisms—soil health, food quality (due to chemical residues), and ultimately human health. This shift is driven by both regulatory policies, such as the European Union’s Green Deal, aiming for a 50% reduction in chemical pesticide use by 2030, and growing consumer demand for safer food production. While the development of environmentally friendly agrochemicals is a priority, it remains costly and time-consuming. Furthermore, medium- and long-term studies have revealed that several chemicals previously considered environmentally benign, including neonicotinoids and organophosphates, can have detrimental ecological effects [68].

Pathogen control in natural ecosystems employs multiple strategies at various levels. For instance, maintaining species diversity in forest environments can significantly reduce the risk of invasion by generalist plant pathogens. Similar principles can be applied in agroecosystems through the promotion of agrobiodiversity, intercropping, and regular crop rotations to enhance resilience. However, fallow and rotational farming, while historically effective, are becoming less economically viable and less effective as pathogens adapt. For example, Australian cotton farms once controlled Fusarium and Verticillium wilt through four to five non-cotton crop rotations; today, five to seven rotations are required to achieve similar disease suppression [29].

Current approaches to these challenges include breeding crops with disease resistance genes—a process requiring 10–20 years to develop new resistant cultivars—as well as transgenic cloning or gene editing, which can be accomplished more rapidly but raises ethical and regulatory concerns. Additionally, rapidly evolving pathogens can overcome plant gene-mediated resistance in some cases [65]. Biological control methods, while promising, face challenges related to inconsistent efficacy and implementation difficulties.

To move beyond the limitations of current disease management paradigms, innovative strategies are needed. Future effective tools may emerge from approaches that leverage ecological and evolutionary principles, alongside other nature-based solutions, to sustainably manage plant diseases.

CONCLUSION

The increasing prevalence of fungal pathogens in the context of CC represents a profound threat to global food security and ecosystem integrity. This review has highlighted the multifaceted ways in which CC drives the proliferation and geographic expansion of fungal pathogens, thereby undermining agricultural productivity and food availability. Rising temperatures have facilitated the emergence of thermotolerant fungal species, some of which pose novel risks to human health. As the climate warms, fungal pathogens adapt by enhancing their virulence and extending their range, introducing health challenges to regions previously unaffected. Addressing the impacts of CC on fungal ecosystems and controlling the spread of invasive fungal diseases constitute complex, global challenges that demand coordinated efforts from policymakers and stakeholders. A critical policy imperative is the advancement of sustainable agricultural practices aimed at bolstering crop resilience and safeguarding food security against the escalating threat of fungal pathogens.

REFERENCES

1. Misiou O., Koutsoumanis K. Climate change and its implications for food safety and spoilage. Trends in Food Science and Technology. 2022;126:142-152.
2. Ploetz R.C. Management of Fusarium wilt of banana: A review with special reference to tropical race 4. Crop Protection. 2015;73:7-15.
3. Avelino J., Cristancho M., Georgiou S., Imbach P., Aguilar L., Bornemann G., Läderach P., Anzueto F., Hruska A.J., Morales C. The coffee rust crises in Colombia and Central America (2008-2013): Impacts, plausible causes and proposed solutions. Food Security. 2015;7:303-321.
4. Singh R.P., Hodson D.P., Huerta-Espino J., Jin Y., Bhavani S., Njau P., Herrera-Foessel S., Singh P.K., Singh S., Govindan V. The emergence of Ug99 races of the stem rust fungus is a threat to world wheat production. Annual Review of Phytopathology. 2011;49(1):465-481.
5. Singh B.K., Delgado-Baquerizo M., Egidi E., Guirado E., Leach J.E., Liu H., Trivedi P. Climate change impacts on plant pathogens, food security and paths forward. Nature Reviews Microbiology. 2023;21(10):640-656.
6. Yadav N., Upadhyay R.K. Global effect of climate change on seasonal cycles, vector population and rising challenges of communicable diseases: A review. Journal of Atmospheric Science Research. 2023;6(1):21-59.

7. Fones H.N., Bebber D.P., Chaloner T.M., Kay W.T., Steinberg G., Gurr S.J. Threats to global food security from emerging fungal and oomycete crop pathogens. Nature Food. 2020;1(6):332-342.
8. Hendrickson J.A., Hu C., Aitken S.L., Beyda N. Antifungal resistance: A concerning trend for the present and future. Current Infectious Disease Reports. 2019;21:47.
9. Nazzaro F., Fratianni F., Coppola R., De Feo V. Essential oils and antifungal activity. Pharmaceuticals. 2017;10(4):86.
10. Deresa E.M., Diriba T.F. Phytochemicals as alternative fungicides for controlling plant diseases: A comprehensive review of their efficacy, commercial representatives, advantages, challenges for adoption, and possible solutions. Heliyon. 2023;9(3).
11. Hayat S., Ahmad A., Ahmad H., Hayat K., Khan M.A., Runan T. Garlic, from medicinal herb to possible plant bioprotectant: A review. Scientia Horticulturae. 2022;304:111296.
12. Parikh L., Agindotan B.O., Burrows M.E. Antifungal activity of plant-derived essential oils on pathogens of pulse crops. Plant Disease. 2021;105(6):1692-1701.
13. Wylie M.R., Merrell D.S. The antimicrobial potential of the neem tree *Azadirachta indica*. Frontiers in Pharmacology. 2022;13:891535.
14. Dietz T., Shwom R.L., Whitley C.T. Climate change and society. Annual Review of Sociology. 2020;46:135-158.
15. Vetrita Y., Cochrane M.A. Fire frequency and related land-use and land-cover changes in Indonesia's peatlands. Remote Sensing. 2019;12(1):5.
16. Garrett K.A., Nita M., De Wolf E.D., Esker P.D., Gomez-Montano L., Sparks A.H. Plant pathogens as indicators of climate change. In Climate change. Elsevier. 2021.
17. Hunjan M.S., Lore J.S. Climate change: Impact on plant pathogens, diseases, and their management. In: Jabran K., Florentine S., Chauhan B. (eds) Crop Protection Under Changing Climate. Springer, Cham. 2020.
18. Delgado-Baquerizo M., Guerra C.A., Cano-Díaz C., Egidi E., Wang J.T., Eisenhauer N., Singh B.K., Maestre F.T. The proportion of soil-borne pathogens increases with warming at the global scale. Nature Climate Change. 2020;10(6):550-554.
19. Hay W.T., McCormick S.P., Vaughan M.M. Effects of atmospheric CO_2 and temperature on wheat and corn susceptibility to *Fusarium graminearum* and deoxynivalenol contamination. Plants. 2021;10(12):2582.
20. Pouresmaeily M. Ecological responses to climate change. InClimate Change: The Social and Scientific Construct. Cham: Springer International Publishing. 2022.
21. Nnadi N.E., Carter D.A. Climate change and the emergence of fungal pathogens. PLoS Pathogens. 2021;17(4):e1009503.
22. Benedict K., Park B.J. Invasive fungal infections after natural disasters. Emerging Infectious Diseases. 2014;20(3):349.
23. Bradley P.W., Brawner M.D., Raffel T.R., Rohr J.R., Olson D.H., Blaustein A.R. Shifts in temperature influence how *Batrachochytrium dendrobatidis* infects amphibian larvae. PLoS One. 2019;14(9):e0222237.
24. Herkert P.F., Hagen F., Pinheiro R.L., Muro M.D., Meis J.F., Queiroz-Telles F. Ecoepidemiology of *Cryptococcus gattii* in developing countries. Journal of Fungi. 2017;3(4):62.
25. de Vallavieille-Pope C., Bahri B., Leconte M., Zurfluh O., Belaid Y., Maghrebi E., Huard F., Huber L., Launay M., Bancal M.O. Thermal generalist behaviour of invasive *Puccinia striiformis* f. sp. *tritici* strains under current and future climate conditions. Plant Pathology. 2018;67(6):1307-1320.
26. Dweba C.C., Figlan S., Shimelis H.A., Motaung T.E., Sydenham S., Mwadzingeni L., Tsilo T.J. Fusarium head blight of wheat: Pathogenesis and control strategies. Crop Protection. 2017;91:114-122.
27. Savary S., Willocquet L., Pethybridge S.J., Esker P., McRoberts N., Nelson A. The global burden of pathogens and pests on major food crops. Nature Ecology & Evolution. 2019;3(3):430-439.
28. Juroszek P., Laborde M., Kleinhenz B., Mellenthin M., Racca P., Sierotzki H. A review on the potential effects of temperature on fungicide effectiveness. Plant Pathology. 2022;71(4):775-784.
29. Chaloner T.M., Gurr S.J., Bebber D.P. Plant pathogen infection risk tracks global crop yields under climate change. Nature Climate Change. 2021;11(8):710-715.
30. Proesmans W., Albrecht M., Gajda A., Neumann P., Paxton R.J., Pioz M., Polzin C., Schweiger O., Settele J., Szentgyörgyi H., Thulke H.H. Pathways for novel epidemiology: plant–pollinator–pathogen networks and global change. Trends in Ecology & Evolution. 2021;36(7):623-636.
31. Cai L., Liu C., Fan G., Liu C., Sun X. Preventing viral disease by ZnONPs through directly deactivating TMV and activating plant immunity in *Nicotiana benthamiana*. Environmental Science: Nano. 2019;6(12):3653-3669.
32. van Bruggen A., Nikolic I., Kwakkel J. Modeling with stakeholders for transformative change. Sustainability. 2019;11(3):825.
33. Musiime O., Tenywa M.M., Majaliwa M.J., Lufafa A., Nanfumba D., Wasige J.E., Woomer P.L., Kyondha M. Constraints to rice production in Bugiri District. InAfrican Crop Science Conference Proceedings. 2005.
34. Simion VE. Dairy cows health risk: Mycotoxins. Ruminants: The Husbandry, Economic and Health Aspects. InTech. 2018.
35. Khaskheli M.A., Nizamani M.M., Tarafder E., Das D., Nosheen S., Muhae-Ud-Din G., Khaskheli R.A., Ren M.J., Wang Y., Yang S.W. Sustainable management of major fungal phytopathogens in sorghum (*Sorghum bicolor* L.) for food security: A comprehensive review. Journal of Fungi. 2025;11(3):207.
36. Fisher M.C., Hawkins N.J., Sanglard D., Gurr S.J. Worldwide emergence of resistance to antifungal drugs challenges human health and food security. Science. 2018;360(6390):739-742.
37. Benedict K., Chiller T.M., Mody R.K. Invasive fungal infections acquired from contaminated food or nutritional supplements: a review of the literature. Foodborne Pathogens and Disease. 2016;13(7):343-349.
38. Liu N., Chen Y., Liu J., Su Q., Zhao B., Sun M., Jia H., Cao Z., Dong J. Transcriptional differences between major Fusarium pathogens of maize, *Fusarium verticillioides* and *Fusarium graminearum* with different optimum growth temperatures. Frontiers in Microbiology. 2022;13:1030523.
39. Pautasso M., Doring T.F., Garbelotto M., Pellis L., Jeger M.J. Impacts of climate change on plant diseases – opinions and trends. European Journal of Plant Pathology. 2012;133:295-313.
40. Gunawardena A.D. Management of Fusarium root rot of lentil and Ascochyta blight of field pea on the Northern Great Plains. Doctoral dissertation, North Dakota State University. 2023.
41. Keswani C., Dilnashin H., Birla H., Singh S.P. Unravelling efficient applications of agriculturally important microorganisms for alleviation of induced inter-cellular oxidative stress in crops. Acta Agriculturae Slovenica. 2019;114(1):121-130.
42. Sanchez-Lucas R., Mayoral C., Raw M., Mousouraki M.A., Luna E. Elevated CO_2 alters photosynthesis, growth and susceptibility to powdery mildew of oak seedlings. Biochemical Journal. 2023;480(17):1429-1443.
43. West J.S., Townsend J.A., Stevens M., Fitt B.D. Comparative biology of different plant pathogens to estimate effects of climate change on crop diseases in Europe. European Journal of Plant Pathology. 2012;133:315-331.
44. Guche M.D., Dalla Costa L., Trenti F., Guella G., Malnoy M., Moser C., Pilati S. Functional study of lipoxygenase-mediated resistance against *Erysiphe necator* in grapevine. In XIth International Symposium on Grapevine Physiology and Biotechnology 2021, Stellenbosch, South Africa, ZA. 2021.

45. Turkington T.K., Xi K. The role of crop rotation, intercropping and tillage practices for foliar disease management of wheat and barley University of Saskatchewan, Canada. InIntegrated disease management of wheat and barley. Burleigh Dodds Science Publishing. 2018.
46. Bekele B., Dawit W. Review on the status and management strategies of Fusarium head blight (*Fusarium graminearum*) of wheat. International Journal of Research in Agricultural Science. 2018;4:2348-3997.
47. Bonfada É.B., Honnef D., Friedrich M.T., Boller W., Deuner C.C. Performance of fungicides on the control of fusarium head blight (*Triticum aestivum* L.) and deoxynivalenol contamination in wheat grains. Summa Phytopathologica. 2020;45:374-380.
48. Klocke B., Sommerfeldt N., Wagner C., Schwarz J., Baumecker M., Ellmer F., Jacobi A., Matschiner K., Petersen J., Wehling P., Sellmann J. Disease threshold-based fungicide applications: potential of multi-disease resistance in winter wheat cultivars in Germany. European Journal of Plant Pathology. 2023;165(2):363-383.
49. Alin D.I.N., Mitrea I., Mitrea R. Natural compounds: an effective and eco-friendly strategies for controlling and combating plant pathogens. Notulae Botanicae Horti Agrobotanici Cluj-Napoca. 2023;51(1):12991-12991.
50. Ahmed H.F., Seleiman M.F., Mohamed I.A., Taha R.S., Wasonga D.O., Battaglia M.L. Activity of essential oils and plant extracts as biofungicides for suppression of soil-borne fungi associated with root rot and wilt of marigold (*Calendula officinalis* L.). Horticulturae. 2023;9(2):222.
51. Sood M., Kapoor D., Kumar V., Sheteiwy M.S., Ramakrishnan M., Landi M., Araniti F., Sharma A. Trichoderma: The "secrets" of a multitalented biocontrol agent. Plants. 2020;9(6):762.
52. Jaisani P., Gohel N.M. Use of novel chitin amended formulation of *Trichoderma asperellum* and *Pseudomonas fluorescens* to induce systemic induced resistance in chickpea (*Cicer arietinum* L.) against biotic stresses. Journal of Food Legumes. 2021;34(1):21-30.
53. Kruidhof H.M., Elmer W.H. Cultural methods for greenhouse pest and disease management. Integrated Pest and Disease Management in Greenhouse Crops. Springer. 2020.
54. Gramaje D., Urbez-Torres J.R., Sosnowski M.R. Managing grapevine trunk diseases with respect to etiology and epidemiology: current strategies and future prospects. Plant Disease. 2018;102(1):12-39.
55. Oliver R.P., Hewitt H.G. Fungicides in crop protection. Cabi. 2014.
56. Kohl J., Kolnaar R., Ravensberg W.J. Mode of action of microbial biological control agents against plant diseases: relevance beyond efficacy. Frontiers in Plant Science. 2019;10:454982.
57. Lynch J.P., Glynn E., Kildea S., Spink J. Yield and optimum fungicide dose rates for winter wheat (*Triticum aestivum* L.) varieties with contrasting ratings for resistance to *Septoria tritici* blotch. Field Crops Research. 2017;204:89-100.
58. Torriani S.F., Melichar J.P., Mills C., Pain N., Sierotzki H., Courbot M. *Zymoseptoria tritici*: A major threat to wheat production, integrated approaches to control. Fungal Genetics and Biology. 2015;79:8-12.
59. Brent K.J., Hollomon D.W. Fungicide resistance in crop pathogens: How can it be managed? CropLife International: Brussels, Belgium. 2007.
60. Keulemans W., Bylemans D., de Coninck B. Farming without plant protection products: Can we grow without using herbicides, fungicides and insecticides?. European Parliamentary Research Service. Scientific Foresight Unit (STOA). 2019.
61. Leadbeater A. Recent developments and challenges in chemical disease control. Plant Protection Science. 2015;51:163-169.
62. Sparks T.C., Lorsbach B.A. Perspectives on the agrochemical industry and agrochemical discovery. Pest Management Science. 2017;73(4):672-677.
63. Mcloughlin A.G., Walker P.L., Wytinck N., Sullivan D.S., Whyard S., Belmonte M.F. Developing new RNA interference technologies to control fungal pathogens. Canadian Journal of Plant Pathology. 2018;40(3):325-335.
64. Dong X., Liu X., Hou Q., Wang Z. From natural environment to animal tissues: A review of microplastics (nanoplastics) translocation and hazards studies. Science of the Total Environment. 2023;855:158686.
65. Davies C.R., Wohlgemuth F., Young T., Violet J., Dickinson M., Sanders J.W., Vallieres C., Avery S.V. Evolving challenges and strategies for fungal control in the food supply chain. Fungal Biology Reviews. 2021;36:15-26.
66. Drakopoulos D., Meca G., Torrijos R., Marty A., Kägi A., Jenny E., Forrer H.R., Six J., Vogelgsang S. Control of *Fusarium graminearum* in wheat with mustard-based botanicals: From in vitro to in planta. Frontiers in Microbiology. 2020;11:1595.
67. Liu H., Trivedi P. Climate change impacts on plant pathogens, food security and paths forward. Nature Reviews Microbiology. 2023;21(10):640-656.
68. Perrone G., Ferrara M., Medina A., Pascale M., Magan N. Toxigenic fungi and mycotoxins in a climate change scenario: Ecology, genomics, distribution, prediction and prevention of the risk. Microorganisms. 2020;8(10):1496.