The Fungi That Degrade Plastic

Subjects: Environmental Sciences

Contributor: Anusha H. Ekanayaka , Saowaluck Tibpromma , Donqin Dai , Ruifang Xu , Nakarin Suwannarach , Steven L. Stephenson , Chengjiao Dao , Samantha C. Karunarathna

Plastic has become established over the world as an essential basic need for our daily life. Plastics have many characteristics such as low production costs, inertness, relatively low weight, and durability. The primary disadvantage of plastics is their extremely slow natural degradation. The latter results in an accumulation of plastic waste in nature. Many fungi can be used to degrade plastics.

fungi global plastic production plastic waste accumulation

1. Introduction

Plastic is one of the most abundant human-produced, versatile materials on the earth. Its high stability and long durability facilitate its integral role in our day-to-day lives, from the kitchen to an industrial level [1][2]. Plastic is a polymer and consists of the elements carbon, hydrogen, silicon, oxygen, chlorine, and nitrogen [1]. Plastic production can be bio-based or synthetic. Bio-based plastics are made from natural compounds such as lignin, cellulose, hemicellulose, terpenes, vegetable oils, carbohydrates, and food waste [3][4][5]. In contrast, crude oil is the main component of synthetic plastics [6][7], which are generally referred to as non-biodegradable [8].

As global plastic production and plastic waste accumulation increase rapidly, people need to look for a quick and efficient solution to save nature and, indeed, the entire planet [9][10][11]. The problem becomes even more acute as the natural degradation rate of all types of plastic is very slow [12]. Hence, it is essential to look at ways to accelerate plastic degradation methods. Several solutions that have been proposed are photo-degradation (degrade by light), chemical degradation, thermal degradation (degrade by heat), irradiation using gamma rays, and biodegradation (degrade by biological additives or microorganisms) [13][14]. Biodegradation has been suggested as the best solution as it is an eco-friendly approach. However, based on the results obtained in previous studies, people select biodegradation since the other options are not cost-effective [14]. The following contents analyzed phylogenetic relationships of plastic-degrading fungi based on a combined ITS, LSU, SSU, TEF, RPB1, and RPB2 dataset from 395 strains and provided brief taxonomy at the level of class.

2. Phylum Ascomycota

2.1. Class Dothideomycetes

The Dothideomycetes is the largest class within the phylum Ascomycota. Most of the taxa within this class are recorded as saprobes in various habitats and substrates [15]. There are some members of Dothideomycetes are capable of plastic degradation. Most of the recorded species of the Dothideomycetes belong to the order Pleosporales, but a few taxa are recorded from the Dothideales and Botryosphaeriales. Plastic degraders in the Dothideomycetes have the ability to degrade low-density polyethylene (LDPE), PUR, polystyrene (PS), PCL, PEA, PPA, PBA, high-density polyethylene (HDPE), polyvinyl chloride (PVC), PE, PU, and Sky-Green plastics. Recent studies on plastic-degrading members of the Dothideomycetes are those of Khruengsai et al. [16] and Brunner et al. [17]. In the phylogenetic tree, the Dothideomycetes formed a well-supported clade sister to the Arthoniomycetes. Most of the plastic-degrading Dothideomycetes were placed in the upper subclade of the main Dothideomycetes clade, and the rest were grouped in a basal subclade.

2.2. Class Eurotiomycetes

The Eurotiomycetes are extremely common saprobes in diverse habitats and substrates [18]. Most plastic-degrading fungal records belong to the Eurotiomycetes. Many plastic-degrading members of the Eurotiomycetes are taxonomically placed under the Eurotiales, and the most common plastic-degrading fungal genera are *Aspergillus* and *Penicillium*. The plastic types they are reported to degrade are HDPE, LDPE, PCL, PE, PVC, PS-PUR, PEA, PPA, PBA, PHB, Poly[3HB-co-(10 mol%) 3HV], Sky-Green, PHV, PBS, polylactic acid (PLA) and PVC. Recent studies on plastic-degrading Eurotiomycetes are those of Rani & Singh [19], Ndahebwa Muhonja et al. [20], Bermúdez-García et al. [21], Laila [22], Khruengsai et al. [16], Munir et al. [23], Alshehrei [24], Sangale et al. [25], Duan et al. [26], El-Morsy et al. [27], Brunner et al. [17] and Ojha et al. [28]. The Eurotiomycetes is the uppermost clade within phylogram. The genera *Aspergillus* and *Penicillium* contain a large number of species with a worldwide distribution and a huge range of ecological habitats [29]. They are mostly widespread saprobes and can be found in both indoor and outdoor environments, including in both the air and soil. In addition, some species of *Aspergillus* and *Penicillium* have the ability to grow under extreme conditions [29]. Hence, further research on these genera would provide better solutions for the environmental accumulation of plastics.

2.3. Class Leotiomycetes

Most of the Leotiomycetes are saprobes on a wide variety of substrates. However, this class also includes many important plant pathogens [30]. It can be showed that the few records of plastic-degrading fungi are phylogenetically related to the Leotiomycetes. In the phylogenetic tree, the Leotiomycetes formed a well-supported clade sister to the Laboulbeniomycetes. However, there is a single record found that clearly belongs to the Leotiomycetes and possibly has the ability of plastic degradation [27]. The other records that grouped within Leotiomycetes in phylogeny were *Cephalosporium gramineum*, which is currently placed under the Sordariomycetes. Therefore, studies with a wide range of taxon sampling are required to resolve the phylogenetic position of *Cephalosporium gramineum*. Furthermore, a recent study on the biodegradation of bio-based and biodegradable plastic, polybutylene succinate-co-adipate (PBSA), identified a species (*Tetracladium furcatum)* within the Leotiomycetes that has the ability to degrade PBSA [31]. However, recent studies on synthetic plastic-degrading members of the

Leotiomycetes are very few. As a result, additional studies on the Leotiomycetes are required to assess their ability to degrade plastics.

2.4. Class Saccharomycetes

The Saccharomycetes is a small class of yeasts with a single order of about 1000 known species, which are classified under the Ascomycota [32]. Most of the Saccharomycetes are saprobes, and few are recorded as human and plant pathogens [32]. Their study discovered five records of five members of the Saccharomycetes capable of degrading plastics. The Saccharomycetes is the second basal clade within the phylum Ascomycota. All Saccharomycetes members that are plastic degraders are grouped in the upper subclade of the main Saccharomycetes clade. *Arxula*, *Candida,* and *Debaryomyces* are the genera to which those plastic-degrading members of the Saccharomycetes belong [33][34]. Some members of the Saccharomycetes are widely used in industrial and biotechnological processes. Species such as *Saccharomyces cerevisiae* are model organisms in many types of research [32]. A recent study used Genetic engineering techniques on two strains of *Saccharomyces cerevisiae* to produce the heterologous protein Polyethylene Terephthalate (PET) hydrolase enzyme, which has been shown to have the capability of degrading PET into its subsequent monomers [35]. It can be believed future research on the Saccharomycetes would find a better solution for plastic accumulation in nature.

2.5. Class Sordariomycetes

The Sordariomycetes is the second largest class within the phylum Ascomycota. The majority of the Sordariomycetes are saprobes, but the group also includes some important plant pathogens [36]. They have a wide ecological distribution in both terrestrial and aquatic habitats [36]. These contents recorded many members of the Sordariomycetes with the ability to degrade plastics. The plastic types they are reported to degrade are PE, PS, PHB, Poly[3HB-co-(10 mol%) 3HV], PUR, PS-PUR, HDPE, LDPE, PVC, PCL, PEA, PPA, and PBA. Recent studies of plastic-degrading Sordariomycetes are those of Munir et al. [23], (Yang et al. [37], Brunner et al. [17], and Khruengsai et al. [16]. The Sordariomycetes formed a middle clade within the main Ascomycota clade that is sister to the Laboulbeniomycetes. Many plastic degraders in the Sordariomycetes are classified under the Hypocreales, while others belong to the Amphisphaeriales, Glomerellales, Phyllachorales, and Sordariales. Even though the Eurotiomycetes include the highest number of records of plastic-degrading fungi, the Sordariomycetes contain the highest number of genera with the capability to degrade plastics.

3. Phylum Basidiomycota

3.1. Class Agaricomycetes

The Agaricomycetes is a morphologically diverse class of macrofungi within the Basidiomycota, containing around 36,000 described species. They are ecologically diverse and include saprobes, mycorrhizal symbionts, and pathogens [38]. Moreover, the Agaricomycetes encompasses several important commercially growing edible mushrooms [39]. Their study found several records of Agaricomycetes with the ability to degrade plastics. They are

reported to degrade Poly[3HB-co-(7 mol%) 3HV], LDPE, PVC, polyethylene, and PHB. Additionally, da Luz et al. [40] performed a study on plastic-degrading Agaricomycetes. They investigated the degradation of oxo-biodegradable plastic bags and green polyethylene by *Pleurotus ostreatus*. The Agaricomycetes is the upper clade within phylum Basidiomycota, and it is highly statistically supported within the present phylogeny. Further studies of edible mushrooms belonging to the Agaricomycetes and their ability to degrade plastics would increase world food production and reduce the plastic accumulation in nature.

3.2. Class Microbotryomycetes

The Microbotryomycetes include mainly mycoparasites, saprobic yeasts, and plant pathogens [41]. A single record of plastic-degrading fungi was found in the order Sporidiobolales of the Microbotryomycetes in their study. In phylogenetic tree, the Microbotryomycetes formed a well-supported clade sister to Tritirachiomycetes.

3.3. Class Tremellomycetes

The Tremellomycetes are classified under the Basidiomycota and consist of saprobic yeasts, dimorphic taxa, and species that form hyphae and/or complex fruiting bodies [42]. Their study identified a few records from the Tremellomycetes that are capable of degrading plastics. All the records belong to the genera *Cryptococcus* and *Papiliotrema* (Tremellales), andthey are capable of degrading PCL, PBS, and PBSA. The Tremellomycetes formed a well-supported clade sister to Agaricomycetes in the present phylogenetic tree. A recent study on synthetic plastic-degrading Tremellomycetes was published by Hung et al. [43]. A recent study on biodegradable plastic mulch films (BDMs) and their associated soil microbial communities found that the Tremellomycetes are capable of degrading agriculturally-weathered BDMs [44].

3.4. Class Tritirachiomycetes

The Tritirachiomycetes is a small class within the Basidiomycota that is made up of filamentous fungi. They are mainly saprobes, but some have been recorded as human pathogens [45]. A single record of a fungus from this class that is capable of degrading plastics was found in their. The Tritirachiomycetes formed a well-supported clade sister to the Microbotryomycetes in phylogenetic tree.

3.5. Class Ustilaginomycetes

The majority of the Ustilaginomycetes are economically important plant pathogens. They are usually unicellular yeasts (sporidia), but some are simple multicellular forms, such as a pseudomycelium, multicellular cluster, or mycelium [46]. Moreover, the Ustilaginomycetes have a comparatively short life cycle, which makes them easy to handle under laboratory conditions. As a result, the Ustilaginomycetes can be considered model organisms for studying fungi [46]. Their study found a single record from the Ustilaginomycetes of a fungus capable of degrading plastics. The Ustilaginomycetes is the basal clade within the main Basidiomycota clade, and it is statistically highly supported.

4. Phylum Mucoromycota

Class Mucoromycetes

The Mucoromycetes are a class within the phylum Mucoromycota and consist of mainly filamentous fungi with a saprobic lifestyle. Several species are also life-threatening human pathogens, plant parasites, and food spoilage organisms. Moreover, members of the Mucoromycetes are used as a traditional fermenting agent for Asian and African foods, such as soybean products and several varieties of European cheese. Fungi belonging to the Mucoromycetes are common in the environment and able to colonize all kinds of wet, organic substrates [47]. Their study found several Mucoromycetes fungi with the ability to degrade plastics. All the recorded plastic-degrading members of the Mucoromycetes belong to the genera *Mucor* and *Rhizopus*. These fungi are capable of degrading PHB, HDPE, LDPE, PVC, PCL, polyalkylene dicarboxylic acids, PPA, and PET copolymers with dicarboxylic acids. A recent study of plastic-degrading Mucoromycetes was that of Pardo-Rodríguez & Zorro-Mateus [48]. The Mucoromycota formed the basal clade within phylogenetic tree. However, the phylum presented a polyphyletic nature in the present phylogenetic tree and was separated into two basal clades.

Even though plastic is currently an important material in the global environment, it is becoming a huge threat to nature. Because current global plastic production is increasing rapidly (300 million tons annually) and plastics have a very low natural degradation rate, they accumulate in natural environments and cause considerable damage to biodiversity and natural ecosystems. At present, scientists and researchers are assessing the usefulness of microorganisms in accelerating plastic degradation. These contents introduced plastic degradation using fungi. Herein these contents list more than 200 records of fungi capable of degrading fungi based on the available literature. Their phylogenetic relationships were analyzed using a combined ITS, LSU, SSU, TEF, RPB1, and RPB2 dataset generated from 395 strains. It can be confirmed that plastic-degrading fungi are taxonomically diverse and belong to three major fungal phyla—the Ascomycota, Basidiomycota, and Mucoromycota. The Ascomycota plastic degraders belong to five major classes: Dothideomycetes, Eurotiomycetes, Leotiomycetes, Saccharomycetes, and Sordariomycetes. Plastic-degrading Basidiomycota fall within the Agaricomycetes, Microbotryomycetes, Tremellomycetes, Tritirachiomycetes, and Ustilaginomycetes. Mucoromycota fungi capable of degrading plastics were found under the Mucoromycetes. The Eurotiomycetes include the highest number of recorded plastic degraders in the fungi kingdom. However, a wide range of plastic-degrading fungal genera was found within the class Sordariomycetes. Moreover, there is an acute need for future research on similar topics to resolve the global problem of plastic accumulation in nature.

References

1. Ogunbayo, A.; Olanipekun, O.; Adamu, I. Preliminary Studies on the Microbial Degradation of Plastic Waste Using Aspergillus niger and Pseudomonas sp. J. Environ. Prot. 2019, 10, 625–631.

2. Sangale, M.K.; Shahnawaz, M.; Ade, A.B. Potential of Fungi Isolated from the Dumping Sites Mangrove Rhizosphere Soil to Degrade Polythene. Sci. Rep. 2019, 9, 5390.
3. Baheti, P. How Is Plastic Made? Available online: https://www.bpf.co.uk/plastipedia/how-is-plastic-made.aspx (accessed on 15 September 2021).
4. Di Bartolo, A.; Infurna, G.; Dintcheva, N.T. A Review of Bioplastics and Their Adoption in the Circular Economy. Polymers 2021, 13, 1229.
5. Weinstein, J.E.; Dekle, J.L.; Leads, R.R.; Hunter, R.A. Degradation of Bio-Based and Biodegradable Plastics in a Salt Marsh Habitat: Another Potential Source of Microplastics in Coastal Waters. Mar. Pollut. Bull. 2020, 160, 111518.
6. Brunner, I.; Fischer, M.; Rüthi, J.; Stierli, B.; Frey, B. Ability of Fungi Isolated from Plastic Debris Floating in the Shoreline of a Lake to Degrade Plastics. PLoS ONE 2018, 13, e0202047.
7. Plastics Europe. How Plastics Are Made. Available online: https://www.plasticseurope.org/en/about-plastics/what-are-plastics/how-plastics-are-made (accessed on 13 September 2021).
8. Wayman, C.; Niemann, H. The Fate of Plastic in the Ocean Environment—A Minireview. Environ. Sci. Process. Impacts 2021, 23, 198–212.
9. Alberto Di Bartolo; Giulia Infurna; Nadka Dintcheva; A Review of Bioplastics and Their Adoption in the Circular Economy. *Polymers* **2021**, *13*, 1229, 10.3390/polym13081229.
10. John E. Weinstein; Jack L. Dekle; Rachel R. Leads; Rebecca A. Hunter; Degradation of bio-based and biodegradable plastics in a salt marsh habitat: Another potential source of microplastics in coastal waters. *Marine Pollution Bulletin* **2020**, *160*, 111518-111518, 10.1016/j.marpolbul.2020.111518.
11. Ivano Brunner; Moira Fischer; Joel Rüthi; Beat Stierli; Beat Frey; Ability of fungi isolated from plastic debris floating in the shoreline of a lake to degrade plastics. *PLOS ONE* **2018**, *13*, e0202047, 10.1371/journal.pone.0202047.
12. Hayden K. Webb; Jaimys Arnott; Russell J. Crawford; Elena P. Ivanova; Plastic Degradation and Its Environmental Implications with Special Reference to Poly(ethylene terephthalate). *Polymers* **2012**, *5*, 1-18, 10.3390/polym5010001.
13. 25. Pramila, R.; Ramesh, K.V.; Biodegradation of Low Density Polyethylene (LDPE) by Fungi Isolated from Municipal Landfill Area. *J. Microbiol. Biotechnol. Res.* **2011**, *1*, e136.
14. Nupur Ojha; Neha Pradhan; Surjit Singh; Anil Barla; Anamika Shrivastava; Pradip Khatua; Vivek Rai; Sutapa Bose; Evaluation of HDPE and LDPE degradation by fungus, implemented by statistical optimization. *Scientific Reports* **2017**, *7*, 39515, 10.1038/srep39515.

15. Hyde, K.D.; Jones, E.G.; Liu, J.-K.; Ariyawansa, H.; Boehm, E.; Boonmee, S.; Braun, U.; Chomnunti, P.; Crous, P.W.; Dai, D.-Q. Families of Dothideomycetes. Fungal Divers. 2013, 63, 1–313.
16. Khruengsai, S.; Sripahco, T.; Pripdeevech, P. Low-Density Polyethylene Film Biodegradation Potential by Fungal Species from Thailand. J. Fungi 2021, 7, 594.
17. Brunner, I.; Fischer, M.; Rüthi, J.; Stierli, B.; Frey, B. Ability of Fungi Isolated from Plastic Debris Floating in the Shoreline of a Lake to Degrade Plastics. PLoS ONE 2018, 13, e0202047.
18. Geiser, D.M.; LoBuglio, K.F.; Gueidan, C. 5 Pezizomycotina: Eurotiomycetes. In Systematics and Evolution; Springer: Berlin/Heidelberg, Germany, 2015; pp. 121–141.
19. Rani, A.; Singh, P. Screening of Polyethylene Degrading Fungi from Polyethylene Dump Site. Int. J. Chem. Tech. Res. 2017, 10, 699–704.
20. Ndahebwa Muhonja, C.; Magoma, G.; Imbuga, M.; Makonde, H.M. Molecular Characterization of Low-Density Polyethene (LDPE) Degrading Bacteria and Fungi from Dandora Dumpsite, Nairobi, Kenya. Int. J. Microbiol. 2018, 2018, 4167845.
21. Bermúdez-García, E.; Peña-Montes, C.; Castro-Rodríguez, J.A.; González-Canto, A.; Navarro-Ocaña, A.; Farrés, A. ANCUT2, a Thermo-Alkaline Cutinase from Aspergillus nidulans and Its Potential Applications. Appl. Biochem. Biotechnol. 2017, 182, 1014–1036.
22. Laila, M.D. The Potential of Fungi Isolated from Pleurotus ostreatus (Oyster Mushroom) Baglog to Degrade Plastics. Ph.D Thesis, Universitas Andalas, Padang, Indonesia, 2021.
23. Munir, E.; Harefa, R.; Priyani, N.; Suryanto, D. Plastic Degrading Fungi Trichoderma viride and Aspergillus nomius Isolated from Local Landfill Soil in Medan; IOP Publishing: Bristol, UK, 2018; Volume 126, p. 01 2145.
24. Alshehrei, F. Biodegradation of Low Density Polyethylene by Fungi Isolated from Red Sea Water. Int. J. Curr. Microbiol. Appl. Sci. 2017, 6, 1703–1709.
25. Sangale, M.K.; Shahnawaz, M.; Ade, A.B. Potential of Fungi Isolated from the Dumping Sites Mangrove Rhizosphere Soil to Degrade Polythene. Sci. Rep. 2019, 9, 5390.
26. Duan, X.; Liu, Y.; You, X.; Jiang, Z.; Yang, S.; Yang, S. High-Level Expression and Characterization of a Novel Cutinase from Malbranchea Cinnamomea Suitable for Butyl Butyrate Production. Biotechnol. Biofuels 2017, 10, 223.
27. Wang, G.Y.; Michailides, T.J.; Hammock, B.D.; Lee, Y.-M.; Bostock, R.M. Molecular Cloning, Characterization, and Expression of a Redox-Responsive Cutinase from Monilinia fructicola (Wint.) Honey. Fungal Genet. Biol. 2002, 35, 261–276.
28. Ojha, N.; Pradhan, N.; Singh, S.; Barla, A.; Shrivastava, A.; Khatua, P.; Rai, V.; Bose, S. Evaluation of HDPE and LDPE Degradation by Fungus, Implemented by Statistical Optimization.

Sci. Rep. 2017, 7, 39515.

29. Tsang, C.-C.; Tang, J.Y.; Lau, S.K.; Woo, P.C. Taxonomy and Evolution of Aspergillus, Penicillium and Talaromyces in the Omics Era–Past, Present and Future. Comput. Struct. Biotechnol. J. 2018, 16, 197–210.
30. Ekanayaka, A.; Hyde, K.; Gentekaki, E.; McKenzie, E.; Zhao, Q.; Bulgakov, T.; Camporesi, E. Preliminary Classification of Leotiomycetes. Mycosphere 2019, 10, 310–489.
31. Tanunchai, B.; Juncheed, K.; Wahdan, S.F.M.; Guliyev, V.; Udovenko, M.; Lehnert, A.-S.; Alves, E.G.; Glaser, B.; Noll, M.; Buscot, F. Analysis of Microbial Populations in Plastic–Soil Systems after Exposure to High Poly (Butylene Succinate-Co-Adipate) Load Using High-Resolution Molecular Technique. Environ. Sci. Eur. 2021, 33, 105.
32. Suh, S.-O.; Blackwell, M.; Kurtzman, C.P.; Lachance, M.-A. Phylogenetics of Saccharomycetales, the Ascomycete Yeasts. Mycologia 2006, 98, 1006–1017.
33. Bischoff, F.; Litwińska, K.; Cordes, A.; Baronian, K.; Bode, R.; Schauer, F.; Kunze, G. Three New Cutinases from the Yeast Arxula adeninivorans That Are Suitable for Biotechnological Applications. Appl. Environ. Microbiol. 2015, 81, 5497–5510.
34. Gonda, K.; Jendrossek, D.; Molitoris, H.-P. Fungal Degradation of the Thermoplastic Polymer Poly-β-Hydroxybutyric Acid (PHB) under Simulated Deep Sea Pressure. In Life at Interfaces and Under Extreme Conditions; Springer: Berlin/Heidelberg, Germany, 2000; pp. 173–183.
35. Issa, N. Towards the Biological Degradation of Plastics: Genetic Engineering of Saccharomyces cerevisiae to Secrete Ideonella Sakaiensis Derived PETase. Ph.D. Thesis, University of Kent, Canterbury, UK, 2021.
36. Maharachchikumbura, S.S.; Hyde, K.D.; Jones, E.G.; McKenzie, E.H.; Huang, S.-K.; Abdel-Wahab, M.A.; Daranagama, D.A.; Dayarathne, M.; D'souza, M.J.; Goonasekara, I.D. Towards a Natural Classification and Backbone Tree for Sordariomycetes. Fungal Divers. 2015, 72, 199–301.
37. Yang, S.; Liu, M.; Long, L.; Zhang, R.; Ding, S. Characterization of a Cutinase from Myceliophthora thermophila and Its Application in Polyester Hydrolysis and Deinking Process. Process Biochem. 2018, 66, 106–112.
38. Sánchez-García, M.; Ryberg, M.; Khan, F.K.; Varga, T.; Nagy, L.G.; Hibbett, D.S. Fruiting Body Form, Not Nutritional Mode, Is the Major Driver of Diversification in Mushroom-Forming Fungi. Proc. Natl. Acad. Sci. USA 2020, 117, 32528–32534.
39. de Mattos-Shipley, K.M.; Ford, K.L.; Alberti, F.; Banks, A.; Bailey, A.M.; Foster, G. The Good, the Bad and the Tasty: The Many Roles of Mushrooms. Stud. Mycol. 2016, 85, 125–157.

40. da Luz, J.M.R.; da Silva, M.d.C.S.; dos Santos, L.F.; Kasuya, M.C.M. Plastics Polymers Degradation by Fungi. In Microorganisms; IntechOpen: Vienna, Austria, 2019.
41. Oberwinkler, F. Yeasts in Pucciniomycotina. Mycol. Prog. 2017, 16, 831–856.
42. Liu, X.-Z.; Wang, Q.-M.; Göker, M.; Groenewald, M.; Kachalkin, A.; Lumbsch, H.T.; Millanes, A.; Wedin, M.; Yurkov, A.; Boekhout, T. Towards an Integrated Phylogenetic Classification of the Tremellomycetes. Stud. Mycol. 2015, 81, 85–147.
43. Hung, C.-S.; Barlow, D.E.; Varaljay, V.A.; Drake, C.A.; Crouch, A.L.; Russell, J.N., Jr.; Nadeau, L.J.; Crookes-Goodson, W.J.; Biffinger, J.C. The Biodegradation of Polyester and Polyester Polyurethane Coatings Using Papiliotrema laurentii. Int. Biodeterior. Biodegrad. 2019, 139, 34–43.
44. Bandopadhyay, S.; Liquet y Gonzalez, J.E.; Henderson, K.B.; Anunciado, M.B.; Hayes, D.G.; DeBruyn, J.M. Soil Microbial Communities Associated with Biodegradable Plastic Mulch Films. Front. Microbiol. 2020, 11, 2840.
45. Manohar, C.S.; Boekhout, T.; Müller, W.H.; Stoeck, T. Tritirachium candoliense sp. nov., a Novel Basidiomycetous Fungus Isolated from the Anoxic Zone of the Arabian Sea. Fungal Biol. 2014, 118, 139–149.
46. Martínez-Soto, D.; Ortiz-Castellanos, L.; Robledo-Briones, M.; León-Ramírez, C.G. Molecular Mechanisms Involved in the Multicellular Growth of Ustilaginomycetes. Microorganisms 2020, 8, 1072.
47. Walther, G.; Wagner, L.; Kurzai, O. Updates on the Taxonomy of Mucorales with an Emphasis on Clinically Important Taxa. J. Fungi 2019, 5, 106.
48. Pardo-Rodríguez, M.L.; Zorro-Mateus, P.J.P. Biodegradation of Polyvinyl Chloride by Mucor sp. and Penicillium sp. Isolated from Soil. Rev. Investig. Desarro. Innovación 2021, 11, 387–400.

Retrieved from https://encyclopedia.pub/entry/history/show/62351