Research Article

Embracing Natural Alternatives to Synthetic Fungicides for Sustainable Agriculture

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Abstract | Synthetic fungicides, while effective at controlling plant diseases, have brought about a range of adverse consequences i.e., environmental implications, the emergence of fungicide-resistant microbes and food poisoning posing a significant challenge in the realm of plant disease control. The persistent need for eco-friendly disease management strategies has arisen as a direct consequence of the detrimental effects associated with the usage of synthetic fungicides, on both food safety and environmental sustainability. Chemical fungicides have had significant and far-reaching consequences on the environment. Perhaps most notably, they have left traces of harmful residues in the food we consume, posing a significant health risk to consumers. To combat these issues, alternative disease management strategies have emerged. Several approaches are categorized as ecofriendly. Among these, the utilization of weed extracts, derived from various plant sources, has gained prominence for their role as natural fungicide in reducing growth of fungi without harming the environment. These strategies collectively aim to alleviate the adverse consequences of synthetic pesticides, promote safe food production, and ensure a more sustainable future for agriculture. Research activities conducted have generated very encouraging data however When compared to traditional techniques, the initial investments needed to implement sustainable approaches may be more. Practitioners and communities may need to adapt and undergo a transition period when switching from traditional techniques to sustainable alternatives.

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Introduction

The exponential growth of the global human population led to an increasing demand for food production. Addressing the increasing demand for food production in the face of a growing global population is a complex issue that requires collaboration between governments, organizations, and individuals. In order to attain the goal of ensuring food security, it is imperative to tackle constraints that cause reduced produce. Among these challenges, plant diseases emerge as a paramount biotic constraint. While synthetic chemicals have traditionally been the most potent means to mitigate losses resulting from plant diseases, they do come with certain adverse consequences, such as water contamination, disruption of ecosystems and harm to non-target species (Marinho *et al*., 2020). They have also given rise to the emergence of resistant pathogens (Thind, 2021) and concerns about chemical residues in food (Ul-Haq *et al*., 2020). Moreover, fungicides exhibit poor biodegradability, causing environmental harm and raising substantial public concerns due to their residue presence in food, which can have adverse effects on human health (Nhat *et al*., 2020).

In response to these challenges, eco-friendly disease management strategies have emerged, emphasizing both food safety and sustainable practices (Afzal *et al*., 2023). Consequently, the current scenario underscores the necessity of embracing organic fungicides, including those derived from weed extracts, as a more sustainable alternative. This shift reflects the need to balance disease management with ecosystem preservation, reduce chemical residues in food, and promote sustainable agriculture. The utilization of weed extracts as potential bio fungicides in integrated plant disease management presents a promising and sustainable approach within the framework of ecologically sound agronomic practices. This strategy offers significant advantages, including reduced dependency on synthetic fungicides, mitigation of chemical residues in the environment, and enhancement of agro-ecosystem resilience. However, it also poses challenges such as variability in efficacy under diverse environmental conditions, the need for standardized extraction and application protocols, and potential phytotoxicity risks. Overcoming these obstacles through targeted research and field validation can position weed extracts as a vital component of modern, sustainable agronomy (Orsoni *et al*., 2020; Jamiolkowska *et al*., 2022). On the positive side, weed extracts presents a natural, sustainable source of compounds with possessing potential as fungicide providing an eco-friendly alternative to synthetic chemicals (Šernaitė, 2017).

The negative impacts of synthetic pesticides on food safety and environmental sustainability have driven the development and adoption of eco-friendly pest management strategies. These strategies focus on reducing fungicide residues, minimizing environmental harm, and promoting sustainable agriculture. There is a growing focus on eco-friendly disease management strategies, emphasizing both food safety and sustainability. One aspect of this phenomenon is the increasing attention given to the fungicidal potential of natural alternatives, such as weed extracts (Zaheer *et al*., 2012). These natural substances are gaining prominence for their role as effective and environmentally friendly antifungal agents in plant disease management. They offer several advantages, including sustainability, compatibility with organic and sustainable farming principles, and the presence of diverse bioactive compounds with potent antifungal properties. The utilization of weed extracts is just one aspect of this broader movement towards safer and more environmentally friendly farming practices. The phenomenon associated with the persistent need for eco-friendly pest management strategies stems from the recognition of the harmful impacts of synthetic fungicides on our food supply and the environment. These detrimental effects have prompted a growing concern for food safety and the long-term sustainability of agricultural practices (Zaker, 2016).

Aims and objectives

The aim of this study is to:

- Evaluate natural alternatives to synthetic fungicides within the context of sustainable agronomy practices.
- It focuses on assessing the efficacy of eco-friendly solutions for disease management while promoting environmental conservation and soil health.

Materials and Methods

Methodology stands as a fundamental pillar in research, delineating a structured framework of procedures, protocols, and techniques by which the researcher conducts the investigation with precision (Jonker and Pennink, 2010). Consequently, this study is rooted in an exhaustive examination of published and unpublished literature comprising journals, articles, and theses within the realm of agriculture science.

- A systematic search of academic databases, such as PubMed, Google Scholar, and JSTOR, was conducted using specific keywords and phrases related to the research topic.

- The data obtained incorporated both local and international information, providing the latest findings and comparative results.
- The search results were screened based on titles and abstracts, followed by a full-text review of the shortlisted articles.
- The data from these articles were extracted and organized thematically to identify common patterns, gaps, and emerging trends.
- The findings were then analyzed critically and discussed in the context of the existing research questions, providing a robust framework for understanding the state of knowledge in the field.

Results and Discussion

The environmental consequences of using synthetic fungicides

The impact of chemical fungicides on the environment and agriculture is a highly troublesome phenomenon. These fungicides have caused severe damage to our natural ecosystems and farming methods, resulting in numerous negative consequences that require our immediate attention. The global use of over 1,000 pesticides in agriculture aims to safeguard crops from pests, with each pesticide possessing distinct properties and toxicological effects (FAO, 2022). These chemicals, including insecticides, herbicides, and fungicides, target specific threats to crops. However, concerns arise from the potential cumulative and synergistic effects of multiple pesticides, surpassing the sum of individual impacts. This complexity raises environmental and human health issues, as residues in food, water contamination, and occupational exposures contribute to the overall risk (Zaller, 2020).

Potential human health risks from synthetic fungicides

Synthetic fungicides, widely used in agriculture to control fungal diseases, can pose several health risks to humans, particularly when not used appropriately. Acute exposure to high concentrations of fungicides may result in symptoms like nausea, headaches, dizziness, and skin irritation (Ballantyne, 2004). Chronic exposure to certain fungicides has been linked to more serious health effects, such as endocrine disruption, cancer (with some fungicides classified as probable or possible carcinogens by the International Agency for Research on Cancer), and neurological damage. Fungicide residues on food can enter the human body, leading to adverse effects if consumed in amounts exceeding safety limits may result in acute or chronic health problems, including cancer, hormone disruption, and neurotoxicity. EFSA (2023), additionally, environmental contamination from fungicides can indirectly affect human health through contaminated water and soil, which in turn impacts ecosystems and food safety. Fungicides like chlorothalonil and mancozeb have been detected in water sources, leading to concerns about their long-term impact on human health. The detection of these chemicals in water sources raises the possibility of exposure through drinking water, which can be particularly concerning for vulnerable populations such as children and pregnant women. Additionally, environmental contamination can disrupt ecosystems, affecting biodiversity and the quality of water used for irrigation and consumption (IARC, 1993; EFSA, 2023; EPA, 2021).

Regulatory efforts, such as setting maximum residue limits and sustainable practices like integrated pest management, strive to mitigate adverse effects. Ongoing research into alternative pesticides, environmental impacts, and public education remains critical in achieving a balance between effective pest control and minimizing risks associated with pesticide use.

Contamination of water bodies

One significant issue is the contamination of water bodies, where pesticide residues from treated fields are carried by rain or irrigation runoff into nearby rivers, lakes, and groundwater. This has disrupted aquatic ecosystems and harmed aquatic life, leading to declines in biodiversity and long-term ecological damage (Anju *et al*., 2010).

Development of fungicide-resistant microbes

Another concerning aspect is the evolution of fungicide-resistant microbes due to the continuous and often haphazard use of these chemicals. Plant pathogens have evolved genetic adaptations that render them less susceptible or entirely resistant to the fungicides designed to control them. This resistance has not only challenged the effectiveness of chemical disease control but also escalated the environmental and economic costs of pest management (Lucas *et al*., 2015).

Apprehension of pesticide residues in our food supply

Secondly, there is the issue of synthetic chemical residues in food. Even when applied properly, these residues can persist on food products, including fruits, vegetables, and grains, potentially posing health risks to consumers. This has raised significant concerns about the safety of the food supply and the need to reduce the presence of chemical residues in what we eat (Byrne *et al*., 1994).

Transitioning from synthetic fungicides to eco-friendly disease management

In response to these challenges, eco-friendly pest management strategies have emerged as a practical solution. These strategies prioritize the safety of our food supply and the sustainability of agricultural practices. They encompass various approaches, including biological control through natural predators and beneficial organisms, organic farming techniques that rely on natural processes with minimal synthetic inputs, and the integrated pest management (IPM) approach, which combines multiple methods to minimize ecological harm. By reducing the reliance on synthetic pesticides, we can decrease the environmental impact of control of plant disease while maintaining thriving and productive gardens and farms (Purkayastha *et al*., 2016; Thind, 2021).

Due to the adverse effects of synthetic fungicides on food safety and environmental sustainability, there is an ongoing need for the development and adoption of eco-friendly disease management strategies. These strategies aim to ensure that food production can proceed without the harmful consequences associated with residues of synthetic chemicals. This article delves into the critical aspects of pesticide usage and its detrimental effects on food safety, as well as the evolution of pest management strategies, particularly the utilization of weed extracts. The primary goal of these strategies is to ensure safe food production while promoting environmentally sustainable agricultural practices.

The article we have mentioned highlights the pressing need for eco-friendly disease management strategies due to the negative impacts of synthetic fungicides on food safety and environmental sustainability. Let's explore into this phenomenon and discuss its various aspects.

Precise and environmentally friendly disease management

Natural plant-based products exhibit a distinct set of qualities that make them exceptionally well-suited for targeted pest management. They possess a narrow spectrum of activity and operate through specific modes of action. This precision ensures their effectiveness while minimizing unintended consequences. These compounds are generally non-toxic to beneficial microorganisms, demonstrate limited persistence in the field, and have a shorter shelf life, thereby posing minimal residual threats. These attributes render natural plant products a vital component of integrated pest management (IPM) strategies. In comparison to conventional synthetic chemical pesticides, they are widely acknowledged for their safety profile concerning both human health and the environment. This safety profile makes them highly adaptable, particularly for adoption by farmers in developing countries. It's worth noting that the use of plant extracts for addressing agricultural challenges aligns with traditional practices, exemplified in the research. In summary, natural plant products represent a precise and eco-friendly approach to pest management, underscoring their potential to revolutionize sustainable farming practices and offer solutions to challenges faced by farmers worldwide.

Harnessing weed extracts for eco-friendly plant disease management

The use of weed extracts as alternatives to synthetic herbicides aligns with extensive research emphasizing the advantages of eco-friendly farming practices. Studies by Orsoni *et al*. (2020), Jamiolkowska *et al*. (2022), and Acheuk *et al*. (2022) have demonstrated the environmental and food safety benefits of adopting natural herbicides. These findings bolster the growing awareness and adoption of sustainable agricultural practices by confirming the efficacy of weed extracts in minimizing chemical residues on crops and enhancing food safety. This body of research underscores the necessity and potential of transitioning to sustainable, eco-friendly farming solutions.

A critical aspect of weed extracts is their rich composition of bioactive compounds, such as alkaloids, phenolics, essential oils, and terpenoids (Pires *et al*., 2019). These compounds have shown significant antifungal properties, effectively managing specific fungal pathogens. The diversity of bioactive compounds in weed extracts provides an exciting opportunity to discover novel agents for disease control, thereby enhancing disease management strategies while minimizing the reliance on synthetic chemicals.

Weeds, characterized by their abundance and biodiversity across various ecosystems, represent an untapped resource for potential antifungal agents. This biodiversity holds the promise of identifying unique compounds to combat fungal diseases, enriching our understanding of natural disease management approaches. Furthermore, the use of weed extracts offers the added benefit of reducing concerns about chemical residues on crops, thereby addressing critical food safety and environmental sustainability challenges (Jamiolkowska *et al*., 2022). The growing adoption of weed extracts reflects a broader trend toward sustainable and environmentally friendly agricultural practices. This shift not only reduces the chemical load on crops but also contributes to enhanced food safety. Ultimately, the transition to natural herbicides symbolizes a critical step in promoting sustainable agriculture and improving public health outcomes.

Harvesting a sustainable future through eco-friendly disease management in agriculture

The use of natural alternatives, such as weed extracts, as eco-friendly fungicides, has gained significant attention for their effectiveness in managing plant diseases while minimizing harm to the environment. This shift towards sustainable plant disease management represents a crucial evolution in agriculture, reflecting a growing awareness of the necessity to harmonize pest control with ecosystem preservation, reduced chemical residues in our food, and the promotion of sustainable farming practices.

However, the adoption of these strategies is not without its challenges, particularly the need for education and support for farmers and the agricultural industry to transition away from conventional synthetic pesticide usage. Nevertheless, the movement towards eco-friendly pest management is a vital step in ensuring food safety and long-term environmental health.

The abundance and biodiversity of weeds within ecosystems offer a vast resource for discovering novel compounds effective in combatting specific fungal pathogens. Utilizing weed extracts as potential antifungal agents in plant disease management not only delivers environmental benefits but also addresses concerns regarding chemical residues in crops, potentially resulting in substantial cost savings.

In contrast to synthetic chemicals, weed extracts provide a natural and sustainable source of antifungal compounds, significantly reducing the accumulation of chemical residues in agricultural produce, thereby mitigating concerns related to food safety and environmental impact. Moreover, the accessibility of weeds as readily available resources makes them a cost-effective alternative to commercial fungicides.

Challenges and adoption

The adoption of these eco-friendly strategies presents limitations, including variations in efficacy, regulatory requirements, and the limited spectrum of effectiveness against specific pathogens (Thembo *et al*., 2010). Moreover, the adoption of these strategies presents its own set of challenges, including the need for education and support for farmers and the agricultural industry to transition away from the conventional use of synthetic pesticides. Nevertheless, the movement towards eco-friendly pest management is a vital step in ensuring the safety of our food supply and the long-term health of our environment. Despite these challenges, the movement towards eco-friendly pest management is seen as a crucial step in ensuring the safety of the food supply and the long-term health of the environment. It represents a shift towards more sustainable and harmonious coexistence between agriculture and the ecosystem, with a growing awareness of the need to balance pest control with environmental preservation and reduced chemical residues in food.

The phenomenon of this shift towards eco-friendly pest management strategies represents a necessary evolution in agriculture. Indeed, the issue of fungicide resistance underscores a growing awareness of the imperative to strike a delicate equilibrium between managing plant pathogen populations and preserving ecosystems. This balance is not only vital for maintaining the health and biodiversity of our environment but also for reducing chemical residues in our food, which is essential for ensuring human and ecological health. Embracing sustainable farming practices, such as integrated pest management and organic agriculture, becomes all the more critical in this context. By recognizing the multifaceted nature of the challenge, we can work towards a more sustainable and harmonious coexistence between agriculture and the environment, ultimately benefiting both present and future generations.

The consistency and efficacy of weed extracts can be unpredictable due to variations in chemical composition, growth conditions, and extraction methods (Opender and Suresh, 2009). Rigorous testing is imperative to pinpoint the most effective extracts for specific pathogens. Regulatory hurdles and approval processes may also pose obstacles in some regions, necessitating compliance with relevant regulations. Furthermore, the limited spectrum of effectiveness against certain fungal pathogens may require the integration of multiple extracts or other disease management strategies (van Bruggen *et al.*, 2016). Residue and environmental persistence, while less of a concern than synthetic chemicals, should still be assessed to minimize ecological impact (Edward, 2013). Development and optimization of application methods can be time-consuming, and the risk of resistance development in fungal populations, as with synthetic fungicides, underscores the importance of rotating or combining different antifungal agents. In conclusion, the utilization of weed extracts as antifungal agents in plant disease management aligns with the growing interest in sustainable and natural farming practices (Ghorbanpour *et al.*, 2018). However, its success hinges on careful research, testing, and consideration of various factors to ensure both effectiveness and practicality in specific agricultural contexts. Ultimately, integrating weed extracts into a comprehensive disease management strategy, in tandem with other control methods, emerges as the most promising and holistic approach.

A glimpse into our research findings

Researchers from around the world have joined forces to explore the unknown, resulting in a rich discoveries unveiled through diligent work in laboratories, field studies, and various disciplines. This collaborative effort is reflected in the diverse insights presented here a mosaic of unique contributions from dedicated scholars (Table 1). This presentation offers a glimpse into the shared corridors of global research, where the

Table 1: *Fungicidal properties of some of plant based products.*

Name of plant product	Compound controlled plant pathogen	Reference
Acacia, sapodilla, pomegranate, eucalyptus, and black plum extracts, datura	*Aspergillus candidus* Link; *A. flavus,* Micheli; *A. fumigatus,* Magnus; *A. niger,* Thome; *A. ochraceus* G. With	Satish *et al.* (2007)
Indian beech, oleander milk weed and turmeric extracts	*Aspergillus fumigatus,* Magnus; *Alternaria solani,* Sorauer; *Helminthosporium* spp. Link.	Masih *et al.* (2014)
Kokum, wild turmeric and jasmine extracts	*Colletotrichum coccodes,* Wallr.; *Rhizopus stolonifer* Vuillemin	Bhagwat and Datar (2014)
Grape seed, thyme, mint, basil, rosemary and sage essential oils	*Botrytis cinerea* Pers.	Mermer-Doğu and Zobar (2014)
Thymol, carvacrol, 1, 8 cineole,Y-terpinene, p-cymene and anethole	*Fusarium moniliforme,* Sheldon; *Rhizoctonia solani,* Kuhn; *Phytophthora capsici* Leonian	Mueller-Riebau *et al.* (1995)
Carvacrol, eugenol, citronellol, geraniol, citral, perillyl and menthol	*Botrytis cinerea,* Pers.; *Monilinia fructicola,* (Wint.) Honey	Tsao and Zhou (2000)
Citral, eugenol and geraniol	*Curvularia lunata* (Wakk.) Boidijn; *Fusarium moniliforme* Sheldon	Krishna Kishore *et al.* (2007)
Anise, cumin, caraway, ammin, pennyroyal, thyme and cinnamon essential oils	*Aspergillus flavus* Link; *Phoma Sorghina* (Sacc.) Boerema, M.R. de Vries and H.L.W. de Gruyter; *Alternaria alternate* (Fr.) Keissler, *Botrytis cinerea* Pers.	Behdani *et al.* (2012)
Pepper and cassia extracts, neem, mustard and cinnamon essential oils	*Phytophthora nicotianae* (Breda de Haan) Takahashi	Bowers and Locke (2004)
Eucalyptus and lavender extracts	*Alternaria alternate* (Fr.) Keissl.	Zaker and Mosallanejad (2010)
Clove bud, cinnamon, ginger, black pepper, garlic and onion extracts	*Aspergillus niger* Vuillemin	Avasthi *et al.* (2010)
Neem, chinaberry, garlic and turmeric extracts	*Fusarium oxysporum* (Schltdl.) Snyder and Hansen; *Rhizoctonia solani* Kuhn	Hadian (2012)
Artemisia, thyme and eucalyptus extracts	*Fusarium solani* (Mart.) Sacc.	Zaker (2014)
Desert date seed extract (DDSE), Neem seed extract (NSE), Jatropha seed extract (JSE)	Cercospora Leaf Spot (CLS) caused by *Cercospora arachidicola* Hori *and Cercosporidium personatum* (Berk. and M.A. Curtis) Ellis, (1885) of Groundnut	Neindow (2017)

collective detection of knowledge exceeds borders. It showcases the intellectual endeavors that drive progress on a worldwide scale, bringing to light a wealth of findings that enrich our understanding of the world.

Examples of sustainable disease management through phytochemical interventions

The application of plant-derived bioactive compounds in phytopathogen management represents a significant development in sustainable agronomic practices. The findings of research conducted by various scientists across different countries are meticulously compiled and presented in Table 2. These naturally occurring antimicrobial agents present an eco-friendly alternative to synthetic agrochemicals, efficiently decreasing pathogen pressure while mitigating environmental impact. Integrating these phytochemical-based interventions into crop protection frameworks support with the principles of integrated pest management (IPM), promoting resilience against pathogen resistance and improving agro-ecosystem sustainability.

Existing gaps towards exploring organic fungicides for eco-friendly disease management

To address existing gaps in sustainable disease management strategies in agriculture, several areas need attention:

Research and development: There is a need for further research into the efficacy and scalability of organic fungicides derived from weed extracts. More studies are required to understand their mechanisms of action, optimal application methods, and potential side effects on crops and ecosystems.

Access and affordability: Organic fungicides may currently be less accessible or more expensive compared to synthetic alternatives. Efforts should be made

Table 2: *Successful management of plant diseases using plant extracts.*

Disease	Key Findings of the Study	Reference
Powdery Mildew (*Erysiphe spp.* and *Sphaerotheca* spp.)	*Azadirachta indica* (neem), *Lantana camara*, *Eucalyptus* spp. were effective.	Ramegowda and Srinivas, 2006
Fusarium wilt (*Fusarium solani*), Damping off, and Root rot (*Pythium aphanidermatum*)	*Allium sativum* (garlic) and *Lantana camara* were highly effective *in vitro*.	Ram and Thakore, 2009
Rust Diseases (*Puccinia* spp.)	*Azadirachta indica* (neem), *Allium sativum* (garlic), *Tithonia diversifolia* showed antifungal activity.	Shabana *et al.*, 2017
Post-harvest anthracnose of mango (*Colletotrichum gloeosporioides*)	Lime (*Citrus limon*) extracts were effective in reducing anthracnose.	Gupta and Dikshit, 2010
Damping off of brinjal (*Pythium aphanidermatum*)	Hot water leaf extract of *Eucalyptus microtheca* inhibited damping off by 90% *in vitro*.	Narayana *et al.*, 1994
Tomato fruit rot (*Fusarium verticillioides* and *Macrophomina phaseolina*)	Aqueous and ethanolic extracts of *Alchornea cordifolia*, *Cassia alata*, and *Moringa oleifera* inhibited mycelial growth *in vitro* and on infected fruits.	Enikuomehin and Oyedeji, 2010
Anthracnose on red pepper (*Colletotrichum coccodes*)	Methanol extract of *Curcuma longa L.* rhizomes controlled anthracnose growth.	Cho *et al.*, 2006
Post-harvest fungi (*Fusarium solani*, *Rhizopus arrhizus*, *Sclerotium rolfsii*)	Controlled using extracts from *Duranta erecta* and *Lasonia ineruis*.	Devi *et al.*, 2017
Post-harvest pathogens (*Penicillium oxalicum* and *Aspergillus niger*) of yams	Extracts from castor oil plant (*Ricinus communis L.*) effectively inhibited pathogen growth.	Patrice *et al.*, 2017
Wilt of chickpea (*Fusarium oxysporum*)	Methanolic extracts of Mexican Tea (*Chenopodium ambrosioides L.*) controlled the disease.	Minz *et al.*, 2012
Wilting in cowpea seedlings (*Sclerotium rolfsii*)	Extracts from basil (*Ocimum gratissimum L.*) and blue gum eucalyptus (*Eucalyptus globulus*) were effective.	Prasad *et al.*, 2003
Tomato rot disease (*Aspergillus niger*, *Fusarium oxysporum*, *Geotrichum candidum*)	*Azadirachta indica* (neem) and *Tithonia diversifolia* extracts suppressed pathogen growth up to 100%.	Ngegba *et al.*, 2018
Bacterial leaf blight of rice (*Xanthomonas oryzae pv. oryzae*)	*Datura metel L.* (datura) reduced pathogen growth *in vitro* and disease severity in greenhouse conditions due to daturilin presence.	Sateesh *et al.*, 2004
Bacterial wilt of potato (*Ralstonia solanacearum*)	Aqueous extracts of *Hibiscus sabdariffa L.*, *Punica granatum* L., and *Eucalyptus globulus* were effective in controlled and field trials.	Hassan *et al.*, 2009

to make these products more affordable and widely available to farmers, especially those in developing countries.

Education and training: Farmers need access to education and training programs on the proper use of organic fungicides and integrated disease management practices. This includes information on application timing, dosage, and rotation strategies to maximize effectiveness and minimize risks.

Regulatory frameworks: Clear regulatory frameworks need to be established to ensure the safety and efficacy of organic fungicides. This includes standards for product labeling, certification processes for organic farming, and monitoring of pesticide residues in food.

Scaling up production: Scaling up the production of organic fungicides derived from weed extracts may require investment in infrastructure and technology. Research into cost-effective production methods and supply chain logistics is needed to meet growing demand.

Monitoring and evaluation: Continuous monitoring and evaluation are essential to assess the long-term impacts of organic fungicides on crop yields, soil health, biodiversity, and human health. This data will inform adaptive management strategies and help identify areas for improvement. Addressing these gaps will be crucial for the widespread adoption of sustainable and eco-friendly disease management strategies in agriculture, ultimately contributing to food security and environmental sustainability.

Conclusions and Recommendations

The shift towards eco-friendly pest management is essential to address the agronomic and ecological concerns associated with synthetic agrochemicals. The adverse impacts on aquatic ecosystems, soil biota, and beneficial non-target organisms, alongside the escalation of pesticide-resistant pest populations, underscore the urgent need for sustainable, integrated pest management (IPM) practices. Recent research into the bio-efficacy of botanical fungicides reflects a growing recognition within agronomic sciences of the need for pest control approaches that maintain ecological equilibrium.

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Novelty Statement

This research addresses the adverse impacts of synthetic fungicides, such as environmental harm, fungicide resistance, and food safety risks. It discovers eco-friendly alternatives, predominantly plant-based fungicides derived from weed extracts, which provide a sustainable solution to fungal infections without injuring the atmosphere. While these natural substitutes may involve higher preliminary investments and a transition era for adoption, the long-term revenues comprise safer food production and a more sustainable agrarian future. The research delivers compelling data supporting the shift toward plant-based fungicides as a viable, eco-friendly alternative to traditional chemical treatments.

Author's Contribution

Dr. Amir Afzal: Conceptualized the research idea, supervised the study, and provided intellectual guidance for the literature review and overall analysis.
Dr. Sairah Syed (Corresponding Author): Led the authorship of the manuscript, conducted a comprehensive literature review, and synthesized findings to align with the study's objectives.
Shiza Atif: Supported the literature search, curated relevant sources, and assisted in organizing the reviewed materials.
Nisa ur Rehman: Identified key publications and contributed to their critical evaluation and relevance analysis.
Muhammad Arsalan: Evaluated the reviewed literature, ensured proper referencing, and provided analytical insights.
Taimoor Hussain: Categorized and summarized findings from the literature to enhance clarity and coherence.
Javed Iqbal: Offered expert thematic insights and

helped refine the focus of the literature review.
Sharmin Ashraf: Organized and structured the reviewed content to ensure logical flow and accessibility.
Zubair Aslam: Reviewed the manuscript draft and provided constructive feedback on integrating literature findings into the discussion.

Conflict of interest

The authors have declared no conflict of interest.

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