



Wood decay fungi in the environment and green technologies

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ABSTRACT: Wood decay fungi (WDF) are a functional group of fungi that mainly includes the types Basidiomycota and Ascomycota. High exoenzymatic activity and osmotic nutrition of WDF are the basis for their use in green technologies. The aim of the work was to summarize scientific data on the potential of WDF in green technologies, including those implemented in practice. The analysis of publications in Web of Science, ScienceDirect, PubMed and eLIBRARY.RU databases was carried out using generally accepted methods of metadata sorting. Industries where the properties of WDF are most in demand were identified using the expert analysis method, they are: processing of lignin- and cellulose-containing waste, wastewater and soil treatment, obtaining medicinal substances in pharmacology, and agriculture. WDF is suitable for processing any lignocellulosic waste. *Trametes*, *Pleurotus* and *Ganoderma* have a high biodegradation potential. *Aspergillus*, *Lentinula* and *Trametes* show the extraction of metals from wastewater at the level of 90%. Fungi of the genera *Trametes*, *Ganoderma*, *Aspergillus*, *Fusarium*, *Pleurotus* and *Phlebia* are suitable for the biodegradation of phenols, oil products, pesticides and antibiotics. Wastewater treatment, soil remediation and industrial waste processing with WDF are based on the mechanisms of biosorption, biodegradation and bioconversion. WDF metabolites are used in pharmacology to improve pre-pathological conditions, prevent diseases, and treat in combination with basic therapy. In agriculture, WDF are multifunctional: from processing difficult-to-decompose waste to obtain feed enriched with biologically active substances to soil mycoremediation and the substitution of synthetic herbicides. Thus, green WDF technologies solve the problems of waste recycling, restoration of polluted water and soil, and inclusion of valuable metabolites in production.

Keywords: wood decay fungi; waste recycling; wastewater treatment; soil bioremediation; biologically active substances.

Fungos de decomposição da madeira no meio ambiente e as tecnologias verdes

RESUMO: Os fungos de decaimento da madeira (FDM) são um grupo funcional de fungos que inclui principalmente os tipos Basidiomycota e Ascomycota. A alta atividade exoenzimática e a nutrição osmótica de FDM são a base do seu uso em tecnologias verdes. O objetivo do trabalho foi resumir dados científicos sobre o potencial da FDM em tecnologias verdes, incluindo as já implementadas na prática. A análise de publicações nas bases de dados Web of Science, ScienceDirect, PubMed e eLIBRARY.RU foi realizada utilizando métodos geralmente aceitos para classificação de metadados. As indústrias onde as propriedades do FDM são mais procuradas foram identificadas usando o método de análise especializada, são elas: processamento de resíduos contendo lignina e celulose, tratamento de efluentes e solos, obtenção de substâncias medicinais em farmacologia, agricultura. FDM são adequados para o processamento de qualquer resíduo lignocelulósico. *Trametes*, *Pleurotus*, *Ganoderma* apresentam alto potencial de biodegradação. *Aspergillus*, *Lentinula* e *Trametes* mostram extração de metais a partir de efluentes em 90%. Fungos dos gêneros *Trametes*, *Ganoderma*, *Aspergillus*, *Fusarium*, *Pleurotus* e *Phlebia* são adequados para a biodegradação de fenóis, derivados do petróleo, pesticidas e antibióticos. O tratamento de efluentes, a remediação do solo e o processamento de resíduos industriais com FDM baseiam-se nos mecanismos de biossorção, biodegradação e bioconversão. Os metabólitos da FDM são usados em farmacologia para melhorar as condições pré-patológicas, prevenir doenças e tratar em combinação com a terapia básica. Na agricultura, os FDM são multifuncionais: desde o processamento de resíduos difíceis de decompor até a obtenção de ração enriquecida com substâncias biologicamente ativas, passando pela micorremediação do solo e pela substituição de herbicidas sintéticos. Assim, as tecnologias FDM verdes resolvem os problemas de reciclagem de resíduos, restauração de água e de solo poluídos e inclusão de metabólitos valiosos na produção.

Palavras-chave: fungos de decomposição da madeira; reciclagem de resíduos; tratamento de efluentes; biorremediação do solo; substâncias biologicamente ativas.

1. INTRODUCTION

A significant part of global environmental and social problems is caused by the chemicalization of agriculture, the food industry, and the increasing need for medicines. The solution to this problem should be in the field of greening technologies for obtaining food, medicines and agricultural products, and recycling the resulting waste. Environmentally friendly technologies are usually called "green". The terms "green production" and "green technologies" began to appear in the late 1980s, when there was a rethinking of the consequences of anthropogenic impact on the environment (QAMAR et al., 2021).

Green technologies are innovations based on the principles of using technical solutions that reduce the burden on the environment and the degree of its degradation. They are aimed at reducing the level of resources consumed and increasing the efficiency of their use. Such technologies are being implemented in many areas: agriculture, medicine, energy, industry and construction. The advantage of using "green" technologies is considered to be the improvement of the environment and human health, saving energy and natural resources, increasing production efficiency and competitiveness of manufactured products, and the use of renewable resources (GANGADHAR, 2017; YADAV et al., 2024).

The environment provides a variety of resources for the implementation of environmentally friendly agriculture, the production of organic food, medicines and other functional products for various fields. It is known that phytotechnology is effective in protecting and growing plants without chemicals, allowing early detection of phytopathogens and strengthening the immune system of agricultural plants (PENG; QIN, 2024). The prevention and treatment of viral diseases, including COVID, have shown positive results with the introduction of extracts from wood decay fungi into the treatment regimen (RANGSINTH et al., 2021).

Many "green" technologies are based on the fact that living organisms can release biologically active substances (BAS). They are used both in the form of unrefined metabolites of bacteria, fungi, plants, and when using technologies for purification and isolation of chemically pure BAS of organic origin.

Wood decay fungi are common in forests around the world, but as a promising source of biologically active compounds, they have not been studied as widely as plants and other groups of fungi (ERMOSHIN et al., 2021). However, the combination of features of their vital activity has already become the basis for some promising "green technologies" (YU et al., 2023; VENÂNCIO et al., 2024).

The purpose of this analytical review was to form a comprehensive understanding of the existing options for using wood decay fungi in "green" technologies of industry and agriculture, based on their ecological and biological characteristics.

2. MATERIAL AND METHODS

Scientific publications for review were selected in the international scientometric databases Web of Science, ScienceDirect, PubMed and eLIBRARY.RU by thematic queries and subsequent filtering by year and type of publication. The criterion for selecting databases was the international coverage of authors and publications. At the

same time, the principle of impartiality to publications was implemented: journals were not filtered by rating.

The keywords were selected in accordance with the plan of the scientific review, including brief information on the ecology of wood decay fungi (WDF), modern achievements of their use in industry and agriculture, and pharmacology. The final set of keywords was as follows: wood-decay* mushroom, wood decay fungi, xylophag* fungi, environmentally friendly technolog*, green technolog*, bioremediation, bioconversion, biodegradation. These keywords were used in various combinations in accordance with the rules of the corresponding database.

The majority of the analyzed papers were published in the last 10 years (2014-2024). The analysis of promising technologies for using WDF is based on papers published in the last 5 years. Earlier papers were included if they had valuable information for revealing the topic and did not have later analogs.

The studies were excluded if they were not related to the ecology of wood decay fungi and green technologies. Papers devoted to the contribution of WDF to the carbon cycle were not considered. We did not analyze unpublished reports and conference proceedings not mentioned in Web of Science, Scopus and ScienceDirect.

In accordance with the concept, 73 references were included in the review.

3. RESULTS

3.1. Ecology of wood decay fungi

Wood decay fungi in ecosystems enter into various relationships with woody and shrubby plants. Many fungi are pathogenic, affecting healthy plants. Thus, *Armillaria spp.* Staude, 1857 (Fungi, Basidiomycota) are among the most pathogenic fungi in woody ecosystems, common both in forests and artificial plantations (BAUMGARTNER; RIZZO, 2001). *Armillaria spp.* causes enormous damage to forest productivity and the economy of the forest industry (FILIP et al., 2009).

Traditionally, pathogenic wood decay fungi are divided into white-rot and brown-rot. White-rot causes the complete decay of plant cell wall components. Brown-rot is different in that lignin remains unchanged or slightly modified. There is criticism of this classification (Riley et al., 2014), which is that not all fungi can be strictly divided into those causing white- or brown-rot. Thus, brown-rot fungi *Botryobasidium botryosum* (Bres.) J. Erikss. (1958) and *Jaapia argillacea* Bresadola (1911), cause decay of all layers of the cell wall, which is typical for the consequences of white-rot of wood.

Wood decay basidiomycetes, both parasitic and saprotrophic, play a positive role in ecosystems as they promote wood decay and, therefore, the activation of the carbon cycle in nature. This function is performed thanks to unique extracellular enzymes acting on stable plant lignocellulosic polymers (VOLOBUEV; SHAKHOVA, 2022). Most wood decay fungi belong to the phylum Basidiomycota, or more specifically to the class *Agaricomycetes* (MARIAN et al., 2021). But there are also wood decay fungi among the *Ascomycota*, for example, *Penicillium oxalicum* Currie & Thom (1915), *P. echinulatum* Raper & Thom ex Fassat (1976) (Lenz, 2020; Ye, 2017; Liang, 2023), *P. chrysogenum* Thom (1910), *Aspergillus niger* van Tieghem (1867) (HAMED, 2013). All fungi of these systematic groups produce

extracellular peptidases for the breakdown of proteins, polypeptides and other compounds into smaller soluble molecules. These molecules are then transported into the fungal cell, providing its osmotrophic nutrition (SEMENOVA et al., 2017).

The ecological importance of white- and brown-rot fungi is not limited to wood mineralization. It has been shown that the type of rot that attacks a tree affects forest regeneration: brown-rot fungi had a positive effect on the germination of *Causonis japonica* (Thunb.) Raf., while white-rot fungi had a negative effect on the reproduction of *Pinus densiflora* Siebold & Zucc. (FUKASAWA et al., 2016). The idea of the importance of fungi, including wood decay fungi, is supported by the study (Borgmann-Winter et al., 2021): maintaining mature forests with fallen trees near logging areas promotes forest regeneration by maintaining natural trophic relationships with fungi.

The division of wood decay basidiomycetes into pathogenic and saprotrophic species is also conditional and refers to certain stages of the fungus's life. In particular, pathogenic *Armillaria* species are facultative parasites, but after colonization and death of the host root cambium, they enter the saprobic phase and decay the tissues of dead wood (DEVKOTA; HAMMERSCHMIDT, 2020). Also, the well-known causative agent of pine root rot - the fungus *Heterobasidion annosum* (Fr.) Bref. (1888) - can colonize the stumps of cut-down trees, after which it spreads through root contact from infected trees to healthy ones (GARBELOTTO et al., 1997).

In the literature, there are also data on potential symbiotic relationships between WDF and woody plant seedlings, but such information is fragmentary. Researchers have identified a functional similarity between mycorrhizal fungi and free-living saprotrophs capable of acting as mycorrhizal symbionts. The potential for symbiotic relationships between living roots of *Picea* and wood decay fungi *Phellinus igniarius* Abies L. (1753) was demonstrated in *in vitro* experiments (SMITH et al., 2017). Other studies describe the results of screening 660 healthy coniferous seedlings in forest tree nurseries for the presence of mycelium on the roots. Sequencing of the material revealed 60 fungal taxa, only 27 of which (45%) were previously known as mycorrhizal. Other fungal species present included WDF *Phlebiopsis gigantea* (Fr.) Jülich, 1978, *Phlebia centrifuga* P. Karst. (1881) and *Hypholoma fasciculare* (Huds. Fr.) Kummer (1871), which are widespread decomposers of dead coniferous wood in temperate and boreal forests (VASILIAUSKAS et al., 2007).

In any case, wood decay fungi are part of natural ecosystems. In boreal forests, they represent a significant part of the fungal biodiversity. Some of them are rare and listed in the Red Books and lists of protected species. For example, *Ganoderma lucidum* Karst (1881) is listed in the Red Book of the Russian Federation; the International Union for Conservation of Nature and Natural Resources assigned the status "On the verge of extinction" to *Bridgeoporus nobilissimus* (W.B.Cooke) T.J.Volk, Burds. & Ammirati (1996). The authors of the research (Junninen et al., 2008) suggested that a decrease in the number of natural forest fires deprives putrefactive fungi of a substrate; however, monitoring anthropogenically burned forests for 4 years did not provide an exact answer to the effectiveness of such a measure to maintain the diversity of fungi.

Thus, wood decay fungi are a group of fungi that are of great importance in natural ecosystems characterized by a

parasitic and saprobic lifestyle, as well as diverse, perhaps not fully understood, relationships in the community (Figure 1).

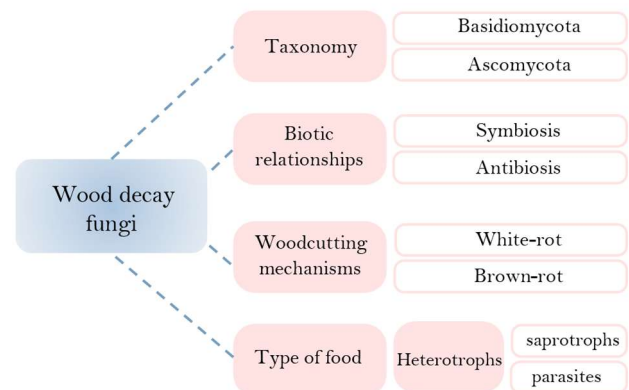


Figure 1. Ecological and biological characteristics of wood decay fungi.

Figura 1. Características ecológicas e biológicas dos fungos decompositores de madeira.

3.2. Wood decay fungi in industry - recycling of waste containing lignin and cellulose

All WDFs are unique natural factories for wood processing, or more precisely, their chemical base – cellulose and lignin. Wood decay fungi can process not only wood residues. They are effective for processing and recycling any difficult-to-process plant waste, such as agricultural crop residues (straw, cake, inedible stems, etc.), waste from the production and use of paper and its derivatives (PIMENTEL, 2008; TIŠMA, 2021). The use of WDF in biotechnologies for processing the listed waste is already contributing to the greening of industry (VOLCHATOVA, 2006; OLIVIERI, 2012).

The lignocellulolytic and biodegradation potential of WDF families and species is different and is of scientific interest. Thus, from 33 species of agaricomycetes and basidiomycetes, strains LE-BIN 3969 *Rhodofomes roseus* (Alb. & Schwein.) Kotl. & Pouzar (1990), LE-BIN 4122 *Trametes hirsuta* (Wulfen) Lloyd (1924) and LE-BIN 4123 *Trametes ochracea* Person (1794) were selected based on the criterion of high content of lignocellulolytic enzymes (SHAKHOVA; VOLOBUEV, 2020).

The most valuable are the fungi that act simultaneously on both lignin and cellulose: *Pleurotus ostreatus* (Jacq. ex Fr.) P. Kumm. (1871), *G. lucidum*, *Armillaria mellea* (Vahl) P. Kumm. (1871) (KAZARTSEV, 2009). Due to this, they can process organic waste most efficiently and deeply.

The production of food and biologically active additives from plant raw materials also has dry and wet plant residues in the waste. It was shown that the proportion of difficultly hydrolyzable polysaccharides, easily hydrolyzable polysaccharides and lignin decreased by an average of 1.6 times due to fungal bioconversion using the example of growing the fungi *Trametes versicolor* (L) Lloyd (1920) and *Pleurotus eryngii* (DC.) Quél. (1872) on the extraction residue of the medicinal plant *Orthilia secunda* (L.) House. The protein content in the resulting mycelial-plant product increased significantly (KOCH, 2020).

Thus, WDFs are suitable for processing any lignocellulose waste. The resulting bioconversion products are valuable. Their use is discussed in other sections.

3.2. Wastewater treatment

Today, biological wastewater treatment methods are considered preferable to physicochemical ones (electrocoagulation, sedimentation, membrane separation, etc.), since they are less expensive and, most importantly, are environmentally friendly technologies.

It was found that WDF has a high ability to extract heavy metals from aqueous solutions due to biosorption. This ability has been proven for *Funalia trogii* (Berk.) Bondartsev & Singer (1941), *G. lucidum* and *Trametes versicolor* (L.) Lloyd, (1920) (LOUKIDOU et al., 2003; SAY et al., 2003; MANI, KUMAR, 2014). The effect of WDF on elements with variable oxidation states helps to reduce their toxicity due to the reducing biological capacity of fungi.

P. ostreatus is capable of removing heavy metals such as lead, zinc, manganese, chromium, cobalt, copper, and nickel present in contaminated wastewater from coal preparation plants. The metals are sorbed by the fungal hyphae. Their accumulation increases the activity of antioxidant enzymes in fungi, which helps them tolerate the toxic effects of metals (AKHTAR, 2020).

The quantitative indices of bioadsorption are quite high. The potential of *Aspergillus versicolor* (Vuillemin) Tiraboschi (1908) in terms of heavy metal bioaccumulation was studied. The best result was obtained for chromium: removal was 99.98% (pH = 6.0, initial content 50 mg L⁻¹ Cr (VI)). The efficiency for nickel and copper was 30.05% and 29.06%, respectively (pH = 6.0, initial content 50 mg L⁻¹ Ni (II); pH = 5.0, initial content 50 mg L⁻¹ Cu (II)) (TAŞTAN, 2010). The obtained results prove that the strain *A. versicolor* can be considered a promising bioaccumulator of chromium ions in wastewater. In another study, the strain of the fungus *Aspergillus fumigatus* Fresenius (1863) was found to be suitable for reducing lead ion content from liquid waste and wastewater: (containing), the maximum lead adsorption was 85.41% at an initial Pb (II) concentration of 100 mg L⁻¹ (RAMASAMY, 2011).

Developments in this area are already being applied on an industrial scale. For example, the mycelium of *Lentinula edodes* (Berk.) Pegler (1976), in the form of granules, is used to adsorb mercury, cadmium and zinc from wastewater. The fungal granules have a porous structure, increasing the total surface area, which reduces diffusion resistance and facilitates mass transfer to increase adsorption (BAYRAMOĞLU; ARICA, 2008).

Removal of organic pollutants from wastewater is based on the biodegradation of substances due to the vital activity of WDF and their metabolites. Thus, manganese peroxidases of the fungi *G. lucidum*, *Trametes Polyzona* (Pers.) Justo (2011) and *T. versicolor* oxidize phenolic compounds through an intermediate redox reaction using Mn²⁺/Mn³⁺ ions. They can also decompose lignin, persistent aromatic pollutants contained in oil waste, dyes from textile industries, and organochlorine compounds from agrochemical waste (YADAV, 2019). For example, these fungi decompose Remazol brilliant blue (25 mg L⁻¹) in 10–30 min (LUEANGJAROENKIT, 2019).

Several WDF taxa are known to biodegrade pesticides. The genera *Trametes*, *Ganoderma*, *Aspergillus*, *Fusarium*, *Pleurotus* and *Phlebia* are the most effective. The removal potential of chlorpyrifos (organophosphorus compound), dicofol (organochlorine compound) and cypermethrin (synthetic pyrethroid) at 25°C was shown to be 95%, 88% and 93%, respectively, over 14 days. *T. versicolor* was found to be a fairly

active degrader of the insecticide fipronil with low water solubility. The same crop contributed to the reduction of the herbicides diuron and bentazone present in agricultural wastewater. *G. lucidum* is also active against diuron (VAKSMAA, 2023).

Three WDF strains (*T. versicolor*, *P. ostreatus* and *Pleurotus pulmonarius* (Fr.) Quél. (1872)) are used to remove humic acids (HA) from industrial wastewater from a food plant in Eindhoven (the Netherlands). For this purpose, a suspension of fungal mycelium is added to the wastewater. *T. versicolor* is the most effective, decolorizing the wastewater by 90% and degrading humic acids by 45% (ZAHMATKESH, 2017).

Therefore, the use of WDF for the treatment of industrial wastewater with mineral and organic contamination is an effective and safe method.

3.3. Soil bioremediation

Soil mycoremediation is based, on the one hand, on the sorbing properties of fungal mycelium; on the other hand, the process can occur due to biologically active metabolites that promote accelerated degradation of unwanted pollutants, which is especially effective against organic pollutants.

WDF in these “green” technologies is a new object of research; however, there is scientific information on the most promising types and methods of their use. Selective adsorption of HM by *P. ostreatus* and *L. edodes* fungi from soil is known (EGGEN et al., 1999; BHARATH, 2019). Also, incubation of *P. ostreatus* on soil samples with a high content of HM significantly reduces their concentration. The technology also proved to be effective in soil contaminated with pesticides (ADELAJA, 2017).

WDF are well-suited for soil purification from organic pollution, since they are heterotrophs and produce active exometabolites. The effectiveness of solid-phase inoculates of *P. ostreatus* and *Schizophyllum commune* Fr. (1815) grown on plant husks, straw, and pine sawdust proved to reduce oil pollution of soils (POZDNYAKOVA et al., 2021).

An active search for WDF capable of decaying highly toxic and persistent pollutants such as dioxins and polychlorinated biphenyls (PCB) is underway. Numerous studies confirmed that *T.versicolor*, *L. edodes*, *Pycnoporus cinnabarinus* (Jacq.) P.Karst. (1881) and *P. ostreatus* can effectively adsorb PCB (CLOETE, 1999; KUBATOVA, 2001; RUIZ-AGUILAR, 2002; CVANCAROVÁ, 2012; CHUN, 2019).

Pollution of wastewater and soils with antibiotics is a serious problem of our time. WDF are generally resistant to many chemical agents, including antibiotics. It was shown that *P. ostreatus* is able to survive and grow in conditions of high concentrations of tetracycline antibiotics, and also completely degrades the drugs in a few days. Oxytetracycline was absorbed by the mycelium, where the drug molecule was subjected to degradation, which was confirmed by a mass spectrometric analysis. Moreover, no antibiotic residues were detected in the treated mycelium by the end of the experiment (MIGLIORE, 2012).

Thus, wastewater treatment, soil remediation and industrial waste processing by WDF are based on the mechanisms of biosorption, biodegradation and bioconversion (Figure 2).

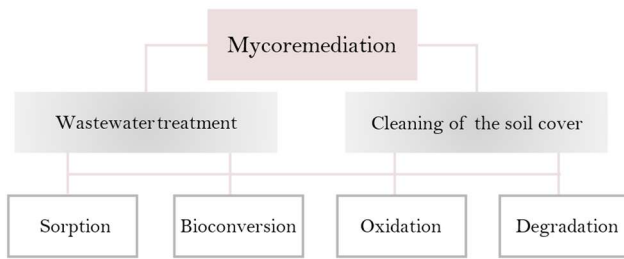


Figure 2. Mechanisms of mycoremediation of contaminated objects using WDF.

Figura 2. Mecanismos de micorremediação de objetos contaminados com WDF.

3.4. WDF in pharmacology

Synthetic drugs certainly save humanity from epidemics and pandemics. However, their production, consumption and disposal cause great harm to the environment. Many pre-pathological conditions are well corrected by natural remedies known in the traditional medicine of various countries.

Basidiomycetes, referred to as WDF, such as *Inonotus obliquus* (Ach. ex Pers.) Pilat (1942), *L. edodes*, *G. lucidum*, *Hericium erinaceus* (Bull.) Persoon (1797) have been used in traditional medicine for over 2000 years. They have antiviral, antibacterial, anti-inflammatory, antitumor and antiallergic effects (PATWARDHAN et al., 2005; PELIZON et al., 2005).

The search for antibiotics that are not xenobiotic in relation to the environment is an important interdisciplinary task. Metabolites of many WDFs have antibacterial activity. Thus, the antibacterial potential of the culture liquids of *L. edodes* and *Fomitopsis betulina* (Bull.) B.K.Cui, M.L. Han & Y.C.Dai (2016) against the bacteria *Bacillus subtilis* (Ehrenberg, 1835) Cohn (1872), *Staphylococcus aureus* Rosenbach (1884), and *Escherichia coli* (Migula, 1895) Castellani and Chalmers (1919) was higher than that of their mycelium (KRUPODOROVA, 2019). The studies of active metabolites contained in the mycelial mass and culture fluid of the macromycete *F. officinalis* showed high activity against *Staphylococcus aureus* after the 21st day of cultivation, while on the 28th day, the growth inhibition zone was maximum (15-25 mm) (MYKCHAYLOVA; POYEDINOK, 2021).

Methanol extract of the fruiting body of *Ganoderma applanatum* (Pers.) Pat., 1887 was more effective against gram-positive bacteria compared to gram-negative bacteria: minimum inhibitory concentration from 0.003 to 2.0 mg/ml and 1.0 to 4.0 mg mL⁻¹, respectively, minimum bactericidal concentration from 0.06 to 4.0 mg mL⁻¹ and from 2.0 to 4.0 mg mL⁻¹, respectively (SMANIA, 1999).

WDF can exhibit antiviral activity against various pathogens. Over 130 triterpenoids isolated from fruiting bodies, mycelium, and spores of the lacquered tinder fungus *G. lucidum* demonstrated the antiviral activity against human immunodeficiency virus type 1 and hepatitis B. Melanin obtained from the sclerotium of chaga *I. obliquus* has the antiviral activity against several viruses, such as HIV-1, Herpes Simplex Virus 2, monkeypox virus, and others. Aqueous extracts and polysaccharides from fungi belonging to the genera *Ganoderma* (*G. lucidum*), *Pleurotus* (*P. eryngii*, *P. djamor*, *P. ostreatus*, *P. pulmonarius*), and *Lentinus* (*L. edodes*) exhibited the antiviral activity against West Nile virus and Herpes Simplex Virus 2 (TEPLYAKOVA, 2014). Various reports have noted the immunomodulatory ability of

basidiomycetes in the treatment of COVID-19; they may be effective as a preventive or adjunctive therapy (HETLAND et al., 2021; ARUNACHALAM, 2022).

Currently, due to the increase in the number of cases of immunodeficiency, an increase in the incidence of infectious and oncological diseases, special emphasis is placed on the search for immunomodulators aimed at enhancing the functioning of the human immune system. *Hericium erinaceus* (Yujiao, 2023; Polezhaeva, 2020), *Flammulina velutipes* (Curtis) Singer (1951) (Jufeng, 2020), *P. ostreatus* and *Pleurotus Eryngii* (DC.) Quel. (1872) (Vetvicka, 2019), *T. versicolor* (Huaqian, 2019), *Lentinula edodes* (Alagbaoso; Mizuno, 2022) have high immunomodulatory activity.

Thus, WDFs have antibacterial and antiviral activity and are effective immunomodulators. Research on the pharmacological properties of WDF has recently received new development due to consumer demand and progress in analytical methods.

3.5. Using wood decay fungi in agriculture

In agriculture, WDF is used at all stages of production: from improving soil properties and biologically active additives to feed to recycling waste. Soil is one of the most important agricultural resources. Soil pollution is considered the most pressing problem in organic farming. The use of extracts of fungi can be a promising green technology for protecting plants from heavy metal pollution. It has been shown that the use of low concentrations of *Fomes fomentarius* (L.) Fr., 1849 extract (1 mg mL⁻¹) reduces the negative effect of cadmium ions (250 µM) when used together, and also practically does not inhibit plant growth (BYZOVA, 2022).

Another common problem in agricultural soils is their depletion, the reduction of macro- and microelements due to intensive use. It turned out that the white-rot fungus *C. lacerata* can mobilize organic phosphorus compounds by producing extracellular phosphatase and inorganic phosphorus compounds by releasing protons and low-molecular organic acids, increasing phosphorus uptake by crops and their yield. As a result, residual phosphorus in the soil is mobilized, and no new doses of fertilizers are required (SUI, 2021).

Fruiting bodies and extracts of fungi that cause white-rot have allelopathic activity. This property is used to create herbicides and agents against fungal diseases (BOROMENSKY, 2021). Tsivileva (2022) describes the WDF technology for combating phytopathogenic infections and increasing potato yields. Biocomposites with polysaccharides from white-rot fungi *Grifola umbellata* (Pers.) Fr. (1821), *G. lucidum* and *P. ostreatus* were created. Biocomposites based on *G. umbellata* had a positive effect on the number of leaves and plant height, and the length of the embryo significantly increased. Potato plants exposed to the biocomposite from *G. lucidum* showed an increase in vegetative potato biomass of up to 55% compared to the control. Biocomposites based on *P. ostreatus* contributed to an increase in potato root biomass by up to 79% compared to the control.

In cattle breeding, white-rot fungi are used as a feed additive for animals and poultry. Due to the enzymes they produce, they provide biological delignification, improving the digestibility and assimilation of coarse plant food, such as wheat straw. Studies have been conducted on the effect of different doses of *G. lucidum* powder on the productivity and physiological parameters of Japanese quail. The results

showed that when *G. lucidum* was added to feed (at a ratio of 1:1000 and 1.5:1000 g of feed), egg production and average egg weight increased, and the feed conversion ratio also improved significantly (AL-TIKRITI, 2019). The value of this food additive has been confirmed in goats. The introduction of *G. lucidum* into their feed led to an increase in weight and growth of goats (LIN et al., 2021).

The problem of the utilization of plant waste is considered in detail above. It should be noted that in agriculture, there are sectors that are not directly associated with large amounts of waste, but the problem does exist. For example, in Colombia, large amounts of waste are generated at the stages of cutting and harvesting ornamental flowers such as chrysanthemums. Fungi have come to the rescue again. Among *T. versicolor*, *Phanerochaete chrysosporium* Burds. (1974) and *P. ostreatus*, the last species demonstrated the best biodegradation potential (QUEVEDO-HIDALGO, 2012).

5. CONCLUSIONS

A summary of scientific data on the ecology of wood decay fungi, their biochemical characteristics and WDF technologies has shown the enormous potential for using these organisms to solve environmental and economic problems of waste processing, wastewater treatment, reclamation of contaminated lands, search for safe pharmacological substances and development of biologically active substances for agriculture.

WDF technologies are indispensable in industries with large lignin- and cellulose-containing wastes. These include woodworking, agriculture, production of paper and its derivatives, production of pharmacological substances and products from medicinal plant materials. In this case, fungi process wastes by bioconversion, i.e., the transformation of some organic compounds into others under the action of enzyme systems. This gives a significant reduction in the volume of waste and the production of new valuable raw materials.

WDF-based technologies are effective for cleaning wastewater saturated with both inorganic and organic substances. Wastewater purification from heavy metals is based on bioadsorption of toxicants. The concentration of organic pollutants (phenols, oil products, pesticides of various purposes) is reduced due to the enzymatic destruction of substances.

Secondary products of organic waste processing using WDF are valuable sources of biologically active substances. The composition of primary and secondary WDF metabolites depends on the biological species of the fungus. The substrate for growth and laboratory cultivation conditions are also important. As a result, agriculture and the pharmaceutical industry receive “green” sources of proteins, amino acids, polysaccharides, vitamins, and bioavailable microelements.

The presented review shows new ways to solve bioethical problems, such as incineration and burial of organic waste without processing, refusal to exploit contaminated soils, and discharge of contaminated wastewater into natural water bodies.

6. REFERENCES

ADELAJA, O. D.; NJOKU, K. L.; AKINOLA, M. O. Mycoremediation of pesticide-contaminated soil using the mushroom *Pleurotus ostreatus*. **International Journal of Health and undefined**, v. 3, n. 2, p. 20-27, 2017.

AKHTAR, N.; MANNAN, M. A-ul. Mycoremediation: Expunging environmental pollutants. **Biotechnology Reports**, v. 26, e00452, 2020. <https://doi.org/10.1016/j.btre.2020.e00452>

ALAGBAOSO, C. A.; MIZUNO, M. *Lentinula edodes* polysaccharides suppressed pro-inflammatory cytokines expression and colitis in mice. **Arquivos de Gastroenterologia**, v. 59, n. 2, p. 288-295, 2022. <https://doi.org/10.1590/S0004-2803.202202000-51>

AL-TIKRITI, S. S.; AL-DOURI, A. H. I. The effect of the adding *Ganoderma Lucidum* fungus powder in the production performance for the Brown Japanese Quail Bird. **Indian Journal of Public Health Research and Development**, v. 10, n. 7, p. 675-679, 2019. <https://doi.org/10.5958/0976-5506.2019.01652.8>

ARUNACHALAM, K.; SASIDHARAN, S. P.; YANG, X. A concise review of mushrooms antiviral and immunomodulatory properties that may combat against COVID-19. **Food Chemistry Advances**, v. 1, e100023, 2022. <https://doi.org/10.1016/j.focha.2022.100023>

BAUMGARTNER, K.; RIZZO, D. M. Ecology of *Armillaria* spp. in mixed-hardwood forests of California. **Plant Diseases**, v. 85, p. 947-951, 2001. <https://doi.org/10.1094/PDIS.2001.85.9.947>

BAYRAMOĞLU, G.; ARICA, M. Y. Removal of heavy mercury (II), cadmium (II) and zinc (II) metal ions by live and heat inactivated *Lentinus edodes* pellets. **Chemical Engineering Journal**, v. 143, n. 1-3, p. 133-140, 2008. <https://doi.org/10.1016/j.cej.2008.01.002>

BHARATH, Y.; SINGH, S. N.; KEERTHIGA, G.; PRABHAKAR, R. Mycoremediation of contaminated soil in MSW Sites. In: GOSH (Eds.) **Waste Management and Resource Efficiency**. Springer Singapore, 2019. p. 321-329. https://doi.org/10.1007/978-981-10-7290-1_28

BORGMANN-WINTER, B. W.; STEPHENS, R. B.; D'AMATO, A. W.; FREY, S. D.; ROWE, R. J. Effects of timber harvest on epigeous fungal fruiting patterns and community structure in a northern hardwood ecosystem. **Canadian Journal of Forest Research**, v. 52, n. 1, p. 51-58, 2021. <https://doi.org/10.1139/cjfr-2021-0029>

BOROMENSKY, D. O. The influence of biomass of *Ganoderma* species on seed germination and seedlings growth of *Cucumis sativus*. **Plant & Fungal Research**, v. 4, n. 1, p. 14-18, 2021. <https://doi.org/10.30546/2664-5297.2021.1.2>

BYZOVA, M. A.; ERMOSHIN, A. A.; KISELEVA, I. S. Polypore fungus extracts reduce cytotoxicity of cadmium ions in the *Hordeum* test. **Biomics**, v. 14, n. 4, p. 310-314, 2022. <https://doi.org/10.31301/2221-6197.bmcs.2022-30>

CHUN, S. C.; MUTHU, M.; HASAN, N.; TASNEEM, S.; GOPAL, J. Mycoremediation of PCBs by *Pleurotus ostreatus*: Possibilities and prospects. **Applied Sciences**, v. 9, n. 19, e4185, 2019. <https://doi.org/10.3390/app9194185>

CLOETE, T. E.; CELLIERS, L. Removal of Aroclor 1254 by the white rot fungus *Corioliolus versicolor* in the presence of different concentrations of Mn (IV) oxide. **International Biodeterioration and Biodegradation**, v. 44, p. 243-253, 1999. [https://doi.org/10.1016/S0964-8305\(99\)00085-2](https://doi.org/10.1016/S0964-8305(99)00085-2)

CVANCAROVÁ, M.; KRESINOVÁ, Z.; FILIPOVÁ, A.; COVINO, S.; CAJTHAML, T. Biodegradation of PCBs

- by ligninolytic fungi and characterization of the degradation products. **Chemosphere**, v. 88, n. 11, p. 1317-1323, 2012. <https://doi.org/10.1016/j.chemosphere.2012.03.107>
- DEVKOTA, P.; HAMMERSCHMIDT, R. The infection process of *Armillaria mellea* and *Armillaria solidipes*. **Physiological and Molecular Plant Pathology**, v. 112, e101543, 2020. <https://doi.org/10.1016/j.pmpp.2020.101543>
- EGGEN, T. Application of fungal substrate from commercial mushroom production - *Pleurotus ostreatus* - for bioremediation of creosote contaminated soil. **International Biodeterioration & Biodegradation**, v. 44, n. 2-3, p. 117-126, 1999. [https://doi.org/10.1016/S0964-8305\(99\)00073-6](https://doi.org/10.1016/S0964-8305(99)00073-6)
- ERMOSHIN, A. A.; KISELEVA, I. S.; NIKKONEN, I. V.; NSENGIYUMVA, D. S.; DUAN, S.; MA, C.; KURCHENKO, V. P. Antioxidant activity and chemical composition of extracts from fruiting bodies of Xylotrophic Fungi growing on birch. **Journal of Siberian Federal University -Biology**, v. 14, n. 3, p. 339-353, 2021. <https://doi.org/10.17516/1997-1389-0354>
- FILIP, G. M.; FITZGERALD, S. A.; CHADWICK, K. L.; MAX, T. A. Thinning Ponderosa pine affected by *Armillaria* root disease: 40 years of growth and mortality on an infected Site in Central Oregon. **Western Journal of Applied Forestry**, v. 24, p. 88-94, 2009.
- FUKASAWA, Y.; KOMAGATA, Y.; USHIJIMA, S. Fungal wood decomposer activity induces niche separation between two dominant tree species seedlings regenerating on coarse woody material. **Canadian Journal of Forest Research**, v. 47, n. 1, p. 106-112, 2016. <https://doi.org/10.1139/cjfr-2016-0218>
- GANGADHAR, B.; RAMAKRISHNA, N. G. Green Technology vs Environmental Sustainability in India-an Overview. **International Journal of Current Advanced Research**, v. 6, n. 3, p. 2465-2468, 2017. <https://doi.org/10.24327/ijcar.2017.2468.0029>
- GARBELOTTO, M. M.; LEE, H. K.; SLAUGHTER, G.; POPENUCK, T.; COBB, F. W.; BRUNS, T. D.; Heterokaryosis is not required for virulence of *Heterobasidium annosum*. **Mycologia**, v. 89, n. 1, p. 92-102, 1997. <https://doi.org/10.2307/3761177>
- HAMED, S. A. M. In-vitro studies on wood degradation in soil by soft-rot fungi: *Aspergillus niger* and *Penicillium chrysogenum*. **International Biodeterioration and Biodegradation**, v. 78, p. 98-102, 2013. <https://doi.org/10.1016/j.ibiod.2012.12.013>
- HETLAND, G.; JOHNSON, E.; BERNARDSHAW, S. V.; GRINDE, B. Can medicinal mushrooms have prophylactic or therapeutic effect against COVID-19 and its pneumonic superinfection and complicating inflammation? **Scandinavian Journal of Immunology**, v. 93, n. 1, e12937, 2021. <https://doi.org/10.1111/sji.12937>
- HUAIQIAN, D.; YAJING, C.; LIJUAN, Z. Chapter Fifteen - *Coriolus versicolor* polysaccharopeptide as an immunotherapeutic in China. In: **Progress in Molecular Biology and Translational Science**, v. 163, p. 361-381, 2019. <https://doi.org/10.1016/bs.pmbts.2019.03.001>
- JUFENG, Y.; XIANGDONG, W.; KE, W.; YUDI, D.; YICHAO, Y.; RUFIDA, A.; FEILONG, C.; ZIJIAN, W.; WENZHEN, L.; LIMEI, M. A novel polysaccharide isolated from *Flammulina velutipes*, characterization, macrophage immunomodulatory activities and its impact on gut microbiota in rats. **Journal of animal physiology and animal nutrition**, v. 104, n. 2, p. 735-748, 2020. <https://doi.org/10.1111/jpn.13290>
- JUNNINEN, K.; KOUKI, J.; RENVAL, P. Restoration of natural legacies of fire in European boreal forests: an experimental approach to the effects on wood-decaying fungi. **Canadian Journal of Forest Research**, v. 38, n. 2, p. 202-215, 2008. <https://doi.org/10.1139/X07-145>
- KAZARTSEV, I. A.; SOLOVIEV, V. A. Changes in the chemical composition of wood under the influence of the lignin-destroying fungus *Phanerochaete sanguinea*. **Bulletin of the St. Petersburg Forest Engineering Academy**, v. 188, p. 253-259, 2009. (in Russian).
- KOCH, Zh. A.; LITOVKA, Yu. A.; ENAZAROV, R. Kh.; MAKOLOVA, P. V.; SHIMOVA, Yu. S.; POCHEKUTOV, I. S.; PAVLOV, I. N. Biotechnological aspects of utilization of postextraction biomass and cell culture of *Ortbilia secunda* (L.) house with basidial fungi. **Chemistry of plant raw materials**, n. 4, p. 359-369, 2020.
- KRUPODOROVA, T. A.; BARSHTEYN, V. Y.; KIZITSKA, T. O.; POKAS, E. V. Effect of cultivation conditions on mycelial growth and antibacterial activity of *Lentinula edodes* and *Fomitopsis betulina*. **Czech Mycology**, v. 7, n. 12, p. 167-186, 2019. <https://doi.org/10.33585/cmy.71204>
- KUBATOVA, A.; ERBANOVA, P.; EICHLEROVA, I.; HOMOLKA, L.; NERUD, F.; SASEK, V. PCB congener selective biodegradation by the white rot fungi *Pleurotus ostreatus* in contaminated soil. **Chemosphere**, v. 43, p. 207-215, 2001. [https://doi.org/10.1016/s0045-6535\(00\)00154-5](https://doi.org/10.1016/s0045-6535(00)00154-5)
- LENZ, A. R.; GALÁN-VÁSQUEZ, E.; BALBINOT, E.; ABREU, F. P.; OLIVEIRA N. S. de; ROSA, L. O.; AVILA E SILVA, S.; CAMASSOLA, M.; DILLON, A. J. P.; PEREZ-RUEDA, E. Gene regulatory networks of *Penicillium echinulatum* 2HH and *Penicillium oxalicum* 114-2 inferred by a computational biology approach. **Frontiers in microbiology**, v. 11, e588263, 2020. <https://doi.org/10.3389/fmicb.2020.588263>
- LIANG, C.; WANG, Q.; WANG, W.; LIN, C. S. K.; HU, Y.; QI, W. Enhancement of an efficient enzyme cocktail from *Penicillium consortium* on biodegradation of pretreated poplar. **Chemical Engineering Journal**, v. 452, n. 2, e139352, 2023. <https://doi.org/10.1016/j.cej.2022.139352>
- LIN, W.-H.; LEE, K.-H.; CHEN, L.-T. The effects of *Ganoderma lucidum* compound on goat weight and anti-inflammatory: A case study of circular agriculture. **AIMS Environmental Science**, v. 8, n. 6, p. 553-566, 2021. <https://doi.org/10.3934/ENVIRONSCI.2021035>
- LOUKIDOU, M. X.; MATIS, K. A.; ZOUBOULIS, A. I. LIAKOPOULOU-KYRIAKIDOU, M. Removal of As (V) from wastewaters by chemically modified fungal biomass. **Water Research**, v. 37, n. 18, p. 4544-4552, 2003. [https://doi.org/10.1016/S0043-1354\(03\)00415-9](https://doi.org/10.1016/S0043-1354(03)00415-9)
- LUEANGJAROENKIT, P.; TEERAPATSAKUL, C.; SAKKA, K.; SAKKA, M.; KIMURA, T.; KUNITAKE, E.; CHITRADON, L. Two manganese peroxidases and a laccase of *Trametes polyzona* KU-RNW027 with novel properties for dye and pharmaceutical product degradation in redox mediator-free system.

- Mycobiology**, v. 47, n. 2, p. 217-229, 2019. <https://doi.org/10.1080/12298093.2019.1589900>
- MANI, D.; KUMAR, C. Biotechnological advances in bioremediation of heavy metals contaminated ecosystems: An overview with special reference to phytoremediation. **International Journal of Environmental Science and Technology**, v. 11, p. 843-872, 2014. <https://doi.org/10.1007/s13762-013-0299-8>
- MARIAN, I.; VONK, P.; VALDES, I.; BARRY, K.; BOSTOCK, B.; CARVER, A.; DAUM, C.; LERNER, H.; LIPZEN, A.; PARK, H.; SCHULLER, M.; TEGELAAR, M.; TRITT, A.; SCHMUTZ, J.; GRIMWOOD, J.; LUGONES, L.; CHOI, I.; WÖSTEN, H.; GRIGORIEV, I.; OHM, R. The Transcription factor Roc1 is a key regulator of cellulose degradation in the wood-decaying mushroom *Schizophyllum commune*. **mBio**, v. 13, n. 3, e0062822m 2021. <https://doi.org/10.1128/mbio.00628-22>
- MIGLIORE, L.; FIORI, M.; SPADONI, A.; GALLI, E. Biodegradation of oxytetracycline by *Pleurotus ostreatus* mycelium: A mycoremediation technique. **Journal of Hazardous Materials**, v. 215-216, p. 227-232, 2012. <https://doi.org/10.1016/j.jhazmat.2012.02.056>
- MYKCHAYLOVA, O. B.; POYEDINOK, N. L. Antimicrobial activity of *Fomitopsis officinalis* (vill.) bondartsev & singer in pure culture. **Innovative Biosystems and Bioengineering**, v. 5, n. 4, p. 220-227, 2021. <https://doi.org/10.20535/ibb.2021.5.4.246668> (in Russian).
- OLIVIERI, G.; RUSSO, M. E.; GIARDINA, P.; MARZOCHELLA, A.; SANNIA, G.; SALATINO, P. Strategies for dephenolization of raw olive mill wastewater by means of *Pleurotus ostreatus*. **Journal of Industrial Microbiology and Biotechnology**, v. 39, n. 5, p. 719-29, 2012. <https://doi.org/10.1007/s10295-011-1072-y>
- PATWARDHAN, B.; WARUDE, D.; PUSHPANGADAN, P.; BHATT, N. Ayurveda and traditional Chinese medicine: A comparative overview. **Evidence-Based Complementary and Alternative Medicine**, v. 2, n. 4, p. 465-473, 2005. <https://doi.org/10.1093/ecam/neh140>
- PELIZON, A. C.; KANENO, R.; SOARES, A. M. V. C.; MEIRA, D. A.; SARTORI, A. Immunomodulatory activities associated with β -glucan derived from *Saccharomyces cerevisiae*. **Physiological Research**, v. 54, n. 5, p. 557-564, 2005.
- PENG, S.; QIN, X. Application of phytonanotechnology for modern sustainable green agriculture: Promising opportunities and scientific challenges. **Industrial Crops and Products**, v. 218, e119001, 2024. <https://doi.org/10.1016/j.indcrop.2024.119001>
- PIMENTEL, D.; MARKLEIN, A.; TOTH, M. A.; KARPOFF, M.; PAUL, G. S.; MCCORMACK, R.; KYRIAZIS, J.; KRUEGER, T. Biofuel impacts on world food supply: use of fossil fuel, land and water resources. **Energies**, v. 1, n. 2, p. 41-78, 2008. <https://doi.org/10.3390/en1010041>
- POLEZHAEVA, T. V.; SHIROKIH, I. G.; SERGUSHKINA, M. I.; NAZAROVA, Y. I.; SHIROKIH, A. A.; KHUDYAKOV, A. N.; ZAITSEVA, O. O.; SOLOMINA, O. N.; PATUROVA, I. G. The effect of *Herichium erinaceus* BP 16 polysaccharides on the phagocytic activity of human blood neutrophils. **Theoretical and Applied Ecology**, v. 2, pp. 166-171, 2020. (in Russian).
- POZDNYAKOVA, N. N.; DUBROVSKAYA, E. V.; GRINEV, V. S.; TURKOVSKAYA, O. V. Prospects for the use of xylophilic fungi *Pleurotus ostreatus* florida and *Schizophyllum commune* for mycoremediation of soils contaminated with oil hydrocarbons and surfactants. **Biotechnologiya**, v. 37, n. 5, p. 108-116. <https://doi.org/10.21519/0234-2758-2021-37-5-108-116> (in Russian).
- QAMAR, M. Z.; NOOR, M.; ALI, W.; QAMAR, M. Green technology and its implications worldwide. **The Inquisitive Meridian**, v. 3, n. 10, p. 1-10, 2021.
- QUEVEDO-HIDALGO, B.; NARVAÉZ-RINCÓN, P. C.; PEDROZA-RODRÍGUEZ, A. M.; VELÁSQUEZ-LOZANO, M. Degradation of Chrysanthemum (*Dendranthema grandiflora*) wastes by *Pleurotus ostreatus* for the production of reducing sugars. **Biotechnology and Bioprocess Engineering**, v. 17, p. 1103-1112, 2012. <https://doi.org/10.1007/s12257-012-0227-7>
- RAMASAMY, R. K.; CONGEEVARAM, S.; THAMARAISELVI, K. Evaluation of isolated fungal strain from e-waste recycling facility for effective sorption of toxic heavy metals Pb(II) ions and fungal protein molecular characterization-a Mycoremediation approach. **Asian Journal of Experimental Biology**, v. 2, n. 2, p. 342-347, 2011.
- RANGSINTH, P.; SILLAPACHAIYAPORN, C.; NILKHET, S.; TENCOMNAO, T.; UNG, A. T.; CHUCHAWANKUL, S. Mushroom-derived bioactive compounds potentially serve as the inhibitors of SARS-CoV-2 main protease: An in-silico approach. **Journal of Traditional and Complementary Medicine**, v. 11, n. 2, p. 158-172, 2021. <https://doi.org/10.1016/j.jtcme.2020.12.002>
- RILEY, R.; SALAMOV, A. A.; BROWN, D. W.; NAGY, L. G.; FLOUDAS, D.; HELD, B. W.; LEVASSEUR, A.; LOMBARD, V.; MORIN, E.; OTILLAR, R.; LINDQUIST, E. A.; SUN, H.; LABUTTI, K. M.; SCHMUTZ, J.; JABBOUR, D.; LUO, H.; BAKER, S. E.; PISABARRO, A. G.; WALTON, J. D.; BLANCHETTE, R. A.; HENRISSAT, B.; MARTIN, F.; CULLEN, D.; HIBBETT, D. S.; GRIGORIEV, I. V. Extensive sampling of basidiomycete genomes demonstrates inadequacy of the white-rot/brown-rot paradigm for wood decay fungi. **Proceedings of the National Academy of Sciences of the USA**, v. 111, p. 9923-9928, 2014. <https://doi.org/10.1073/pnas.1400592111>
- RUIZ-AGUILAR, G. M. L.; FERNÁNDEZ-SÁNCHEZ, J. M.; RODRÍGUEZ-VÁZQUEZ, R.; POGGI-VARALDO, H. Degradation by white-rot fungi of high concentrations of PCB extracted from a contaminated soil. **Advances in Environment Research**, v. 6, n. 4, p. 559-568, 2002. [https://doi.org/10.1016/S1093-0191\(01\)00102-2](https://doi.org/10.1016/S1093-0191(01)00102-2)
- SAY, R.; YIMAZ, N.; DENIZLI, A. Removal of heavy metal ions using the fungus *Penicillium canescens*. **Adsorption Science and Technology**, v. 21, p. 643-650, 2003. <https://doi.org/10.1260/026361703772776>
- SEMENOVA, T. A.; DUNAEVSKY, Y. E.; BELJAKOVA, G. A.; BORISOV, B. A.; SHAMRAICHUK, I. L.; BELOZERSKY, M. A. Extracellular peptidases as possible markers of fungal ecology. **Applied Soil**

- Ecology**, v. 113, p. 110, 2017. <https://doi.org/10.1016/j.apsoil.2017.01.002>
- SHAKHOVA, N. V.; VOLOBUEV, S. V. Revealing new active and biotechnologically perspective producers of oxidative and cellulolytic enzymes among pure cultures of xylotrophic *Agaricomycetes* from the southern non-chernozem zone of the European part of Russia. **Current Research in Environmental and Applied Mycology**, v. 10, n. 1, p. 113-119, 2020. <https://doi.org/10.5943/cream/10/1/12>
- SMANIA JR., A.; MONACHE, F. D.; SMANIA, E. de F. A.; CUNEO, R. S. Antibacterial Activity of steroidal compounds isolated from *Ganoderma applanatum* (Pers.) Pat. (Aphyllorphomycetidae) fruit body. **International Journal of Medicinal Mushrooms**, v. 1, n. 4, p. 325-330, 1999. <https://doi.org/10.1615/intjmedmushr.v1.i4.40>
- SMITH, G. R.; FINLAY, R. D.; STENLID, J.; VASAITIS, R.; MENKIS, A. Growing evidence for facultative biotrophy in saprotrophic fungi: data from microcosm tests with 201 species of wood-decay basidiomycetes. **The New Phytologist**, v. 215, p. 747-755, 2017. <https://doi.org/10.1111/nph.14551>
- SUI, Z.; YIN, J.; HUANG, J.; YUAN, L. Phosphorus mobilization and improvement of crop agronomic performances by a new white-rot fungus *Ceriporia lacerata* HG2011. **Journal of the Science of Food and Agriculture**, v. 102, n. 4, p. 1640-1650, 2022. <https://doi.org/10.1002/jsfa.11501>
- TAŞTAN, B. E.; ERTUĞRUL, S.; DÖNMEZ, G. Effective bioremoval of reactive dye and heavy metals by *Aspergillus versicolor*. **Bioresource Technology**, v. 101, n. 3, p. 870-876, 2010. <https://doi.org/10.1016/j.biortech.2009.08.099>
- TEPLYAKOVA, T. V.; KOSOGOVA, T. A.; ANANKO, G. G.; BARDASHEVA, A. V.; ILYICHEVA, T. N. Antiviral activity of basidial fungi. Literature review. **Problems of Medical Mycology**, v. 16, n. 2, pp. 15-25, 2014. (in Russian).
- TIŠMA, M.; ŽNIDARŠIČ-PLAZL, P.; ŠELO, G.; TOLJ, I.; ŠPERANDA, M.; BUCIĆ-KOJIĆ, A.; PLANINIĆ, M. *Trametes versicolor* in lignocellulose-based bioeconomy: State of the art, challenges and opportunities. **Bioresource Technology**, v. 330, e124997, 2021. <https://doi.org/10.1016/j.biortech.2021.124997>
- TSIVILEVA, O. M.; PERFILEVA, A. I. Mushroom-derived novel selenium nanocomposites' effects on potato plant growth and tuber germination. **Molecules**, v. 27, n. 14, e4438, 2022. <https://doi.org/10.3390/molecules27144438>
- VAKSMAA, A.; GUERRERO-CRUZ, S.; GHOSH, P.; ZEGHAL, E.; HERNANDO-MORALES, V.; NIEMANN, H. Role of fungi in bioremediation of emerging pollutants. **Frontiers in Marine Science**, v. 10, e1070905, 2023. <https://doi.org/10.3389/fmars.2023.1070905>
- VASILIAUSKAS, R.; MENKIS, A.; FINLAY, R. D.; STENLID, J. Wood-decay fungi in fine living roots of conifer seedlings. **New Phytologist**, v. 174, n. 2, p. 441-446, 2007. <https://doi.org/10.1111/j.1469-8137.2007.02014.x>
- VENÂNCIO, C.; CARDOSO, P.; EKNER-GRZYB, A.; CHMIEŁOWSKA-BAK, J.; GRZYB, T.; LOPES, I. Sources, sinks, and solutions: How decaying fungi may devise sustainable farming practices for plastics degradation in terrestrial ecosystems. **Trends in Analytical Chemistry**, v. 180, e117898, 2024. <https://doi.org/10.1016/j.trac.2024.117898>
- VETVICKA, V.; GOVER, O.; KARPOVSKY, M.; HAYBY, H.; DANAY, O.; EZOV, N.; SCHWARTZ, B. Immune-modulating activities of glucans extracted from *Pleurotus ostreatus* and *Pleurotus eryngii*. **Journal of Functional Foods**, v. 54, p. 81-91, 2019. <https://doi.org/10.1016/j.jff.2018.12.034>
- VOLCHATOVA, I. V.; MEDVEDEVA, S. A. Use of fungi for removal of wood debris in urbanized ecosystems. **Advances in Medical Mycology**, v. VII, p. 234-235, 2006. (in Russian).
- VOLOBUEV, S.; SHAKHOVA, N. Towards the discovery of active lignocellulolytic enzyme producers: a screening study of xylotrophic macrofungi from the Central Russian Upland. **Iranian Journal of Science and Technology, Transaction A: Science**, v. 46, n. 1, p. 91-100, 2022. <https://doi.org/10.1007/s40995-021-01245-7>
- YADAV, S.; YADAV, A.; MOHAN, C. H.; GARG, V. K.; KUMARI, N. Chapter 1 - Introduction to environmental and green chemistry. In: GARG, V. K.; YADAV, A.; MOHAN, C.; YADAV, S.; KUMARI, N. (Eds.). **In Green chemistry approaches to environmental sustainability: Status, challenges and prospective**. Elsevier, 2024. p. 1-22. <https://doi.org/10.1016/B978-0-443-18959-3.00005-7>
- YADAV, A. N.; SINGH, S.; MISHRA, S.; GUPTA, A. **Recent advancement in white biotechnology through fungi: diversity and enzymes perspectives**. (Vol. 1). Springer International Publishing, 2019, 571p. <https://doi.org/10.1007/978-3-030-10480-1>
- YE, Y.; LI, X.; ZHAO, J. Production and characteristics of a novel xylose-and alkali-tolerant GH 43 β -xylosidase from *Penicillium oxalicum* for promoting hemicellulose degradation. **Scientific Reports**, v. 7, n. 1, e11600, 2017. <https://doi.org/10.1038/s41598-017-11573-7>
- YU, H.; LEI, P.; MA, J.; JIN, J.; MA, Y.; FANG, Y.; ZENG, G.; ZHANG, K.; JIN, L.; SUN, D. The potential of white-rot fungi for algal control: Mechanisms, Strategies, and Challenges. **Environmental Research**, v. 236, n. 1, e116738, 2023. <https://doi.org/10.1016/j.envres.2023.116738>
- YUJIAO, H.; JIALIANG, H.; CHUNFANG, Z.; FENG, Z.; YOUFANG, G.; CHENFANG, W.; ERHUI, J. *Hericium erinaceus* polysaccharide improves the microstructure, immune function, proliferation and reduces apoptosis of thymus and spleen tissue cells of immunosuppressed mice. **Bioscience, Biotechnology, and Biochemistry**, v. 87, n. 3, p. 279-289, 2023. <https://doi.org/10.1093/bbb/zbac198>
- ZAHMATKESH, M.; SPANJERS, H.; LIER, J. B. Fungal treatment of humic-rich industrial wastewater: application of white rot fungi in remediation of food-processing wastewater. **Environmental Technology**, v. 38, n. 21, p. 2752-2762, 2017. <https://doi.org/10.1080/09593330.2016.1276969>

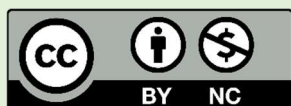
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