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Basidiomycetes as a Source for Developing Sustainable Biopesticides and Biostimulants in Agriculture: A Review

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ABSTRACT

This review aimed to synthesize current knowledge on the potential of Basidiomycetes fungi as a foundation for developing eco-friendly plant protection products, effective in the fight against plant diseases and weeds. The study conducts a comprehensive literature review using the PRISMA framework, focusing on peer-reviewed articles published between 2000 and 2023. It systematically examines the potential of Basidiomycetes in plant protection and growth stimulation, assessing their mechanisms of action, efficacy, and environmental impact in comparison to traditional chemical methods. The study reveals a number of important *Basidiomycete* species, such as *Ganoderma lucidum*, *Trametes versicolour*, and *Fomes fomentarius*, that have a great deal of promise for protecting plants. These fungi have a variety of ways of working, including the production of chitinases, glucanases, and antibacterial polysaccharides that increase plant resistance to infections and promote growth. The review stresses the advantages of these species for the environment over conventional chemical pesticides and their efficacy as biocontrol agents against a variety of phytopathogens and pests. The study also emphasizes how Basidiomycetes can create bioactive substances, which support their phytostimulant and biocontrol capabilities. The findings show that basidiomycetes have a promising role in sustainable agriculture as a substitute for chemical fertilizers and pesticides.

1. INTRODUCTION

Modern agricultural production volumes require the use of an array of chemical plant protection products, which are a priority way to influence yields. At the same time, the extensive use of all pesticides has a destructive impact on local ecosystems, causes secondary pollution, and creates an imbalance in Kazakhstan's green development strategy. In search of optimal solutions, some agricultural producers minimize the chemicalization of agronomic processes, losing part of the harvest, while others spend huge efforts on breeding disease-resistant varieties, but pathogens adapt to conditions much faster than breeding. As the negative impact of the unlimited use of synthetic chemical plant protection products on the biosphere is becoming apparent, the problem of finding alternative solutions to pest and disease control is becoming more urgent [1]. It becomes obvious that the process of developing ecological methods of plant protection should take into account economic parameters, environmental and sanitary requirements, as well as social aspects. Recently, scientific interest in biological methods as a means of maximizing the potential of natural resources has grown significantly [2].

The issues of biological safety and biosecurity in modern conditions of agricultural activity, particularly in the context of the destructive effects of chemical accumulation on the environment, have been a subject of significant research. For instance, Abugalieva et al. [3] emphasised the detrimental impacts of widespread pesticide use, which has led to the hunt for sustainable substitutes that can lessen these effects while maintaining agricultural output. Sarbaev and Ydyrys [4] talked about the creation of integrated pest management systems that take into account the toxicity of chemical fungicides and insecticides in an effort to find more ecologically friendly plant protection techniques. Furthermore, studies by Mustafin et al. [5] highlighted how adaptable basidiomycetes, such as *Ganoderma lucidum* and *Trametes versicolour*, are, allowing them to occupy a variety of ecological niches and support the sustainability of ecosystems.

For use in biotechnology and medicine, basidiomycetes' potential has been extensively investigated, especially in the synthesis of bioactive polysaccharides. Some species, such as *Hericium coralloides* and *Hericium erinaceus*, showed considerable potential for extracellular polysaccharide production, which could be used for health-benefit applications, according to Narmuratova et al.'s [6] investigation into the antimicrobial qualities and polysaccharide production of different *Hericium* strains. Their research highlights the increasing interest in basidiomycetes as potential sources of new bioactive substances. Mustafin et al. [7] supplemented this study by examining the impact of metal salts on *Trametes versicolor*'s polysaccharide production. According to their research, copper and zinc citrates greatly increased biomass yield and exopolysaccharide content. This suggests that metal ion supplementation can maximize polysaccharide formation, which is a crucial component in enhancing the effectiveness of biological products derived from fungi. Furthermore, after screening 20 strains of basidiomycetes, Mustafin et al. [8] identified *Ganoderma lucidum* and *Trametes versicolour* as being especially promising due to their high polysaccharide content, which supports their well-known therapeutic effects, such as immunomodulatory and anti-tumor properties.

Most contemporary researchers, in particular Adeyeye et al. [9], analysing ways to enhance the long-term resilience of agricultural systems and to reduce ecological risks associated with biological and environmental threats, emphasise that the development and implementation of innovative biosecurity approaches constitute a strategic priority for modern agriculture. In their study, the authors argue that traditional protective measures are insufficient under conditions of increasing climate variability, pathogen spread, and ecosystem vulnerability. They conclude that the integration of biosecurity strategies with continuous, data-driven monitoring of environmental parameters represents an optimal ecosystem-based approach to agricultural production. According to the authors, such convergence enables early detection of biological threats, supports preventive decision-making, and significantly reduces negative impacts on agroecosystems, thereby strengthening the sustainability and adaptability of agricultural systems in the long term.

Though their potential for biological pest management and plant growth stimulation is widely recognized, there are still a number of important gaps in current assessments of basidiomycetes. A major barrier to expanding the practical uses of basidiomycetes in agriculture is a lack of thorough descriptions of the precise processes by which they cause systemic resistance in plants [10]. The difficulties that arise when moving from laboratory research to extensive commercial applications are also not sufficiently analyzed. The commercial scalability of these biotechnologies and the reasons behind their effectiveness in actual agricultural settings are still underexplored, despite several studies highlighting the environmental benefits of employing fungal-based products.

The study aims to analyze the potential role of basidiomycetes as a basis for the development of new and improvement of existing environmentally friendly phytoprotective and phytostimulating products of various spectrums of action, which can show maximum efficiency in the process of organic production development. The main objectives of the study are:

(1) To summarize basidiomycete species with plant protection potential and their active substances.
(2) To analyze their mechanisms of action in plant disease and pest control.
(3) To review challenges in scaling these products for commercial use.
(4) To explore future research directions for improving basidiomycete-based biopesticides.

2. MATERIALS AND METHODS

A thorough literature search was done to find pertinent studies, reviews, and research articles about the function of Basidiomycetes in the creation of biologically based plant protection products. The review process was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, ensuring that each stage of the review was undertaken in a systematic, transparent, and reproducible manner.

The literature search was conducted across multiple academic databases, including Web of Science, Scopus, and Google Scholar, to ensure a comprehensive selection of relevant studies. A combination of keywords such as "Basidiomycetes" AND "biological plant protection", "Basidiomycetes" AND "biotechnology", "Fungal biopesticides" AND "plant protection", "Basidiomycetes" AND "phytostimulants", "Antagonistic fungi" AND "plant pathogens", "Biological control" AND "fungi" was used. These keywords were designed to capture studies relevant to the ecological role of Basidiomycetes in agriculture, their use in pest and disease management, and the development of environmentally friendly agricultural solutions.

In order to include both foundational research and the most current advancements in the field, the literature review concentrated on publications published between 2000 and 2023. This period of time made it possible to analyze the most recent developments in technology as well as changing patterns in the application of Basidiomycetes in plant protection.

This review's inclusion criteria were as follows: Only conference papers, reviews, and peer-reviewed articles were taken into account. The investigations have to concentrate on fungi or Basidiomycetes as phytostimulants or in the context of biological plant protection. Studies that looked into the agronomic, biochemical, or ecological roles of Basidiomycetes on plant health were also included. Rejecting non-peer-reviewed sources, including reports or grey literature, was one of the exclusion criteria. Articles unrelated to the use of Basidiomycetes in plant protection or agriculture were not included. Additionally, research on fungi or synthetic compounds unrelated to Basidiomycetes was excluded.

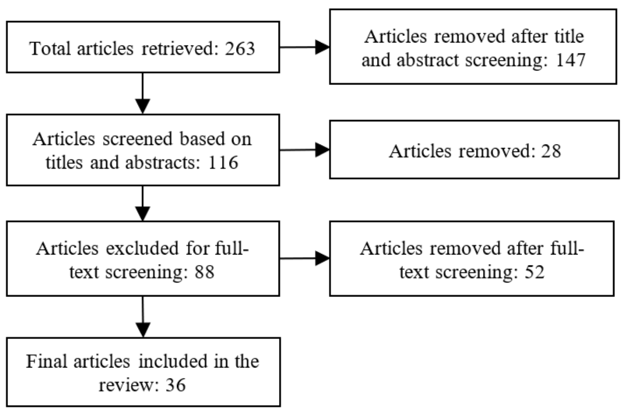

Figure 1. PRISMA flowchart of the literature search and selection process

263 articles in all were first obtained from the two databases (Figure 1). The concentration on synthetic compounds, non-peer-reviewed sources, or fungi unrelated to Basidiomycetes led to the exclusion of 147 publications after the titles and

abstracts were screened for relevancy. During the title and abstract screening phase, 28 articles were excluded due to irrelevance, either not addressing the use of Basidiomycetes in plant protection or being focused on unrelated aspects of the Basidiomycetes. Following a comprehensive full-text analysis of the remaining 88 papers, 52 studies were further excluded because they did not fit the research focus on the use of Basidiomycetes in agriculture. In the end, 36 publications were chosen for the review because they satisfied all the requirements and offered insightful information about the function of Basidiomycetes in phytostimulation and biological plant defense.

Important details, including the kinds of Basidiomycetes used in biological plant protection and their particular uses in agriculture, such as their functions as biopesticides, growth stimulants, and disease resistance agents, were carefully gleaned from the identified studies. Furthermore, the efficacy, sustainability, and environmental impact of these fungal-based products were evaluated in comparison to traditional chemical treatments. The retrieved data were then combined to show the strengths of the existing research, reveal gaps that require more study, and identify new trends in the field. This thorough investigation made it easier to comprehend how Basidiomycetes might promote sustainable and ecologically friendly farming methods.

3. POTENTIALS AND MECHANISMS OF BASIDIOMYCETES IN PLANT PROTECTION

Plants are the backbone of agricultural ecosystems, and they are subject to attacks by phytophagous insects and phytopathogenic microorganisms, as well as weeds and unfavorable environmental factors. Traditionally, various methods were used to protect plants from pests and diseases, of which synthetic chemicals with a high level of efficiency are the most common. Today, biological products are an environmentally tolerant alternative to chemical protection products, which are based on the natural ability to protect plants from pests and pathogens, as well as to stimulate plant growth and development. The maximum potential of the natural characteristics of microorganisms and fungi is used. The latter are of scientific interest, as they have a wide range of antagonistic properties, compete for nutrient substrates, and are capable of producing antibiotics and other specific substances that inhibit the vital activity of phytopathogens [11]. Basidiomycetes are higher fungi with multicellular mycelium. These include more than 30% of all fungal species known to date [8]. Mycelia of basidiomycetes have a huge functional potential for the decomposition of organic matter and the processing of nutrients, as they are characterized by the ability to produce various extracellular enzymes that break down complex chemicals [12].

Numerous species of basidiomycetes, widespread in nature, produce biologically active compounds that catalyze pathogenicity factors [13, 14]. Biotechnologists identify muscarinic fungi and entomotrophic fungi as the most promising in terms of development potential. Fungal pathogens, in particular, the causative agents of white and green muscaria – *Enthomophthora* [8, 15, 16] are noteworthy. Among the widespread species, extracts of the common tinder fungus, *Fomes fomentarius,* demonstrate high elicitor activity. Preparations based on *Fomes fomentarius* extracts, in the form of a biofungicide, are not inferior in efficiency to leading synthetic chemicals, showing the properties of a biostimulant, improving the biometric parameters of plants, while being positioned as a non-toxic and safe method of biological protection [17, 18]. Examples of successful practices of introducing biotechnology into agricultural production create real opportunities for replacing synthetic drugs with innovative biological methods that can perform protective functions while allowing for good yields of environmentally friendly products at low cost.

Table 1 offers a thorough assessment of the many strains of basidiomycetes that have demonstrated promise in plant protection. It provides an overview of each strain's sources, biological activity, target organisms, and mechanisms of action. These fungi have shown a variety of biological impacts, such as the ability to promote plant development, have antibacterial qualities, and act as biocontrol agents against diseases and pests. The table provides a better understanding of these strains' potential uses in plant protection and sustainable agriculture by methodically comparing them and highlighting their diverse methods and levels of efficacy.

Table 1. Comparison of basidiomycete strains

Strain	Source	Biological Activity	Target	Mechanism of Action	Efficacy Indicators
Entomopathogenicus	Fungal culture collections	Antagonistic activity against plant pests	Insect pests, including beetles	Produces toxic metabolites and enzymes (e.g., chitinases) that disrupt insect exoskeletons, leading to mortality.	Mortality rate: 70-95% (5-10 days); $LC_{50} = 1 \times 10^6$–1×10^7 conidia/mL; larval development inhibition: 55-80%
Fomitopsis pinnatifida	Wood-decaying basidiomycete	Antifungal, antimicrobial activity	Plant pathogens, fungi	Releases extracellular enzymes (e.g., laccases, peroxidases) that degrade fungal cell walls and inhibit pathogen growth.	Mycelial growth inhibition: 60-85%; EC_{50} = 150–320 µg/mL
Ganoderma lucidum	Medicinal mushroom, forested areas	Antioxidant, antimicrobial, and immunomodulatory activities	Bacteria, fungi, and plant diseases	Produces polysaccharides and terpenoids that enhance plant resistance, inhibit pathogen growth, and regulate immune responses.	Pathogen inhibition: 50-75%; EC_{50} = 80–200 µg/mL; plant antioxidant activity increased by 20-40%
Trametes versicolor	Decaying wood, forest floors	Antifungal, antimicrobial, and plant growth-promoting activity	Fungal pathogens, nematodes	Secretes extracellular polysaccharides and enzymes (e.g., glucanases) that stimulate plant growth and suppress disease pathogens.	Fungal growth inhibition: 65-90%; EC_{50} = 40–100 µg/mL; nematode mortality: 55-78%

Hericium erinaceus	Forested areas, medicinal use	Antioxidant, antimicrobial, anti-inflammatory, and anti-cancer properties	Bacteria, fungi, and inflammation sites	Produces bioactive compounds like polysaccharides that modulate immune responses and inhibit pathogen growth through glucan production.	Antimicrobial inhibition: 45-70%; EC_{50} = 100–250 μg/mL
Phanerochaete chrysosporium	Wood decaying fungi	Bioremediation, antioxidant activity	Environmental pollutants, lignin	Degrades lignin and complex organic compounds via lignin peroxidases, aiding in the breakdown of pollutants and promoting plant health.	Lignin degradation: 50-80%; pollutant reduction: 30-60%; enzyme activity increased 2-4-fold

Source: Compiled by the authors based on studies [19-21].

It should be noted that mushrooms can grow and reproduce rapidly. To effectively use fungal-based biological products, it is necessary to use their potential at a certain time of the season and in the optimal concentration, which requires knowledge of the etiology of fungal damage and the principles of their interaction with insects [22-24]. It is worth noting that biological products based on fungal extracts are best used when there is a 3-4-week period of positive temperatures and sufficient humidity for their optimal adaptation to the new biocoenosis. Otherwise, their effectiveness will be significantly reduced. The proposed conceptual approach will make it possible to develop effective and environmentally friendly pesticides based on the biological potential of basidiomycetes, which have acceptable economic requirements. It should be noted that there are two types of protective biological agents based on the nature of their impact: contact products that act directly on contact with the object, and systemic products that act on the conductive system and plant tissues that feed on pests.

To ensure the effectiveness of the cultivation process of biological agents, it is necessary to choose the right optimal culture medium [25-27]. In this case, the deep method of cultivation in a liquid nutrient medium, the surface method using bulk substrates, and the deep-surface cultivation are practiced. The study noted that fungal blastospores obtained in deep culture are less viable and active than conidia formed by fungi on the surface of the nutrient medium, so surface cultivation has recently become popular [15]. A commonly used method is to produce a biological product for plant protection against phytopathogens and nematodes based on a fungal strain by mixing the product with mineral, organic, or bacterial fertilizer. The biological agent obtained as a result of the method has high antagonistic activity against a wide range of phytopathogens and nematodes. An important aspect of developing fungus-based biotechnologies is the optimal choice of formulation, which is directly related to the technology of biological products and their shelf life. Modern developers of biological defense products focus on the need to optimize existing formulations following current technological requirements.

The effectiveness of biological products based on *Basidiomycetes* is influenced by several key factors. These include the optimal cultivation conditions for the fungi, such as temperature, humidity, and the type of substrate used for growth. The virulence of the fungal strain also plays a crucial role, as does its ability to produce specific enzymes and metabolites that can target plant pathogens or stimulate growth. Additionally, the formulation of the biological product and its quality control are critical in ensuring its stability and shelf life. Together, these elements determine the overall efficacy of the fungal-based phytoprotective and phytostimulant products, making them effective alternatives to synthetic chemicals in plant protection and growth enhancement.

The effectiveness of phytoprotective and phytostimulating preparations based on basidiomycetes is not always commensurate with the effectiveness of synthetic chemicals. This can be determined by the significant dependence of biological products on the parameters of temperature, humidity, and isolation. To mitigate this effect, a detailed study of the mechanisms of interaction between biological agents and the target and the environment is required, which will increase the activity of the active principle. Particular attention should be paid to the research and development of biological products with polyfunctional action, which is a practical expression of the combined potential of fungi and microbial antagonists and can expand the scope of effective use of biological plant protection products through targeted strain selection. In addition, one of the most promising ways to increase the effectiveness of mushroom-based biological products is through their genetic modification. The use of genetic transformation can significantly increase the virulence of the strains used and their resistance to abiotic environmental factors [28].

The biological safety of using fungi as objects of biotechnology is due to their natural tendency to have symbiotic relationships with plants [29]. In addition, some basidiomycetes can affect organisms through metabolites. The use of phytoprotective products derived from certain fungi is considered a way to manage the size of agricultural pest populations, including insects and nematodes. For example, entomopathogenic fungi are used as biopesticides, and fly agaric has insecticidal properties. In the process of developing innovative biotechnologies, higher edible basidiomycetes, which form organized, large fruiting bodies, are also considered targets. *Basidiomycetes* are characterized by the presence of multicellular septated mycelium and the formation of basidia-bearing basidiospores [17]. There are species of fungi that parasitize insects – entomopathogenic fungi [30]. Their representatives, which are pathogenic to agricultural plant pests, can be effectively used as biopesticides to control pest populations. To develop effective mycoinsecticidal drugs, it is necessary to use highly active strains of entomopathogenic fungi. Entomophthoric fungi from the *Zygomycete* class (entomophthora, tarichium, massospore) are particularly effective in causing severe epizootics [8, 31].

The distribution of fungi in different ecosystems is based on general biological patterns and functionality [32-34]. The basic function of fungi in the natural environment is the decomposition of organic matter, as well as the symbiotic relationship of mycorrhizal fungi with woody and herbaceous higher plants. Under the conditions of environmental parameter dynamics, new forms and species of fungi are formed, and their substrate-specificity is identified. At the same time, the metabolites synthesized by fungi have extremely high biological activity. In the production of biotechnological drugs, mushrooms are considered a potential source of enzymes, steroids, glycerol, organic acids, antibiotics, and other valuable substances [18]. The ability of fungi to biotransform certain substrates makes it possible to use them for steroid production. In addition, the use of fungi creates the basis for effective biological control of populations of pests, nematodes, and phytopathogens.

The problem of effective plant protection using biological methods can only be solved if the principles of relationships between the participants in the process are applied. Plants have a system of natural defenses against pests and diseases, but as a result of cultivation, many have lost the timeliness of their immune response. Plant defenses can be activated by treating plants with special substances called elicitors, which are inducers of resistance to various diseases [35, 36]. Bioextracts of some mushrooms are positioned as non-toxic substances that function as signaling molecules in very low concentrations. The most well-known inducers of resistance are polysaccharides, such as glucans, chitin, and chitosan [31, 37]. The development of the latter's potential has led to the emergence of several chitosan-based products on the market, but their widespread popularity lags due to their low efficiency compared to synthetic chemicals. The development of the industry for the efficient development of plant protection products using biologically active substances requires addressing multifactorial issues, as it is one of the most advanced science-intensive technologies.

The main issues of development and application of biotechnology of plant protection products against pests and diseases are the selection of the most effective agents of biological regulation of the number of phytophages and phytopathogens, the mechanism of their influence and interaction with the environment, methods of production, and determination of the form of preparations, and increasing the efficiency of practical use in agriculture. It should be noted that the basis for the development of bioprotection products is both representatives of basidiomycetes and their metabolic products in the form of toxins, enzymes, and other compounds. Antagonist fungi play a key role in suppressing the development of plant diseases. Even though certain species of basidiomycetes can suppress the development of phytopathogens through direct parasitism, antagonism by producing a range of antibiotic substances often prevails. The range of fungal antagonists used to create biological products for plant protection is gradually expanding. In the process of determining the preferred biological control agent for the development of plant protection products, it is necessary to select the initial strains in terms of virulence, productivity, and the ability to synthesize enzymes or toxins. The result of this selection concept is a strain that is superior in quality to the reference cultures of the drug manufacturer.

Figure 2 demonstrates complex mechanisms through which basidiomycetes interact with plants and pathogens, including competition, antibiosis, parasitism, and induction of systemic resistance. This visual representation highlights the key processes that facilitate plant protection and growth promotion.

Figure 2 highlights basidiomycetes' dual function as growth boosters and biocontrol agents. They present a viable substitute for chemical pesticides due to their capacity to inhibit infections while fostering plant growth via mycorrhizal symbiosis and systemic resistance induction. This diagram gives a clear picture of how these fungi support more resilient, healthier plants without the environmental hazards of synthetic chemicals, therefore supporting sustainable farming methods.

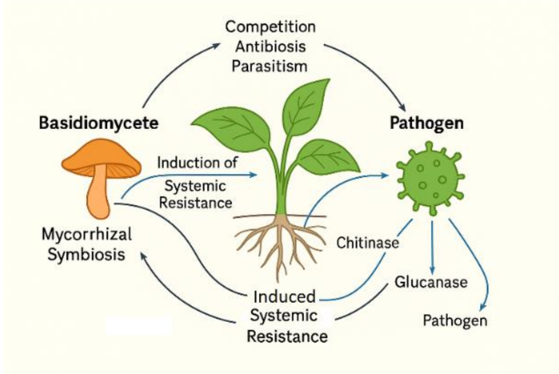

Figure 2. Mechanisms of action of basidiomycetes in plant protection and growth promotion

Thus, despite the existing limitations, fungal biological products are being actively researched and have significant potential. Their low popularity is determined by the technological complexity of mushroom cultivation and narrow requirements for environmental factors, as a high level of activity of mushroom-based biological products is typical only in the presence of sufficient moisture. There is also a need for serious research to identify the etiology of pests, which will allow for predicting the consequences of the interaction between plants, pests, and biopesticides. In addition, the expediency of developing genetic engineering methods in the context of basidiomycetes has been proven, which will provoke greater scientific and practical interest in fungi as potential producers of biopesticides, which will allow the development of more stable and effective drugs based on them.

Intensification of the production of biological products for plant protection and environmental stimulation of their growth requires further research to identify the most effective agents of biological regulation of phytophages and the development of their production technology. The process is complicated by the economic conditions of the transition period and the lack of a transparent regulatory framework for the registration of biological products, which is typical for Kazakhstan. Targeted government support for scientific achievements in the field of biotechnology of plant protection products and the implementation of a system of benefits for producers using biological products for plant protection can significantly catalyze the trend towards greening crop production in line with the course of sustainable green agricultural development.

4. DISCUSSION

The periodic renewal of interest in research and development of biological products for plant protection against pests and diseases is due to the global trend towards environmentally friendly plant protection products. The process is complicated by production problems in the development and use of biological products, as well as socio-economic constraints. Many scientific studies confirm the fact that greening of agricultural activities is a priority. Modern scientists, in particular, Araujo [38], determined the need to introduce modern biological plant protection measures within organic farming, along with the use of gentle tillage technologies and agrotechnical measures. According to the researcher, this concept will form sustainable phytocoenoses as a result of the selection of tolerant species and varieties, minimization of destructive environmental impact, and biological control of phytophages and plant diseases. The findings of the current study corroborate this viewpoint, aligning with the researcher's emphasis on the holistic approach to sustainable agricultural practices.

Basidiomycetes, according to Sipping et al. [39], have high adaptive capabilities, occupy various ecological niches, and play a significant role in ecosystems. Scientists, at the same time, argue that the long-term consequences of such features of basidiomycetes are the formation of local sustainable ecosystems, and with the competent use of fungal properties, quality indicators of sustainability are implemented in agrocenoses together with basidiomycete-based biopreparations. The current study concurs with the conclusion that Basidiomycetes, when properly harnessed, can contribute to sustainable agricultural practices by providing an environmentally friendly alternative to chemical pesticides. Singh et al. [40] emphasized that research should be based on knowledge of the structure of the fungal cell wall to utilize the maximum natural functionality of basidiomycetes. Scientists believe that when developing drugs that should be positioned as inducers of plant disease resistance, the priority belongs to glucan eliminators. The scientists emphasize that further research should be focused on the identification of biologically active glucans in higher basidiomycetes. This aligns with the findings of the current study, where the use of Basidiomycetes as effective plant disease resistance inducers was explored, highlighting their potential for further research in this area. However, the study by Singh et al. [40] lacks a detailed exploration of the practical application of these findings. The current study critiques this gap by suggesting that the effectiveness of glucans in plant protection could be enhanced through their integration with other biotic agents, such as microorganisms, to provide more targeted and robust disease resistance. This contrast suggests that focusing solely on fungal cell wall components may limit the full potential of biological products.

The results of studies by Geetha et al. [41] and Liu and Poobathy [42] focused on the ability of biological products not only to inhibit pathogens of infectious plant diseases but also to prevent the development of diseases when applied to the surface of leaves or fruits. The scientists also suggest using the unique synergy potential of microbial-basidiomycete interaction. Geetha et al. [41] highlighted the fact that almost all micro- and macro-mycetes, on the use of which biotechnology is based, are extracted from natural sources, and they are, in the scientist's opinion, distinguished by high biological activity. This study extends this notion by focusing on the potential synergy between Basidiomycetes and microbial interactions, as these synergies enhance the protective effects of these biological agents.

At the same time, Hernández-Santiago et al. [43] determined that specific biocontrol mechanisms in basidiomycetes, which include rhizosphere competence and induced systemic resistance, can provide a long-term protective effect. While these findings are valuable, the current study suggests that there is still much to explore in terms of optimizing the use of such mechanisms across different crops. The study acknowledges that these biocontrol agents are still in the early stages of development and that further refinement of their application could lead to more sustainable and effective plant protection strategies. In the development of this scientific research, Hanif et al. [44] pointed out that there are several limitations to the use of fungal-based biological products. Among them, scientists point out the preventive nature of biological products, the possibility of their use only within a limited framework or as part of a specific strategy, and a low level of effectiveness against systemic diseases against a high infection burden. The current study highlights these constraints, emphasizing the need for future research to improve the effectiveness of Basidiomycetes, particularly in combating systemic diseases under high infection pressure.

Many scientists of our time, for instance, Zhang et al. [45] and Cobos et al. [46], asserted that in the future the predominant role should be given to the biological method of plant protection under any initial conditions. The authors emphasized that at the stage of adaptive transformation of conventional crop production into ecologically oriented organic production, it is advisable to combine fungal biological products with a small number of fungicides. Their emphasis on integrating fungal biological products with minimal fungicide use resonates with the findings of this study, which demonstrate that a systematic, eco-friendly approach (minimizing synthetic chemical treatments) can indeed steer crop production toward sustainable organic practices without significant economic detriment. This consistent trend supports the broader argument that biological methods, specifically basidiomycetes, offer an efficient and viable alternative. However, there are some contradictions. While the current study recognizes the ongoing necessity for modest pharmacological intervention throughout the transitional phase, Zhang et al. [47] argued for the exclusive reliance on biological approaches as a holistic solution. This disparity can be attributed to the gradual nature of the shift to organic farming and the possibility that not all areas, especially those with very intensive agricultural operations, will be able to quickly adopt a fully biological approach.

These findings of the current study also align with those of Sabotič et al. [48], who advocated for biological products made from basidiomycetes due to their low level of secondary contamination, affordability, and environmental safety. The findings of the study support these theories and provide more information on the possible cooperation between fungi and microbes. Although Sabotič et al. [48] did not thoroughly investigate this combination, it has been emphasized as a possible path for biotechnology, especially in terms of improving efficacy. This idea was partially considered by Zhang et al. [47], who emphasized the fact that subsequent colonization of the rhizosphere by fungi results in suppression of pathogens, stimulation of crop growth, an increase in the quality and quantity of crops, and enhancement of plant resistance. Scientists believe that this optimizes the metabolic process, contributing to an increase in the size of the root system, active growth, and plant resistance to negative factors by controlling the rhizosphere microflora and affecting metabolism. This study expands on this concept, emphasizing the metabolic benefits and ecological balance achieved through microbial-fungal interactions, which warrant further exploration to fully exploit their potential.

The use of organisms and products of their vital activity to control the population density of insect pests and pathogens of crops is, according to Wu et al. [49], the most operative and technological variant of the biological method of plant protection. The researchers argue that modern methods of biological defense are often superior to synthetic chemical compounds in terms of their effectiveness due to their high selectivity and environmental safety. This aligns with the current study's results, which demonstrate how biological agents enhance soil quality, plant resistance, and environmental sustainability. The study contributes a crucial insight, proposing that the future of plant protection should prioritize combined preparations based on both fungi and microorganisms, as these compounds not only complement each other's actions but also enhance the specificity of the biological agents used in varying concentrations. Brown et al. [50] drew attention to the overall optimizing effect for local ecosystems in the case of a decisive replacement of the chemical treatment of agrocenoses with bioprotection. In particular, it builds plant resistance to adverse climatic factors, improves soil parameters, and detoxifies it from nitrates, heavy metals, and accumulated chemicals in pesticides. At the same time, scientists insist that in the future, priority will be given to combined preparations based on fungi and bacterial microorganisms, which not only enhance each other's action but also help to form the target specificity of the drugs' action in different compositions and ratios [51].

Many specialists, in particular, Wan Mohtar et al. [51] and Grabka et al. [52], developed and implemented multicomponent plant protection biological products consisting of fungi, living microbial groups of different taxonomic status and functionality, as well as mineral and organic compounds into the agrocenotic environment. According to the researchers, such multifunctional preparations allow for solving several agrotechnical problems simultaneously. For example, when biological ingredients such as potassium humate, immunocytophyte, and chelate are added to the biosynthesis process, new complex fungicides with growth stimulants and immunomodulatory effects are formed. According to their research, these diverse products can concurrently address a number of agricultural issues. This research agrees, pointing out that complex substances like immunocytophyte and potassium humate can be included to create strong biological agents that promote growth and ward off illness. The present study, however, emphasizes the necessity of more experimental investigations into the functional characteristics of basidiomycetes, especially with regard to their incorporation into intricate biological products.

Despite the ongoing search for scientifically based ways to effectively use the natural potential to increase the productivity of organic production, there is a lack of theoretical and experimental research on the functional capabilities of basidiomycetes as a source of innovative complex biological products. To improve plant protection based on basidiomycetes, future studies should concentrate on several important areas. To further understand plant defense mechanisms, research should specifically identify receptor proteins in plants that are activated by elicitors produced from basidiomycetes. Additionally, for targeted enhancements in biocontrol qualities, effective genetic modification methods for filamentous fungi must be developed. Research should also look into how fungal metabolites affect plant organogenesis and optimize basidiomycete formulations for increased efficacy and environmental safety. In order to stabilize Kazakhstan's agricultural output and improve sustainable plant protection, these approaches are essential.

5. CONCLUSIONS

The significant potential of basidiomycetes as ecologically friendly substitutes for traditional chemical pesticides in agriculture is highlighted in this research. The study's analysis of different strains of Basidiomycetes reveals their varied phytoprotective and phytostimulant qualities, which allow these fungi to fight plant diseases, manage pests, and stimulate plant development. The results demonstrate that basidiomycetes offer a viable way to lessen the negative effects of synthetic chemicals on the environment because of their antagonistic activity and capacity to boost plant defenses. Their incorporation into farming operations may greatly aid in the development of more environmentally friendly crop protection techniques.

Furthermore, by investigating the mechanisms of action of Basidiomycetes in plant disease and pest control, the review advances both academic and practical applications. It fills in the existing research gaps, especially with regard to the commercialization and practical effectiveness of biopesticides based on Basidiomycete. The investigation highlights the significance of comprehending these fungi's genetic potential and capacity to improve plant resistance, indicating that additional study into their genetic alteration and biotechnological formulation optimization may optimize their efficacy. These discoveries are essential for developing biocontrol techniques in agriculture, which provide a more environmentally friendly substitute for conventional techniques.

As a result, certain policy measures are required to encourage the development and use of biopesticides based on basidiomycetes. Governments should create a special funding program to encourage research and innovation in fungal-based plant protection, as well as a fast-track licensing mechanism for biopesticides to speed up their market entry. Furthermore, offering financial incentives to farmers who employ these sustainable products may hasten their adoption. Such targeted policy actions will be crucial in advancing the integration of biopesticides into mainstream agricultural practices and ensuring long-term sustainability.

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