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Field-grown fungi for soil health: In-field mushroom cultivation as soil amendment and bioremediation

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Abstract
Soil health is a critical determinant of agricultural productivity and ecosystem sustainability, yet intensive farming practices have led to widespread soil degradation, nutrient depletion, and contamination. Field-grown fungi, including mushrooms, is a sustainable solution for restoring depleted soil because they function as soil amendments and bioremediating agents. Mushrooms' amelioration enhances the soil's structure, promoting water retention and aeration. Moreover, fungi have showcased the potential to degrade organic compounds such as pesticides and hydrocarbons also restricting heavy metals by enzymatic activity and bio-absorption. Integration of mushroom cultivation with crop systems through rotation or intercropping further enhances plant growth, yield, and soil resilience. However, various challenges to scaling have prevented its implementation in broader landscapes, including sensitivity to environmental factors, pest and disease pressures, economic considerations, and a lack of knowledge. Advances in fungal biotechnology, new improved strains, nano-formulations, precision agriculture tools, and policy for this approach may improve how field mushrooms can be used. This review describes mechanisms of how soil health benefits from mushrooms and their abilities to remediate contaminants, presents some evidence from field trials, and discusses practices for incorporating fungi into sustainable agriculture. By promoting the use of field-grown fungi, this approach offers an eco-friendly, cost-effective, and scalable solution for restoring soil fertility and enhancing agricultural sustainability.

Keywords: Field-grown fungi, mushroom cultivation, soil health, bioremediation, spent mushroom substrate, Mycoremediation, sustainable agriculture, crop-fungi integration

1. Introduction

Soil is the basis for all land ecosystems and of agricultural production. The healthy soil supplies plants with nutrients, water, and mechanical support and has population of microbial species that play crucial roles in ecological processes, including biogeochemical cycles (Hu *et al.*, 2021) [1]. Soil erosion, soil nutrient depletion, lack of soil fertility, and water scarcity can be associated to poor land management, including excessive use of chemical fertilisers, deforestation, and intensive agriculture. These challenges require new soil restoration and fertilization practices that does not compromise food security. Traditional soil fertility methods like synthetic fertilisers, organic manures, and compost application are still used (Bhagarathi *et al.*, 2023) [2]. Chemical fertilisers provide faster release of nutrients, but overuse can result in groundwater contamination, soil acidification, and alteration in soil ecosystem. Thus, adding compost, crop waste, and farmyard manure to soil is beneficial to increase structural development and microbial diversity. It can take a long time and a lot of material to improve soil health with these materials. Therefore, sustainable and long-term solutions that promote soil biology, resilience, and nitrogen release are required. Fungal degradation of organic compounds maintains soil health in natural ecosystems. Symbiotic interactions with plant roots increase development and stress tolerance, improve soil aggregation via hyphal networks, and transform complex organic compounds into simpler accessible forms for nutrient cycling (Sipasi, 2024) [3]. In agroecosystems, mushrooms, a subset of soil-associated fungus and macro-fungi, are increasingly recognised for their multifunctional capabilities. Field mushrooming offers many benefits. They have significant nutritional content, can add organic matter and boost the microbial diversity in the soil.

The recent studies regarding the use of field-grown fungi, particularly mushrooms, as bioremediation tools are reviewed.

Objectives of the paper are to understand the function of mushrooms in synthesizing healthy soil out of unhealthy ones, their capacity for organic matter addition and nutritional content, and contaminant degradation; as well as provide information on the prospects and challenges associated with the practical management of field-based soils using fungi. The present work offers a complete vision of the mushrooms' use in an ecological sense to apply them for sustainable agriculture and soil fertility progress.

2. Overview of Field-Grown Fungi

Field-based fungi and mushrooms are important for soil improvement because of their ecological functions and their enzymatic capability for degradation. These fungi have been subdivided into four categories-edible, medicinal, lignicolous, and saprotrophic types.

2.1 Types of Mushrooms Suitable for Field Cultivation

- **Edible Mushrooms**: Species like *Agaricus bisporus* (button mushroom), *Pleurotus ostreatus* (oyster mushroom), and *Lentinula edodes* (shiitake) are cultivated for human consumption (Dighton, 2019) [4]. These mushrooms can be beneficial for soil health. As they break down organic materials and nutrients to the soil.
- **Medicinal Mushrooms**: Mushrooms, such as *Ganoderma lucidum* (reishi) and some species of Cordyceps, are cultivated for their medicinal properties. Even though they are less cultivated, they have an impact on soil's decomposition activities as well as soil health.
- **Lignicolous Fungi**: Fungi, e.g., some species of *Ganoderma* and *Polyporus*, are known for lignin-rich substrate degradation, such as wood (Fungi, 2018). Their degradation of complex organic substances plays a role in the nutrient cycle in soil habitats.
- **Saprotrophic Fungi**: Fungi such as *Pleurotus ostreatus* can break down organic matter, adding essential nutrients to the soil. Their contribution to nutrient cycling is an important part for maintaining soil fertility.

2.2 Life Cycle and Ecological Roles

Mycelium grows through the substrate and digests organic material while collecting nutrients. Fruiting bodies are the final stage of growth cycle. Then the process repeats itself with spores (Ntsobi, 2020) [6]. As decomposers, they degrade complex chemical compounds into plant food. As organic matter breaks down, more nitrogen, calcium, and potassium added to soil.

Mycorrhizal relationships are observed between fungi and plants. These relationships enable exchanges such as fungi receiving carbohydrates from plants, water, and nutrients from fungal hyphae that help plants grow longer roots. This relationship between the living beings is beneficial for both plant and soil.

2.3 Decomposers and Their Interaction with Soil Microbiota

Fungi, which break down organic matter, are very important to the carbon cycle because they recover carbon and other nutrients (Ahmad *et al.*, 2018) [7]. This method increases the number of microbes and soil nutrients. Microbes in the soil and fungi are interlinked in a complicated but beneficial manner. Soil microorganisms are crucial for breaking down organic matter, suppressing diseases, and recycling nutrients. Plants, in turn, benefit from fungi because they can compete against harmful microbes for food and space. Competitive exclusion is the basis of soil health and plant production.

2.4 Commonly Cultivated Mushrooms

The most cultivated species of mushrooms include *Agaricus bisporus, Lentinula edodes*, and *Pleurotus ostreatus*. These mushrooms are suited for sustainable agriculture since they have a wide range of culinary and medicinal uses and have remarkable field adaptability (Dubey *et al.*, 2020) [8]. Several mushrooms, including *Agaricus bisporus, Pleurotus spp., Volvariella volvacea, Calocybe indica,* and *Lentinula edodes*, have been grown in India since ancient times. Various agricultural by-products are commonly used in the mushroom cultivation process.

2.5 Symbiotic vs. Saprotrophic Fungi

Fungi, such as mycorrhizal and other symbiotic species, assist plants in taking up water and nutrients. Saprotrophic fungi break down organic matter to recycle the nutrients into the soil. No soil is fertile in the absence of both types of fungi; regulating fertility and ecological balance (Visconti *et al.*, 2020) [9]. Due to their variety and ecological benefits, field-grown fungi boost soil health. Their ability of degrading organic matter and soil microbial associations make them significant in sustainable agriculture.

3. Mushroom Cultivation Techniques in the Field

Several things must be done to grow the mushrooms in the field, including selecting the substrate, introducing the mushrooms, managing the environment, and post-harvesting management of mushrooms (Roy *et al.*, 2018) [10]. These methods help grow mushrooms well and contribute to the soil's health by introducing organic matter and cycling nutrients.

3.1 Substrate Selection

Using the right substrate for growing mushrooms is important, as it provides the nutrients they will extract. Crop residues such as wheat straw, rice straw and sugarcane bagasse are used as substrates. Lignin and cellulose in these components provide nutrients for mushrooms when degraded by enzymatic action (Yang *et al.*, 2024) [11]. To grow milky mushrooms (*Calocybe indica*), people in Arunachal Pradesh put pasteurised rice straw on top of spawn in plastic bags. This method gives fruiting within a month. The weather there is suitable for growth of milky mushrooms.

3.2 Inoculation Methods and Spawn Types

Inoculation is the process of placing mushroom spawn into a medium i.e. primarily of two types of spawn: 'plug' and 'sawdust'. The speed with which sawdust spawn grows colonies makes it a great inoculant for use with bulk materials (Chandwani & Amaresan, 2024) [12]. Nonetheless, shiitake and other species of mushrooms are usually grown conventionally by placing plug spawn in drilled holes within logs. The inoculation should be performed in a clean environment to ensure good colonisation and prevention of contamination.

3.3 Seasonal Considerations and Growth Conditions
There are several requirements to grow mushrooms. The growth conditions that influence fruiting are light, humidity, and temperature." For example, to grow shiitake mushrooms, a temperature of 22-25 °C is needed, and with oyster mushrooms (*Pleurotus ostreatus*), a temperature range of 24-29 °C obtains best results. In places with different seasons, farming is usually set to happen when the weather is good (Sun *et al.*, 2025) [13]. On the contrary to many other countries, where mushrooms are grown seasonally, it is warm enough in some parts of India to produce them year-round. For instance, species that grow well in warm regions, such as *Calocybe indica*.

3.4 Harvesting and Post-Harvest Handling
Harvesting ripe fruit of mushrooms at the right time preserves quality and enables a long shelf life. Afterwards, mushrooms are cleaned, sorted, and packaged to prevent them from spoilage. Proper storage includes refrigeration which extends shelf life and reduces spoiling (Mishra *et al.*, 2021) [14]. By contributing organic matter to the soil, discarded mushroom substrates can also aid sustainable agriculture.

Growing mushrooms in the field improves soil quality and crop yields sustainably. Organic matter enrichment and nutrient cycling boost soil fertility, and farmers can profit from farmed mushrooms. Nutritional and environmental benefits can be achieved by adopting appropriate inoculation, substrate selection, and environmental control.

4. Fungi as Soil Amendments
Fungi benefit soil health and productivity, especially the ones used in mushroom cultivation (Tovar-Sánchez *et al.*, 2023) [15]. Through multiple pathways they can increase nutrient availability, organic matter and microbial diversity in the soil, which ultimately helps to improve the soil texture, infiltration capacity of water, and aeration.

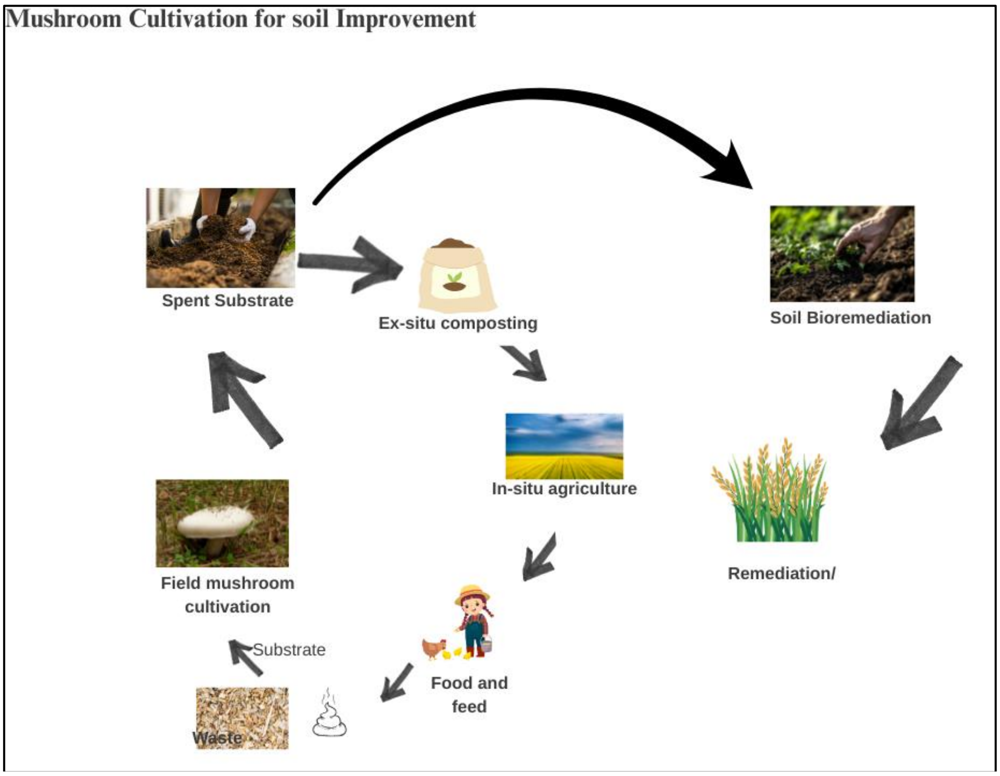

Fig 1: Roles of field cultivation of mushrooms in soil (Hu *et al.*, 2021) [1]

4.1 Mechanisms of Soil Improvement
4.1.1 Nutrient Enrichment: Mushrooms and spent mushroom products are a good source of nutrients which includes potassium, nitrogen, and organic matter. Studies have shown that adding spent mushroom substrate (SMS) to soils increases the content of these nutrients. Pooler (2025) [16] says that farms that were SMS Max A Press-adjusted had about five times higher amounts of soil mineral nitrogen. Stratton and Jack (2020) [17] discovered that fields treated with SMS Max A were easier to get to for N, P, and K.

4.1.2 Organic Matter Addition: Fungal waste breaks down organic matter, which helps make humus, a stable form of organic matter that makes soil more fertile. Adding SMS to soils has proven to raise the amount of organic matter present in the soil, which improves its structure and ability to hold nutrients.

4.1.3 Enhancement of Microbial Diversity: Fungi are very important for creating the communities of microbes in soil. Adding SMS to soil has been shown to increase the variety of microbes and enzyme functions, which are signs of better soil health (Katiyar *et al.*, 2024) [18]. For instance, Lou *et al.*'s study showed that SMS-amended soils had higher amounts of microbial diversity and enzyme activities than PMC soils that had not been treated.

4.1.4 Effect on Soil Structure, Water Retention, and Aeration
SMS enhances soil aggregation and reduces compaction. The improvement of root penetration and water infiltration resulted from enhanced porosity. According to Penn State Extension, SMS organic matter improves the water-holding capacity of soils and decreases the irrigation frequency. Soil aeration is increased by the better soil structure and reduced

bulk density after SMS application (Lanfranco & Fiorilli, 2022) [19]. This is especially useful in clayey soils, which are compacted and aerate poorly. SMS helps aerate soils, which supports soil microorganisms and root growth.

4.2 Case Studies of Soil Amendment Using Mushroom Residues or Spent Substrates

Multiple studies have proven that SMS and mushroom leftovers improve soil (Pessarakli, 2019) [20]. For instance, multiple SMS applications significantly increase the concentration of soil organic matter, pH, and the microbial activity in vineyards soils. SMS enhanced grapevine growth and yield, indicates its potential as a viticultural soil amendment.

Cucumbers are cultivated in horticulture using SMS. SMS was found to improve plant height and fruit yield (Pessarakli, 2019) [20]. SMS may be a viable peat substitute in horticulture. Mushroom remnants and SMS boost soil fertility and health over time. Fungi adds organic matter, increases microbial diversity, and enriches nutrients in soils. The addition of SMS also improves structure, water retention, and aeration. Several case studies illustrate that fungi improve soil in various agricultural settings. Using fungi-derived compounds in soil management can help sustain agriculture and soil health.

Table 2: Effect of Different Mushroom Residues on Soil Properties

Mushroom Species/Residue Type	Application Rate	Soil Property Affected	Observed Effect	Reference
Pleurotus ostreatus SMS	5 t/ha	Organic Matter	Increased by 18-22%	(Stratto & Rechcigl, 2020) [21]
Agaricus bisporus SMS	4 t/ha	Soil Nitrogen (N)	Increased by 12-15%	(Bhatt *et al.*, 2020) [22]
Lentinula edodes SMS	3 t/ha	Soil Phosphorus (P)	Increased by 10-13%	(Aranco & Solarte, 2019) [23]
Mixed Oyster + Shiitake SMS	5 t/ha	Microbial Diversity	Enhanced bacterial & fungal populations	(Verma *et al.*, 2019) [24]
Calocybe indica SMS	5 t/ha	Soil Water Retention	Improved by 15-20%	(Chaudhary, (2022) [25]
Pleurotus ostreatus + Compost	5 t/ha	Soil Aeration	Reduced compaction; improved porosity	(Hu *et al.*, 2021) [1]
Agaricus bisporus SMS	4 t/ha	Soil Potassium (K)	Increased by 8-12%	(Bhagarathi *et al.*, 2023) [2]

5. Bioremediation Potential of Field-Grown Fungi

Field-grown fungi (mainly macrofungi), which can restore damaged soils based on their special metabolic ability, are a workable example. Mycoremediation uses fungi's powerful enzymatic and physiological properties to break down or neutralise environmental contaminants for soil health. Fungi are ideal for bioremediation due to their prolific hyphal networks, large adsorption capacity, and different extracellular enzymes that decompose various complex chemical compounds. Mycoremediation is also less expensive and more sustainable than physical and chemical restoration (Sipasi, 2024) [3].

Mycoremediation by fungi may be a metabolically mediated biodegradative or even bioaccumulative process. Saprophyte fungi *Pleurotus ostreatus* and *Phanerochaete chrysosporium* produce the ligninolytic enzymes. These enzymes oxidize and decompose many of the persistent organic pollutants. Fungal enzymes are degrading synthetic dyes, PCBs, and PAH. Since their enzymes are extracellular and can act on contaminants in soil or water matrices without internalisation, fungi are excellent remediators (Dighton, 2019) [4].

Fungal bioremediation degrades hydrocarbons and pesticides. Numerous studies show that field fungus can decompose organophosphate insecticides, polycyclic aromatic hydrocarbons, petroleum hydrocarbons, and more. *Pleurotus ostreatus'* ligninolytic and cellulolytic enzymes may break down diesel hydrocarbons in field-polluted soils in weeks (Fungi, 2018). *Phanerochaete chrysosporium*, used to detoxify synthetic pesticide-polluted soils, produces fewer toxic intermediates that local soil bacteria can mineralise (Ntsobi, 2020) [6].

Fungi are crucial to heavy metal detoxification. Fungal cell wall made of polysaccharides like chitin and glucans have metal-chelating groups. These ions are cadmium, lead, chromium, and arsenic. Biosorption by fungi reduces metal bioavailability and toxicity from polluted soils. Some fungi can stabilise soil by enzymatically reducing or methylating metals into insoluble or less toxic forms, according to (Ahmad *et al.*, 2018) [7]. Pleurotus spp. can remove lead and cadmium from agricultural soils, and even after harvest, the remaining substrates can bind metals (Dubey *et al.*, 2020) [8].

Fungi also showed promise in a few field studies on soil bioremediation. Applying the oyster mushroom mycelium in contaminated soil with petroleum enhanced species of microorganisms in terms of the biomass and number, changed soil structure, and increased nutrient accessibility. It also accelerated hydrocarbon decomposition. Another study indicated that pesticide-contaminated soils decomposed organophosphate residues faster after adding leftover mushroom substrate, indicating that trash can remediate soil and use waste (Visconti *et al.*, 2020) [9]. (Roy *et al.*, 2018) [10] Noted that the repeated applications of *Pleurotus ostreatus* mycelium could increase soil organic matter content and microbial diversity, but lower bioavailable lead and cadmium levels in heavy metal-polluted farmlands.

Fungi are excellent bioremediation agents that can grow in varied environmental niches and work with the soil's microflora. Fungal hyphae can enter micropores that bacteria cannot to breakdown contaminants deep in the soil matrix (Yang *et al.*, 2024) [11]. Furthermore, fungi may enhance bioremediation by stimulating bacteria with complementary degrading pathways. Fungal bioremediation should be fed into soil recovery strategies for its complementary action.

In addition, their enzymatic, metal sequestration, and soil microfloral associations effects are appropriate for field-grown mushrooms to be used as bioremediation tools. Fungus communities degrade organic pollutants, detoxify heavy metals, and promote microbial diversity to rehabilitate the degraded soil. Several fieldworks demonstrate that the mycoremediation soil rehabilitation is a sustainable, inexpensive, and eco-friendly method. Research into fungal strains, substrate formulations, and field deployment methods can increase fungal bioremediation in industrial and agricultural settings.

6. Synergy with Crop Systems

Fungi growing in the field, especially mushrooms, interact with agricultural crops and assist regulate soil health in addition to providing food and medicine. The interaction between crops and mushrooms influences plant growth and harvest by the cycle of nutrients addition, proliferation in microbial diversity in the soil, and improvement in soil physical characteristics. Fungi decompose complex organic detritus, and their nutrients can then be easily absorbed by crops resulting in a nutrient-rich system. This optimises crop growth. Waste mushroom substrate (SMS) is used as biofertilizer to enrich soil with organic matter, which improves structure and water-holding capacity and delivers macronutrients like nitrogen, phosphorus, and potassium (Chandwani & Amaresan, 2024) [12].

Mushrooms improve soil fertility and agricultural yield in crop rotation and intercropping. Growing mushrooms and intercropping with crops such as cereals or legumes can improve soil nitrogen balance, use of residue, and pest and disease control by eliminating the hosts (crop residue). Cultivating *Pleurotus ostreatus* on paddy straw or sugarcane bagasse in neighbouring vegetable crops will increase the soil organic matter (SOM) and microbial activity, leading to improved vegetable yield. Soil nitrogen biologically fixed by legume-mushroom rotations increases crop yields in succeeding cycles (Sun *et al.*, 20225) [13]. Fungal and crop collaboration can eliminate artificial fertilisers and enhance nutrient management.

The fungal hyphae interact with the soil microbes and establish themselves as competitors of pathogens in the soil. These exchanges suppress soil-borne diseases and enhance plant stress tolerance, as well, according to (Mishra *et al.*, 2021) [14]. Result: better crop stands and higher yields. Fungal mycelium improves soil aeration and water penetration, which helps intercropped plants grow roots and absorb nutrients.

Field trials show that mushroom integration into crop systems is beneficial. SMS or mushroom cultivation has improved plant height, biomass, and fruit output in vegetable cropping systems. Decaying mushroom substrates improved soil fertility indices in cereal-legume rotations, increasing grain and legume yields and lowering input costs (Tovar-Sánchez *et al.*, 2023) [15]. These results support the hypothesis that mushrooms can serve as an agricultural method for integrated soil health management, incorporating improved nutrition, reduced pests, and improved soil structure, which are key to sustainable agriculture. Finally, crop systems incorporating field-grown fungus show potential as a sustainable agricultural method. Plants show enhanced growth, yield, and resistance with mushrooms, and soil physical properties, microbial interactions, and nutrient cycling are increased. Crop rotation and mushroom interplanting make the most of growing areas, decreasing industrial synthesis, enhancing soil fertility, and ecological security. Agronomic and ecological merits of the cultivation of mushrooms through traditional cropping systems have positioned them in the integrated soil-crop management system.

7. Challenges and Limitations

The field cultivation may contribute substantially to the participation of the fungus in soil health and bioremediation, but some obstacles prevent a broad use of such mechanisms. Fungal growth and development depend on soil pH, moisture, and temperature, so the environment is the primary barrier. Many mushrooms require a specific temperature, mycelial colonization, and fruiting. Temperatures beyond and below these temperatures will cause reduced yields or no fruit set. Excess water in soil encourages competing microorganisms, and too little water slows mycelial growth. Most farmed mushrooms flourish in slightly acidic to neutral soil, which affects food availability and fungal metabolism (Pooler, 2025) [16]. Pests and illnesses complicate field farming. Mushroom-consuming bugs, invertebrates, and mites can destroy mycelium to fruiting bodies, while bacterial and fungal infections, such as *Trichoderma* spp., can significantly reduce mushroom yields. These biotic stresses are labor-intensive to monitor and keep clean. It is economics, labour, and resources that are the problem. However, poor farmers would be unable to use these systems for cultivation because of the costly substrates, spawn, infrastructure costs, and the need for trained workers. Market volatility and seasonal limitations may also result in the unpredictability of mushroom production financial returns (Stratton & Jack, 2020) [17].

Significant research and knowledge gaps remain. Although the potentials of spent mushroom substrate (SMS) and mycoremediation are already known on a laboratory scale, little work has been done in the field conditions with agroecology zones. Further studies are required to understand how species respond to soil, stress conditions, and integration practices. Uniform application rates and substrate compositions, combined with uniform management practices, result in consistency of soil growth. Filling knowledge gaps through research and extension is essential for fungal-based soil management to become more popular.

8. Future Directions and Opportunities

Biotechnologies and fungal strains provide field-grown fungi a bright future in sustainable agriculture. Some persistent or genetically modified mushroom strains with stress tolerance can enhance bioremediation, nutrient cycling, and yield in adverse environmental conditions. Nano formulation, bio-fertilizer, and mushroom cultivation can help increase soil microbial activity, plant growth, and nutrient supply

Precision agricultural equipment can improve field conditions and resource usage. They include mobile crop or mushroom management apps, sensor-based monitoring, and AI-driven environmental controls. Both systems offer immediate measuring of substrate moisture, temperature, and pH to minimize contamination and enhance mushroom yields. Sustainable agricultural programs that incorporate mushroom-derived soil additives and farmer education are crucial for their uptake. Even for smallholder farmers, the substrate preparation, inoculation, cropping system integration, and post-harvest processing can be taught in farmer field schools or offered through extension services and demonstration plots.

9. Conclusion

Growing fungi in the field is a long-lasting and flexible way to fix up damaged soils, boost general soil health, and increase crop yields. Mushrooms and the things they make are good for farming because they break down pollution and add nutrients, organic matter, and different kinds of microbes. Even though there are problems like bugs, a lack of knowledge, and concern for the environment, there are clear ways to move forward thanks to progress in fungal biotechnology, nano-formulations, ICT applications, and laws that support their use. Researchers and farmers should focus on species-specific optimisation, test on a large scale in the field, and use integrated soil management methods to get the most out of mushrooms for sustainable farming. Long-term benefits of using fungus in farming systems include fixing up the soil, keeping the environment stable, and making sure there is enough food for everyone.

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