

Review

The Quirky Rot Fungi: Underexploited Potential for Soil Remediation and Rehabilitation

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Abstract: Currently, when the role of biodiversity in maintaining and restoring ecosystems is widely discussed, rot fungi are far from being integrated into common policies, conservation laws, or risk assessment frameworks. Despite the widespread recognition of the natural role of rot fungi as decomposers and their capabilities for various industrial purposes (the treatment of effluents rich in organic or inorganic substances), their peculiar characteristics are poorly understood and investigated. Highlighting the potential of rot fungi is of paramount importance because, as natural resources, rot fungi align perfectly with soil sustainability and the green growth policies and strategies outlined in this decade by the European Commission (2021) and United Nations (2021). This short piece aims to highlight and encourage efforts that channel into the exploration of this group of organisms as bioinoculants and biofertilizers for agriculture and forestry, as remediators and rehabilitators of soils affected by anthropogenic contamination (e.g., metals, agrochemicals, and plastics), and devastated by phenomena arising from climate change (e.g., forest fires) by briefly presenting the pros and cons of each of these lines of action and how rot fungi characteristics may fill in the current knowledge gap on degraded soil rehabilitation.

Keywords: decaying fungi; sustainable development; nature-inspired solutions; restoration; soils



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1. Soil Ecology, Health, and Erosion Control

It is important to highlight the primary functions of rot fungi in soils because these functions are fundamental to soil maintenance. They are also known as saprotrophic and decaying fungi. Rot fungi are ubiquitous, occupying a prominent position in nature. Although they often go unnoticed, they play a fundamental role in the decomposition of materials, such as cellulose and lignin [1]. Cellulose and lignin are recalcitrant carbon (C) compounds; that is, forms of C that are resistant to decomposition and are therefore not readily available for use by other soil organisms, such as other microorganisms or plants. Without the action of fungi, plant matter remains in the environment for an indefinite period. The ability to degrade recalcitrant C forms is due to the set of enzymes present in the secretome that act on these sources of organic matter and allow its degradation into more easily decomposable (labile) C forms, which can serve as sources of nutrients for others. Rot fungi largely contribute to the nutrient cycle in the soil; namely, phosphorus (P) and nitrogen (N) [2,3]. By promoting the degradation of organic matter, this group of fungi also contributes to the formation of soil, particularly the upper part called humus [4], improving the physical structure of the soil, its water retention capacity, and, generally, soil productivity (Figure 1). It is also worth highlighting that the growth of these fungi can result in hyphal extensions of hundreds of meters, which constitute up to 70% of soil biomass.

This network can function as an expansion route for other decomposer microorganisms with less mobility capacity (e.g., bacteria; [5]) and a communication route between other organisms, such as trees, but it also allows the maximization of soil resources (Figure 1). Soil habitat modification by fungal hyphae dictates the establishment and resilience of bacteria, whereas fungi are unaffected by modifications introduced by bacteria [6]. Soils are spatially heterogeneous, and the hyphal network of these fungi allows the translocation of nutrients from more nutritious places to places of greater scarcity [4], thus indirectly fostering soil-related ecosystem services. These characteristics are highlighted below in the context of environmental rehabilitation, focusing on scenarios of agriculture, forest fires, and land reclamation in mining areas, and are perfectly harmonized with the current political agendas of the European Union [7,8].

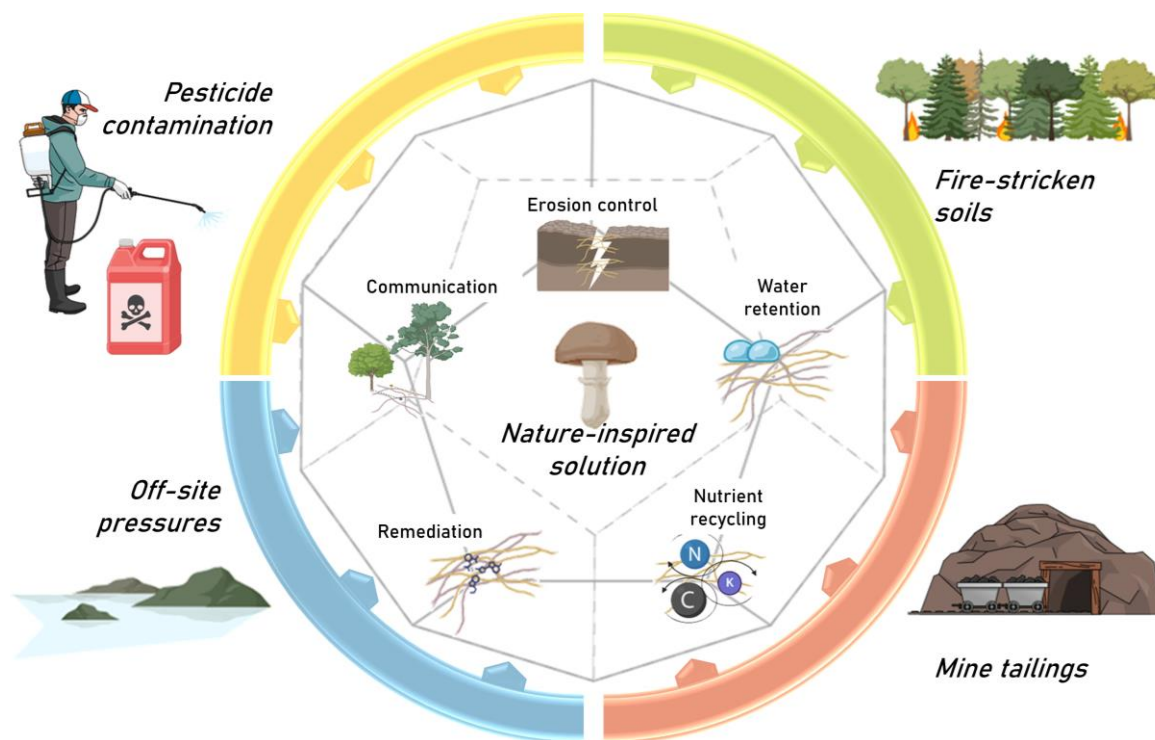


Figure 1. Overview of the main characteristics of rot fungi that can be harnessed and fostered to restore and reclaim anthropogenically stressed or climate change-stressed soils.

2. Agricultural Sustainability, Post-Fire Forest Management, and Ore-Affected Soils: Shared Challenges with Common Goals

Why address and explore the characteristics of rot fungi in scenarios of agricultural sustainability, forest management after fires, and soil affected by mining activities? Although each has its own intrinsic characteristics, they have common challenges that revolve around the need to balance the use of resources in relation to soil degradation and converge towards the same objectives of environmental protection and soil rehabilitation, which can be met by the natural activity of these fungi. Soils that are affected by mineral activities, are devoid of nutrients, and are loaded with heavy metals are unsuitable for agriculture or forestry in their raw state. Mining disrupts land and ecosystems and alters soil quality, water resources, and vegetation cover [9–11]. Areas affected by fires generally face the same challenges as those affected by mines, with soils being devoid of nutrients or lacking structures, prone to erosion by water or wind [12], and agricultural soils being increasingly pressured by the entry of various synthetic products [13]. All three scenarios, each with different weights, contribute negatively to various ecosystem services. Contamination

scenarios contribute to soil erosion and nutrient depletion and threaten soil productivity (and product safety). These three scenarios also contribute to the loss and fragmentation of habitats, which, in turn, is reflected in the loss of biodiversity. It is worth highlighting here that soil productivity is not only related to food production but also to a series of ecosystem services, such as C sequestration and water and air regulation, which together are related to human well-being ([14]; Figure 1). Thus, the key objectives of this review are defined based on recent European Commission programs that call for more environmentally friendly practices to restore soil fertility and productivity, while designing them with tools to be resilient under current and future climate change scenarios [14]. The use of rot fungi as potential rehabilitators, described below in more detail for each of these scenarios, aims to promote them as partial replacements for synthetic improvers in forestry or agricultural contexts (reducing the burden of traditional chemical inputs) and remediating contaminated sites (along with the development and implementation of effective remediation technologies to clean up contaminated mines, restore ecological function, and prevent future contamination), and to strengthen regulations and enforcement to prevent future chemical contamination. All three sectors lack the establishment of robust monitoring programs to track the levels of chemical contamination and assess the effectiveness of remediation efforts, although they have evolved to promote the development of rehabilitation techniques harmonized with the environment itself. These scenarios are adequately addressed in the following sections, highlighting how rot fungi can be valued. As natural resources, they are therefore eco-friendly and a tool ready to be explored in each of these contexts. However, fundamental research in this field is lacking. By facing these challenges and pursuing these goals, we can protect human health, safeguard ecosystems, and ensure the long-term sustainability of agriculture, forestry, and mining.

The remediation processes carried out by the organisms are described, in a transdisciplinary way, as a sustainable and nature-based alternative to traditional remediation methods, which may involve aggressive chemicals or the physical removal of contaminated materials. Rot fungi have the versatility to deal with a wide range of persistent chemicals (e.g., metals, polycyclic aromatic hydrocarbons (PAH), dyes [15]), and this characteristic has been prominent in several biotechnological applications, such as the treatment of waste and/or effluents [15–18]. Therefore, the ability to decompose complex organic compounds must also be tested in situ for the degradation of pollutants of anthropogenic origin in soils, and in this way help to reclaim soils (Figure 1). The ability of rot fungi to degrade recalcitrant materials arises from their ability to release a comprehensive, nonspecific, and nonstereoselective lignin-modifying enzymatic toolkit into the environment. The composition of the rot fungi secretome can be changed both qualitatively and quantitatively. Its composition and concentration may not only depend on the nutritional needs of the fungus, but also on the confrontation with hard and recalcitrant substrates or stressful conditions that may upregulate its production to increase resilience to adverse conditions [19–22]. For example, the enzymatic toolkit of *Pycnoporus coccineus* has been found to expand appropriately when dealing with increasingly woody substrates (ranging from liquid maltose media to soft and hardwood substrates; [19]); similarly, the enzymes manganese peroxidase (MnP), lignin peroxidase (LiP), and laccase (Lac) gradually increased when *Pleurotus ostreatus* was grown in medium supplemented with decabromodiphenyl ethane, a brominated flame retardant, with the MnP, LiP, and Lac reaching their highest values (of 4.01, 3.62, and 17.29 U/mL, respectively) after 120 h of incubation with the chemical [19]; or, the incubation of salt-stressed soil with rot fungal exudates could improve the effects of osmotic stress on the growth and germination of agricultural-valued species [20]. Furthermore, the potential of rotting fungi does not end. It has been known for some time that rot fungi are capable of successfully colonizing and degrading plastics [22] and, considering the current panorama

of plastic pollution around the world, their biotechnological potential to overcome plastic pollution in soil matrices is increasing substantially. In summary, the bioremediation of soils by rot fungi involves the use of these fungi to facilitate the degradation, transformation, or immobilization of contaminants in the soil, ultimately restoring or improving the overall health and environmental quality of the soil.

2.1. Pesticides

It is indisputable that pesticides have been introduced to many sectors, especially in the global demand for satisfying food production. The benefits include, among many others, increasing crop yields by protecting crops against pests, diseases, and weeds (the maintenance and prevention of post-harvest crop losses), increasing the quality of food products, reducing the need for pest control methods and the adjacent workforce, and allowing the monetization of investments and profits for small and medium-sized producers [23].

However, the balance between its use and environmental and health safety to minimize risks to ecosystems and human populations is becoming increasingly impaired. Indiscriminate use, inadequate storage and disposal, or ignorance of more environmentally friendly alternatives are the main precursors of consequences (i) at an environmental level, related to the loss of biodiversity, the contamination of matrices (soil, water, and air), and interfering with ecosystem functions such as nutrient recycling and pollination; (ii) at the level of human health, correlating with occupational exposure, but also related to the increase in pesticide residues in products that reach consumers, and even incurring economical losses since the poor management of these products can lead to lower crop yields due to damaged ecosystems and poor soil health and require greater investment in research into alternatives (Figure 2).

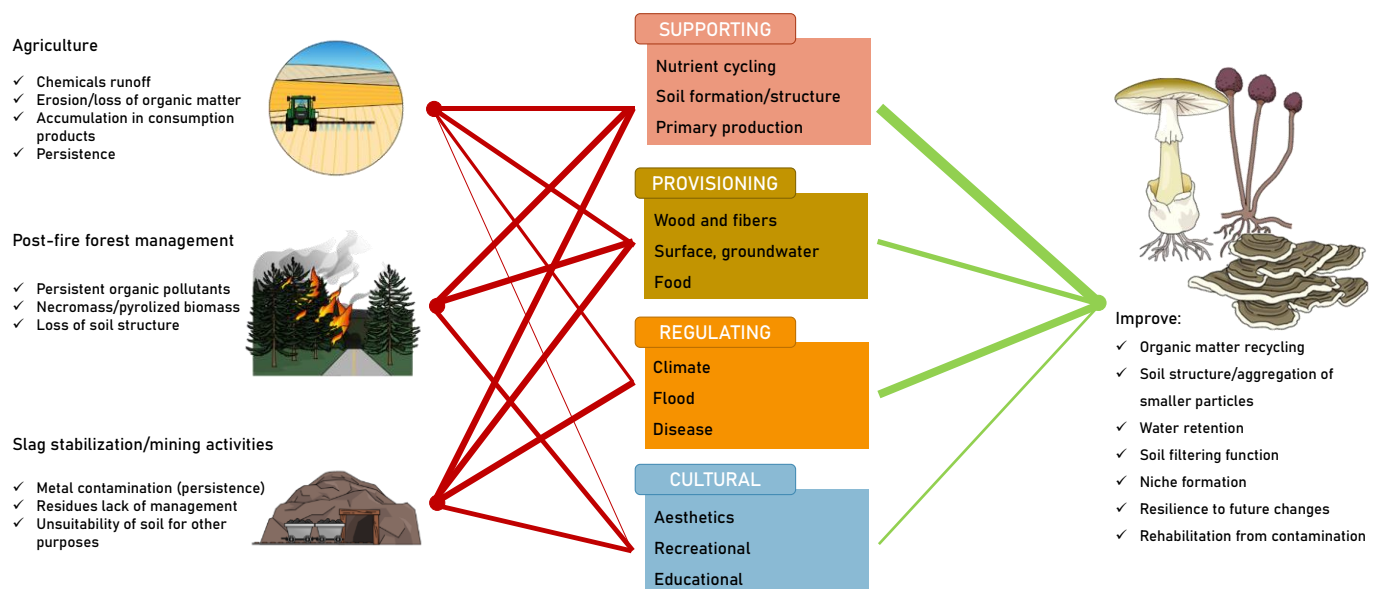


Figure 2. The ecosystem services affected by the three explored scenarios of soil degradation and an overview of the main characteristics of rot fungi that can be harnessed and fostered to restore and reclaim soils in these contexts. The thickness of the lines indicates the more or less direct an action on a given ecosystem service is, and it should be noted that only some more relevant directions are explored.

Taken together, the recurrent and long-term use of pesticides in agriculture has led to significant soil contamination. Agricultural practices involving pesticides have been identified as the main factor in soil degradation, with approximately 60% of soil already

flagged as degraded. However, this figure is set to reach 90% by 2050 [24]. A survey on the prevalence of pesticide residues in European soils revealed that 83% of the tested European agricultural soil samples were positive for pesticide residues and over 50% contained multiple pesticide compounds. Commonly detected pesticides include glyphosate, boscalid, epoxiconazole, and tebuconazole. The presence of these residues poses significant ecological risks, particularly to soil organisms, with 14% of sites exhibiting potential harm from pesticide mixtures, primarily due to insecticides such as imidacloprid and chlorpyrifos and the fungicide epoxiconazole. These findings underscore the need for sustainable agricultural practices and stricter regulations to mitigate the long-term effects of pesticide use on soil health and biodiversity in Europe [25].

In the context of the remediation of pesticide-contaminated soils, white-rot fungi have been studied for some time, but in a very scattered manner, not systematically. However, many studies have reported promising results on the ability of rot fungi to degrade a wide array of persistent organic pollutants and have put forward the idea of rot fungi as a promising green remediation tool [26,27]. This ability arises from the secretion of extracellular and powerful oxidative enzymes, such as lignin peroxidase, manganese peroxidase, and laccase [28]. These enzymes break down complex chemical structures in the same way that rot fungi depolymerize lignin and other recalcitrant molecules in their normal functions in nature. The patterns of degradation may include the generation of reactive radicals that enable the decomposition of pesticides into less toxic compounds by destabilizing the organic molecules, as well as the direct attack of extracellular enzymes on the chemical bonds of the compounds, leading to cleavage through oxidation or hydrolysis [28,29]. In a 12-day experiment, Mileski et al. [30] confirmed that *Phanerochaete chrysosporium* could degrade the organochlorine pesticide pentachlorophenol and its metabolites by approximately 80%. In the same line of evidence, Xie et al. [31], using the same white-rot fungi species, have reported degradation rates between 73% and 98% for the neonicotinoid insecticide imidacloprid (for concentrations ranging from 10 to 30 mg/L), after only three days of incubation. In another study, *P. chrysosporium* was shown to significantly degrade several PAHs (acenaphthene, anthracene, fluoranthene, naphthalene, phenanthrene, and pyrene) in seven days in the presence of an inducer of manganese peroxidase [32]. For pyrene, the degradation rate reached 100% under all tested conditions of agitation and inducer concentrations [32]. Most of these studies were carried out under laboratory-controlled conditions, supplying conditions for optimized degradation. However, the effectiveness of the rot-fungi-mediated remediation of pesticide-contaminated soils may be influenced by environmental factors such as water availability, temperature, pH, substrate condition, and availability. Therefore, suitable conditions for species thriving and/or compound degradation may not always be desirable. For example, Abo-State et al. [32] showed that, unlike pyrene, phenanthrene degradation is concentration- and agitation-dependent. Despite this, the non-specificity of white-rot fungi for substrates and their high adaptability and resilience under stressful conditions foresee their successful application in realistic environmental scenarios. A few studies conducted in this sense have shown the potential of white-rot fungi to degrade crude oil contaminants in the soil of Nigeria (an oil-producing country often confronted with spillage situations). Adenipekun and Fasidi et al. [33] were able to reduce the total petroleum hydrocarbons in crude oil-contaminated soils by 20% and 40%, respectively, after 3 and 6 months of incubation with *Lentinus subnudus*, while Okparanma et al. [34] reduced the total PAH concentration in oil-based drill cuttings by 90% within 56 days. In situ research regarding this issue is scarce and lacks further confirmation; this is herein flagged as a knowledge gap ready to be filled for other types of organic compounds. However, white-rot fungi have strong potential for the in situ remediation

of pesticide-contaminated soils (Figure 2), particularly under challenging environmental conditions, making them a promising tool for ecological restoration.

2.2. Slag Stabilization and Mining-Affected Soil

There is a consensus that mining activities have been and will continue to be one of the most important activities for the extraction of heavy metals. Despite this, it is also agreed that this is one of the activities that leaves the greatest pollution legacy in the environment [9–11,35,36]. There are two major problems associated with ore mining activities: the large amount of slag produced, and the on-site and off-site pollution caused by slag (Figure 2). The slag itself is inherently loose and poorly aggregated, rendering it highly susceptible to erosion and dust formation, and with practically no water retention. The permanence of slag under weathering conditions facilitates the mobility of potentially toxic elements through the frequent release of acid drainage and the transport of dust. Mining activities (even at a small scale) can thus contribute, in the short- and long-term, to an increase in heavy metals in the air, water, and soil in the vicinity of the mining site or several kilometers away [9,10,37,38]. Because of these characteristics of mine spoils, studies focusing on this type of pollution, in a cross-sectional way, have reported that the levels of potentially toxic elements are, as expected, higher in the vicinity of mines, decreasing with distance; but, even at a distance, they remain high, sometimes well above the permissible limits established by international standards such as the World Health Organization [9,36]. Therefore, the implementation of stabilization and rehabilitation strategies for these mine spoils close to the mine sites could have a very significant off-site contribution, whether to the environment or to the population.

The application of rot fungi as a first amendment can address three important aspects and is in line with the primary functional role of these fungi in the environment. Rot fungi are pioneer species; unlike other types of fungi commonly used in rehabilitation processes (such as mycorrhizal fungi), these fungi do not require a biotrophic link. They can better support themselves in aggressive environments than other microorganisms because of their higher tolerance and more efficient use of resources, partly overriding the negative impacts of heavy metals [38,39]. In this way, rot fungi can shape these environments, helping to establish other microorganisms by creating microhabitats with a hyphal network (e.g., as in [6,40]), and with the same network, allowing the translocation of nutrients and fostering a more hospitable environment for subsequent colonization by plants (e.g. [4]). In turn, the root system of established plants can also help stabilize debris. On the other hand, when they establish themselves in the soil or in these harsh environments, the hyphae network has a physical function, aggregating particles (through the production of natural glues based on polysaccharides), thereby improving water retention and aeration [41,42]. For instance, under simulated rainfall events, mushroom residue-amended tailings were found to outperform all erosion metrics (lower runoff volume, decreased sediment yield, or the minimization of rill formation) compared to untreated tailings or other tailing treatments such as soil incorporation [41]. The use of mushroom-based amendments has been useful in other cases where the objective is to stabilize degraded and eroded soil. Udom et al. [42] reported that a 10 ton per hectare application of mushroom residues would greatly increase the proportion of 0.5 mm macro-aggregates, and that the upgrade in microaggregates leads to positive feedback on organic matter storage and a 2-fold increase in saturated hydraulic conductivity [42].

Finally, as part of their natural function, rot fungi (responsible for the degradation of recalcitrant natural materials) secrete organic acids and chelating compounds that can bind heavy metals, thereby reducing their bioavailability and toxicity through three main pathways: biosorption, bioaccumulation, and precipitation. For example, fungal cell walls

contain compounds such as chitin and glucans, which provide cohesion and flexibility to the hyphae. Chitin contains negatively charged N-acetylglucosamine residues, which have a high affinity for numerous metal cations [43]. The production of siderophores, low-molecular-weight molecules with affinity for iron, has also been documented for rot fungi and may also play a role in the binding of potentially toxic elements. Arsenic (As) may co-precipitate or form complexes with iron in siderophores, thus reducing As mobility in soils and sediments and its leaching into aquatic matrices [44,45]. In addition, white-rot and brown-rot fungi may also display the ability to transform metals into less toxic forms through biochemical processes, such as precipitation or crystallization through oxalate secretion. This seems to be an efficient process for dealing with divalent cations such as copper (Cu), cadmium (Cd), and lead (Pb) [45–47]. For example, Wang et al. [46] found that Pb removal from aqueous suspensions by the white-rot fungus *P. ostreatus* reached a rate of approximately 90%. The authors concluded that this was mainly achieved through fungal cell functional group (carboxyl, hydroxyl, and amine groups) interactions with the cations, and the fungal cells were able to actively transport the cations to their interior and store them in vacuoles [46]. It is also worth highlighting that the resilience of decomposer fungi in these environments may be due to the fact that some metals are considered essential to their metabolism. For example, Cu is used as a cofactor in laccase enzymes [47], just as zinc (Zn) can enter the secondary metabolic pathways of the fungus, such as the structural stabilization and catalytic activity of enzymes with lower expression, such as dehydrogenases [46].

Saprophytic fungi can enrich mining waste, improve soil with nutrients, break down recalcitrant materials, and contribute to their structure by extending the hyphal network (Figure 2). The lack of studies on the stabilization or remediation of slag or waste is practically nonexistent; however, the limited evidence collected in other contexts allows us to hypothesize that the use of rot fungi in this context warrants further research. Studies are crucial to assess the long-term sustainability and economic viability of these approaches, because the effectiveness of fungal-based remediation strategies depends on several factors, including substrate characteristics, the selection of fungal species, environmental conditions, and microbial interactions, which urgently need to be addressed. Careful consideration of these factors, along with comprehensive monitoring and assessment, is essential to optimize remediation strategies and achieve the successful restoration of mining sites.

2.3. Fire-Stricken Soils

Forest fires are catastrophic disruptions of terrestrial ecosystems. Depending on their intensity and duration, the impact of fires can range from slight/minimal to the complete destabilization of the soil structure and its sterilization [12,48,49]. This loss of biodiversity can disrupt nutrient cycling, increase the risk of erosion, and hinder ecosystem recovery. Fires immediately generate a loss of biomass above the ground and create a large input of recalcitrant pyrolyzed organic matter into the soil (necromass; Figure 2). This sudden influx of organic matter requires a robust decomposition system; otherwise, it can lead to aggravated long-term soil degradation. Notwithstanding the decline in microbial activity in these affected ecosystems, the large necromass input often hinges on the rapid response and activity of decomposing organisms, particularly saprophytic fungi.

Rot fungi are kickstarts that play a pivotal role in initiating and driving the process of decomposition and unlocking the essential resources necessary for the establishment of other biota. For instance, García-Carmona et al. [50] verified that seven months after a moderate-to-high wildfire severity in a semi-arid Mediterranean region, the percentage of mycorrhizal fungi decreased from 36.6% (unburnt) to 2.6%, in favor of an increase in the percentage of saprotrophs (from 41.8% to 74%). Their pioneering role is believed to

arise from their ability to exploit aromatic compounds that are usually part of this organic matter as food sources and the lack of the mandatory biotrophic relationships needed by other fungi (e.g., mycorrhizae). The saprotroph *Pyronema domesticum* successfully colonized and degraded pyrolyzed substrates (charcoal and ash) by producing specific enzymes that degrade the complex structure of aromatic compounds such as PAH and phenols. After 57 days of the experiment, the fungus could significantly break down recalcitrant matter into less toxic and more bioavailable compounds, contributing to the nutrient cycle and the recovery of the soil post fire [51]. Another similar study using the same species, noted the rapid colonization of the charred substrate as a nutrient source under very poor nutritional conditions, and the dominance of saprotrophic fungi at the early stages of succession in these fire scenarios [52]. However, it is important to highlight that this fungus, *P. domesticum*, is a pyrophilous (“a fire lover”), but other reports on non-pyrophilous species such as *Pleurotus pulmonaris* and *Coriolus versicolor* provide accounts of charred biomass colonization in time frames shorter than 70 days [53]. Yet, the potential beneficial role of non-pyrophilous rot fungi should not be ignored because there is plenty of evidence of their resilience under PAH-induced stress—e.g. [32,54–57]. In fact, Kouki and Salo [54] observed the number of fungal occurrences in a burnt area undergoing recovery over a three-year period and showed that, of the 15 species that could be used as recovery bioindicators, 13 were saprophytic fungi and/or associated with wood (for example, *Trametes hirsuta*), without having reported a pyrophyte species. Although some studies have focused on the observation and evolution of the recovery of this group of organisms in burnt area rehabilitation scenarios, no study has focused on fundamental research into the real role of these fungi or how their biology can be optimized for fire remediation scenarios.

However, the role of fungi in post-fire soil recovery is not limited to decomposition, but also contributes to soil aggregation and water retention (Figure 2). Again, the mycelial network may act in a manner similar to that previously outlined for mining-derived slags. The extension of hyphae leads to the interweaving of soil components, including minerals, organic matter, and char residues. By promoting aggregation, there is also increased porosity and a consequent improvement in water infiltration and storage capacity, which are particularly crucial in fire-damaged soils that are prone to hydrophobicity. There is evidence of hyphal network expansion and resilience even in packed soils, although in a more diffuse or patchy pattern [58]. The organic acids and natural glues secreted by these rot fungi (exopolymeric substances) play a dual role, aiding in more robust fine-particle aggregation cohesion (reducing the potential of erosion) and holding several times their weight in water [51,52,58,59]. In addition, different rot fungal species may exhibit similar enzymatic capacities, leading to functional convergence and substantially improving necromass decomposition processes [60].

3. Drawbacks and Weaknesses

Taking advantage of the advantages of rot fungi mentioned above may be achieved in two ways: by bioaugmentation or biostimulation, each with its advantages and disadvantages that must be discussed.

Bioaugmentation involves the introduction of microbial strains with specialized metabolic capabilities that can efficiently break down or transform specific contaminants. It is typically used when the indigenous microbial population lacks the metabolic pathways necessary to effectively degrade certain pollutants. The success of this technique depends on factors such as the compatibility of the introduced strains with the environment, their ability to compete with existing microorganisms, and the general conditions of the contaminated site, which do not appear to be a restriction for rot fungi. However, it is worth noting that with scientific advances, inoculants based on this type of microorganism can

be not only naturally occurring strains but also genetically modified organisms, which require strict regulations [61,62]. In the latter case, it is necessary to determine whether native biodiversity is being replaced and surpassed by introduced microorganisms, as this could lead to harmful changes in terrestrial ecosystems, and to avoid that, knowing the biology of rot fungi systems is recommended (Figure 3).

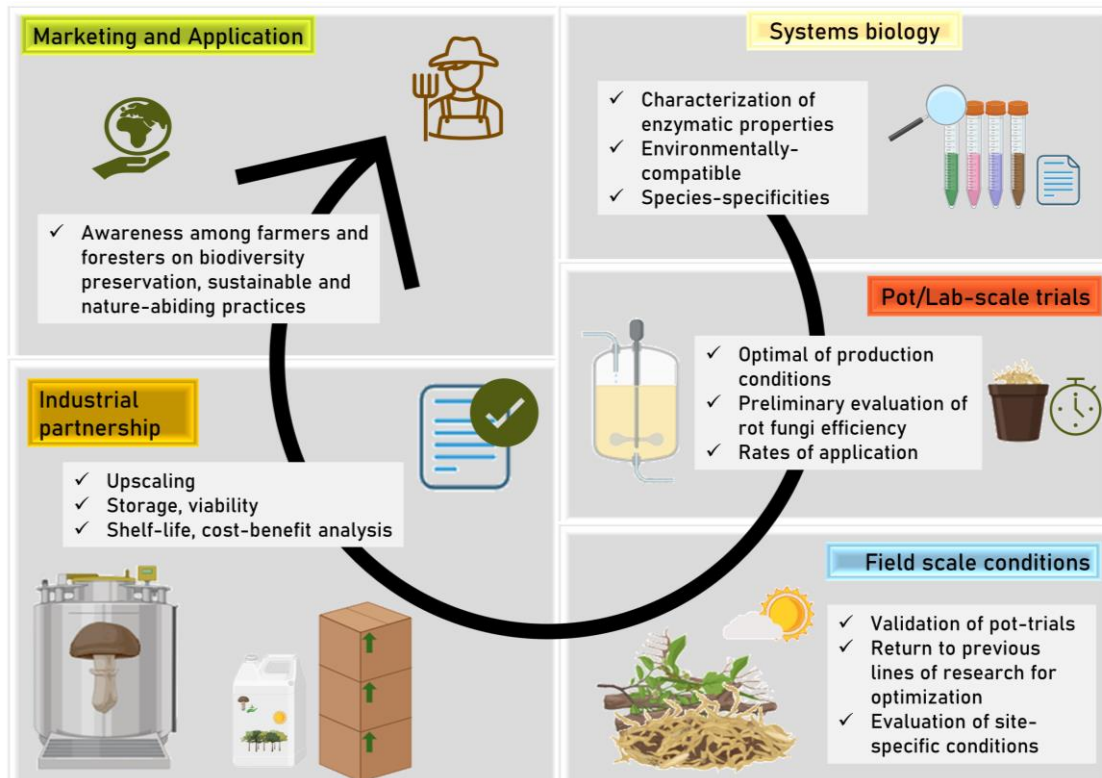


Figure 3. The proposed steps (amongst others) should be considered when developing an inoculant product based on rot fungi, in accordance with the proposed management frameworks for the monetization or rehabilitation of agricultural or forestry/natural soils under various stresses. Despite the unidirectionality of the illustration, there may be feedback and communication between the different steps of the process.

Biostimulation, the second technique, involves modifying environmental conditions to stimulate the growth and activity of microorganisms already existing on site, and is capable of naturally degrading contaminants through the supply of nutrients or other growth-promoting factors. Biostimulation techniques are often applied when the indigenous microbial community has the potential to degrade contaminants; however, for the success of this technique, it is necessary to first know the microbial community of that location and then understand its specific needs so that optimization can be carried out in an ecosystem [63]. In this case, success depends on the time scale because the action of microorganisms may undergo an initial lag phase. In the case of rot fungi, this problem can be minimized because they have low maintenance requirements. However, the combined use of both techniques, whether in the case of agriculture, forestry, or reclaimed soils stressed by different contaminants, could be the most fruitful strategy to be employed [63]. Nevertheless, it is important to keep in mind that field-scale efficiency may not reflect laboratory- or pot-scale trials due to a variety of confounding factors under realistic exposure scenarios (Figure 3).

The options for one of the strategies, or even a combination of the two, are very limited currently due to the lack of knowledge about the role of environmental factors,

whether in simulated laboratory conditions or at the field scale. The effectiveness of fungal bioremediation is influenced by environmental factors such as water potential, temperature, and pH [64]. For instance, small temperature increments can substantially increase the secretion of polymeric substances by rot fungi, while water potential rarely influences their activity [64], and the excellent degradation rates of pernicious compounds are usually accomplished under optimal growth conditions according to the species or genus [32]. However, these conditions may be achieved anywhere under realistic conditions of exposure; to realize this, not only must research fill in these knowledge gaps but it must be accompanied by the optimization of fungal formulations and delivery methods for greater bioremediation efficacy [64].

In line with this, other limitations stand out; namely, regarding the development of formulations or delivery methods. The biomass of these fungi can be obtained in large quantities with few resources and very quickly under ideal conditions. This feature may facilitate their expansion into the soil and/or the production of bioinoculant products. However, in the latter case, some difficulties may be identified in terms of industrial-scale production. The mycelial structure that rotting fungi develop in liquid cultures is very different from that in liquid suspensions of bacteria-based inoculants. This can be a disadvantage for their application, as it involves additional processes (such as grinding) prior to the potential packaging and storage of the product, to obtain a product for application that is as homogeneous as possible. Other fungi-based inoculants (such as those based on mycorrhizal fungi) are freeze-dried. This process increases the price of the final product and may therefore reduce its popularity in the market. The storage of rot fungi and their application to soils are two very important knowledge fields; however, in the case of rot fungi, owing to their compatibility with various matrices, it may be possible to place them in matrices containing liquid waste from other food processing industries. In these later steps, establishing connections with industrial partners to increase the technological readiness level of the proposal is a crucial measure (Figure 3).

4. Conclusions

The exploitation of rot fungi on a large industrial scale for remediation is already known worldwide. It is of utmost importance to call on the scientific community to recognize these small ecosystem “engineers” and explore their value in terms of restorative measures for degraded soils in various contexts, such as chemical inputs in agriculture and areas affected by fires and mining. The main advantages of rot fungi include: (i) a wide range of substrates—that is, various pesticides, including organochlorines, organophosphates, and carbamates, or carbonized biomasses or ash—can be used as C sources and, through decomposition, allow for the formation of compounds less toxic; (ii) a predominant ligninolytic enzyme system that includes powerful oxidative enzymes such as lignin peroxidase, manganese peroxidase, and laccase; and (iii) a network of hyphae that allows for the allocation of nutrients to critical areas and the formation of niches, while at the same time providing a complex web that binds together fine particles, reducing the risk of erosion. Together, these characteristics contribute to the rehabilitation of degraded environments, increasing their resilience to future climate change scenarios, and transforming affected landscapes into fertile ground for ecological succession. Exploiting these rot fungi may have new implications in land management. Today, governments prioritize a combination of regulatory enforcement, technological innovation, financial responsibility, and community engagement to ensure the effective remediation of degraded areas. Policies adapted to local conditions and sustained collaboration between the public and private sectors are essential for long-term success and are increasingly featured in the field of nature-based technological innovation.

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