CHAPTER

10

Environmental mycology in the Philippines

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1. Introduction: the growing environmental concern in Southeast Asia

Countries in Southeast Asia have experienced rapid urbanization in the last 30 years. The total population is estimated to reach 700 million in 2025 (United Nations Population Division, 2020), and that 65% of this will live in urban centers (Thuzar, 2011). This scenario is far from the historically low-density Southeast Asia before 1750 (Hirschman & Bonaparte, 2012). Although megacities, like Manila and Bangkok, differ in urban land changes, they face the potential loss of spaces (Estoque & Murayama, 2015) and the occurrence of many urban heat islands (Estoque et al., 2017). The vibrant economic dynamism in this part of the world is also met with a dilemma such as pollution, congestion, and poor urban environmental conditions (Thuzar, 2011). Expansion to the countryside (Melia, 2020; Redman & Jones, 2005), as well as meeting the needs of the growing population, requires the increase and better-quality food supply, transport, and storage (Hammond et al., 2015; McClements et al., 2020), smart transport systems (Kumar et al., 2018), and efficient manufacturing (Siemieniuch et al., 2015), among others. All of these put pressure on a finite healthy environment.

This, in turn, creates more waste that goes into soil and water systems. It is estimated that 275 million tons of plastic wastes were produced worldwide in 2010, of which 31.9 million tons were mismanaged and ended up either in land or water systems (Jambeck et al., 2015; Ritchie & Roser, 2018). At least 80% of the plastic problem originates from Asia (Marks

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et al., 2020). Vietnam, Indonesia, and the Philippines are among the three Southeast Asian countries in the top 5 marine plastic polluters globally (Garcia et al., 2019). This scenario is greatly complexified by our increasing understanding of microplastics (Rochman & Hoillien, 2020), and quite recently, nanoplastics (Mitrano et al., 2021), and the risks they pose to the environment and biosphere.

Similarly, 1.7–8.8 million metric tons of petroleum hydrocarbons are estimated to have been released into the ocean (Ossai et al., 2020) and find their way into shores and land areas. The entry of petroleum hydrocarbon into the environment alters the ecosystem's functionality (Truskewycz et al., 2019). They have been shown to cause alterations to soil characteristics (Osuji & Nwoye, 2007; Wang et al., 2013) and cause harm among marine animals (Khan et al., 2005), birds (Albers, 2006), microbiota (Klimek et al., 2016), and humans (Adipah, 2019). Countries like Thailand, Malaysia, and the Philippines have recognized the increasing petroleum hydrocarbon in water systems (Balce, 1997; Sakari et al., 2012; Wattayakorn, 2012).

In 2019, 56.3 million metric tons of e-waste were generated worldwide (Houessionon et al., 2021), which translates to heavy metals finding their way into landfills and sewage systems every year. In addition, Southeast Asia has recorded heavy metal contamination in soil and crops (Zarcinas, Ishak et al., 2004; Zarcinas, Pongsakul et al., 2004), groundwater (Rahman et al., 2009), food supply (Agusa et al., 2007, and eventually to the human population (Kladsomboom et al., 2020). This is besides the pressure applied in extracting raw materials from mines and deposits deep beneath the Earth's surface.

With the strong reliance on agriculture in Southeast Asian countries, fertilizers and pesticides are common. Small-scale farmers rely on pesticides (Schreinemachers et al., 2017), with over 77% considered overuse (Schreinemachers et al., 2020). Pesticide-contaminated foods have also been reported (Lam et al., 2017), such as in the Philippines (Del Prado, 2015) and Cambodia (Wang et al., 2011). Part of the sustainable trajectory of countries is to minimize consumption, both at the individual and country levels, and to provide solutions to the mounting pollution of soil and water systems. As the waste accumulates, more technologies are evaluated for their potential application to clean up contaminated soils and water environments.

2. Mycoremediation

Bioremediation has been performed worldwide to restore the functionality of heavily contaminated soils and water systems. The process usually utilizes indigenous plant species or a consortium of microorganisms to expedite the cleaning process. The choice of an organism depends largely on the pollutant to be remediated, the organism's tolerance to that specific pollutant and the environmental factors to optimize the bioremediation mechanism. It is also important to consider the potential harm on nontarget organisms and the safety of handling by humans.

Microbial bioremediation research in the Philippines is largely along bacterial isolates (Adriano et al., 2018; Dela Cruz & Halos, 1997; Lim & Halos, 1995; Su, 2016; Villegas et al., 2018). However, fungi also have characteristics that make them good candidates for remediation. Unlike bacteria, they have longer life cycles, greater biomass, and an extensive hyphal network (Singh et al., 2015). The ramification of the hyphal networks provides mechanical support and a larger surface area through which enzymes can be released to break down chemical pollutants (Singh & Gauba, 2014). The fungal cell wall is also helpful in binding pollutants (Igir et al., 2018). Further, the diversity of fungi allows one to mix and match so that the correct species are used to target a particular pollutant (Rhodes, 2014). How the fungal cells interact with different pollutants, especially recalcitrant or persistent ones, have been researched extensively, and Yadav et al. (2021) summarize these in Fig. 10.1.

Environmental mycology, particularly on remediating and rehabilitating soil and water ecosystems, is a viable field to address mounting environmental problems. Several researchers harnessed the potentials of fungi in remediating soils and water contaminated with heavy metals, pesticides, and fertilizers, plastics, and hydrocarbons. This chapter compiles these studies to present better the current picture of environmental mycology in the Philippines.

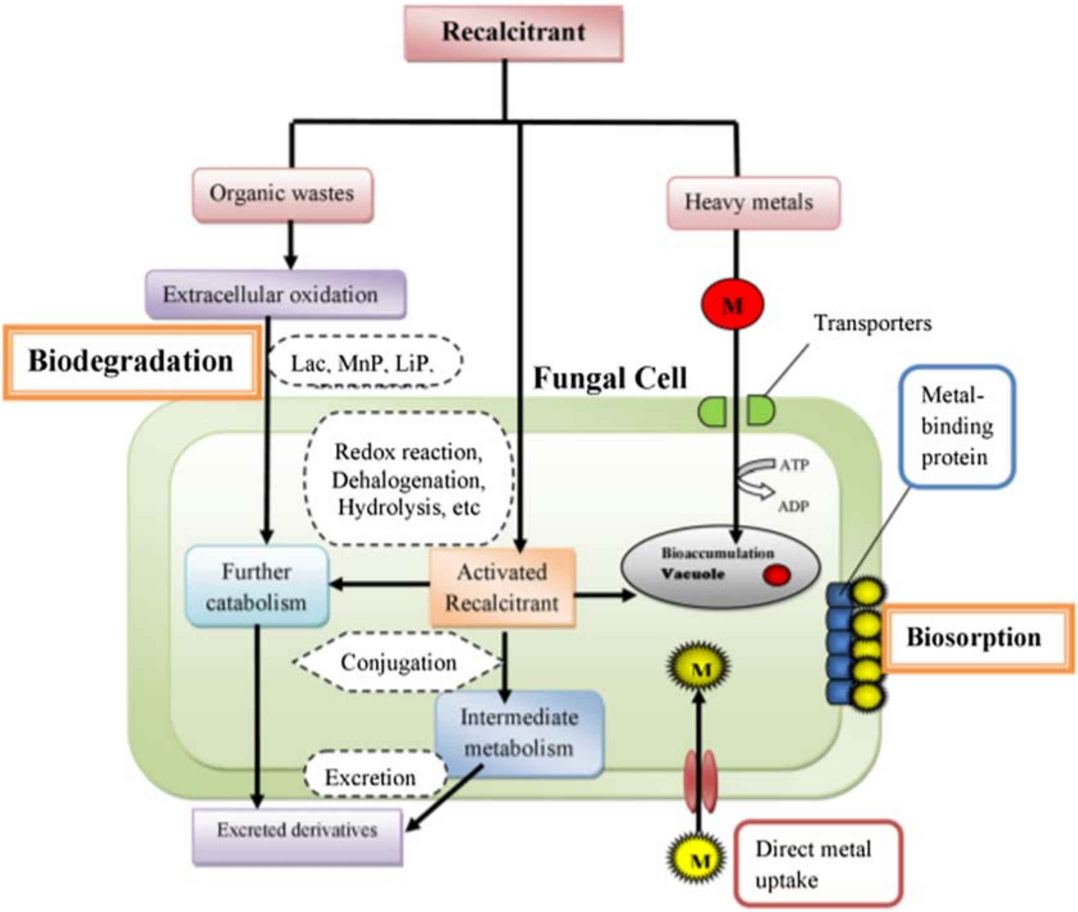

FIGURE 10.1 The fungal cell is an active player in the biodegradation and biosorption of chemical wastes. *Figure adapted from Yadav, P., Rai, S.N., Mishra, V., & Singh, M.P. (2021). Mycoremediation of environmental pollutants: A review with special emphasis on mushrooms.* Environmental Sustainability, *4(4), 605-618..*

3. Mycoremediation of heavy metals

An intrinsic advantage of the Philippines is its being an archipelago. This gives rise to a diversity of soil taxa, and these have been comprehensively presented by Carating et al. (2014). In addition, this provides the country with a diversity of environmental conditions that gives rise to a corresponding microbial diversity. For example, geothermal springs (Lacap et al., 2005), underwater plateaus (Gajigan et al., 2018), and various farming systems (Monsalud et al., 2009) across the country have unique microbiota.

The Philippines is also a metal-rich country. As such, mining companies are spread across many islands targeting particular metals. The country has one of the largest copper and gold resources globally and is rich in nickel and other precious metals (Hicks et al., 2012). Continuous mining, however, contributes to environmental degradation. Eventually, mining companies leave sites after the expiration of contracts leaving the soil nutrient-poor and unviable for use due to the highly extractive nature of mining. As a result, abandoned and inactive sites are high in toxic wastes. They have altered soil characteristics such as high pH, high salinity, low water retention capacity, and high heavy metal concentrations (Samaniego et al., 2020). As of 2019, there are 27 abandoned and inactive mines in the Philippines, according to the Mines and Geosciences Bureau (Aggangan et al., 2019).

Several studies have tapped on this opportunity to isolate fungal species tolerant to high levels of heavy metals and potentially revitalize the abandoned mines through remediation, including mycoremediation. Most isolation areas are mining sites, tailings, or nearby areas where effluents flow. However, few species were isolated *ex situ*, such as from banana and citrus peels (Casamorin et al., 2014) and the mangrove *Avicennia* L. (Marcelo et al., 2018) and tested for their tolerance and mycoremediation ability (Table 10.1).

In all the researches presented in the Philippines, most isolates are from already-contaminated soil or wastewater. Autochthonous fungi, or those which are indigenous to a particular area, have shown to be important catalysts in the remediation of soils and water systems polluted with hydrocarbons (Covino et al., 2015; D-Annibale et al., 2006), leachates from municipal landfills (Zegzouti et al., 2020), and heavy metals (Muñoz et al., 2012; Prigioni et al., 2009). Aside from the innate morphological and physiological characteristics, these native fungal isolates perform well because they are well-adapted to the site's conditions. It is important to note that the soil and water environments are complex, and thus organisms first need to acclimate before starting the remediation process. On this note, autochthonous fungi have an advantage over allochthonous or foreign counterparts. Hosokawa et al. (2009) also detailed that allochthonous microorganisms tend to be only stable at the start of the process and decline midway.

The creation of fungal consortia or fungal combinations to optimize efficacy has also been seen as a good mycoremediation strategy. However, most of these were limited to the use of mycorrhizal isolates, either the commercially available MYKOVAM and similar products or indigenous isolates from contaminated areas. Moreover, because these are members of Glomeromycota, these are used with host plants to improve survivability in contaminated soil or improve their metal uptake. Some of the host plants are *Desmodium cinereum* (Adiova et al., 2013; Aggangan & Cortes, 2018; Aggangan et al., 2019), *Chrysopogon zizanioides* (L.) Roberty (Bretaña et al., 2019), and *Paraserianthes falcataria* (Rollon et al., 2017). In addition, the species

TABLE 10.1 Fungal isolates were tested for tolerance against metals and remediating ability.

Species	Place of isolation	Substrate	Activity	Reference
Glomus etunicatum W.N. Becker & Gerd *Glomus macrocarpum* Tul & C. Tul, *Gigaspora margarita* W.N. Becker & I.R. Hall	–	Mycorrhizal inoculant from the BIOTECH, University of the Philippines Los Baños, Laguna	Improved uptake of Cu by *Desmodium cinereum* (Kunth) DC at 800, 1200, and 1600 ppm	Adiova et al. (2013)
Glomus etunicatum *Glomus macrocarpum* *Gigaspora margarita* + *Glomus* spp.	–	MYKOVAM from BIOTECH, University of the Philippines Los Baños, Laguna	Increased uptake rate of mercury by *Chrysopogon zizanioides* (L.) Roberty at high Hg concentration	Bretaña et al. (2019)
Debaryomyces hansenii (Zopf) Lodder & Kreger-van Rij *Candida parapsilosis* Langeron & Talice	Mankayan, Benguet	Cu-rich soil	Alleviate heavy metal stress in plant host (*Phragmites australis* Cav.)	Hipol et al. (2015)
Salispilia tartarea S1YP1	Samal Island, Davao del Norte	Mangrove (*Avicennia* sp.)	With Fe-chelating activity with IC50 of 541.32 ± 5.43 μg/mL	Marcelo et al. (2018)
Aspergillus sp.	Coto Chromite Deposit, Masinloc, Zambales	Soil	Tolerated 1440 mg/L of Cr(VI)	De Sotto et al. (2015)
Aspergillus sp.	Motolite Battery Plant, Novaliches, Quezon City	Soil	Tolerated 1800 mg/L of Cr(VI)	De Sotto et al. (2015)
Acyra cinerea (Bull.) Pers.	Central Luzon Region	Soil	High Bioconcentration factor for Mn	Rea-Maminta et al. (2015)
Physarum album (Bull.) Chevall. *Physarum pusillum* (Berk. & M.A. Curtis) G. Lister	Central Luzon Region	Soil	High bioconcentration factor for Mn and Cr	Rea-Maminta et al. (2015)
Vanrija sp.	Philex Mining Site, Benguet Province	Soil	Multi-metal biosorption for Cu, Cr, Mn, Ni, and Zn	Coronado et al. (2016)
Aspergillus sp. (fungal isolate 3)	Brgy. Ibo, Lapu-Lapu City, Cebu	Effluents of industrial plants	Cd biosorption efficiency of 13.87% in 100 mL potato dextrose broth with 10 mL $CdSO_4$	Manguilimotan and Bitacura (2018)
Aspergillus sp. (fungal isolate 4)	Brgy. Ibo, Lapu-Lapu City, Cebu	Effluents of industrial plants	Cd biosorption efficiency of 10.71% in 100 mL potato dextrose broth with 10 mL $CdSO_4$	Manguilimotan and Bitacura (2018)

(*Continued*)

TABLE 10.1 Fungal isolates were tested for tolerance against metals and remediating ability.—cont'd

Species	Place of isolation	Substrate	Activity	Reference
Penicillium sp. (fungal isolate 6)	Brgy. Ibo, Lapu-Lapu City, Cebu	Effluents of industrial plants	Cd biosorption efficiency of 11.46% in 100 mL potato dextrose broth with 10 mL $CdSO_4$	Manguilimotan and Bitacura (2018)
Aspergillus flavus Link	Meycauayan, Bulacan, Guimaras, Iloilo	Heavy metal-contaminated soil and hydrocarbon-contaminated soil	Able to reduce hexavalent Cr from Cr^{6+} to Cr^{3+} through reduced-coupled biotransformation	Bennett et al. (2013)
Aspergillus niger van Tieghem	Meycauayan, Bulacan, Guimaras, Iloilo	Heavy metal-contaminated soil and hydrocarbon-contaminated soil	Able to reduce hexavalent Cr from Cr^{6+} to Cr^{3+} through reduced-coupled biotransformation	Bennett et al. (2013)
Aspergillus sp.	Meycauayan, Bulacan, Guimaras, Iloilo	Heavy metal-contaminated soil and hydrocarbon-contaminated soil	Able to reduce hexavalent Cr from Cr^{6+} to Cr^{3+} through reduced-coupled biotransformation	Bennett et al. (2013)
Penicillium spp. *Fonsecaea* sp. *Aspergillus* spp. *Fusarium* sp. *Trichoderma* sp.	Calancan Bay, Marinduque	Copper-laden sediments	With possible bioaccumulation activities	Su et al. (2014)
Aspergillus unguis Weill & L. Gaudin *Penicillium griseofulvum* Dierckx, R.P.	Guimaras, Iloilo	Oil-contaminated soils	In consortia degraded 72 ± 1.3% Nickel protoporphyrin disodium and 90 ± 2.8% Vanadium oxide octaethylporphyrin, both at 20 mg/L	Cordero et al. (2015)
Penicillium canescens Sopp, O.J. *Penicillium* sp. *Talaromyces macrosporus* (Stolk & Samson) Frisvad et al. *Talaromyces* sp.	Marilao River within the Meycauayan-Marilao-Obando river system	Pb-contaminated Soil and water	Tolerant to 500 μg/mL of Pb; removal efficiency of 35.75%–99.5% of Pb at 3000 μg/mL	Zomesh et al. (2019)
Trichoderma harzianum Rifai *Trichoderma virens* Pers. *Trichoderma saturnisporum* Hammill *Trichoderma gamsii* Samuels & Druzhinina	Mine tailing sites in Itogon, Benguet	Wastewater with Cr, Cu, and Pb exceeding allowable standards	All tolerant to 1000 ppm of Cr and Pb; *T. harzianum* and *T. virens* tolerates up to 1000 ppm Cu; *T. virens* able to remove Pb 91% –96% in liquid media	Tansengco et al. (2018)
Rhodotorula toruloides Banno *Candida tropicalis* (Castellani) Berkhout *Papiliotrema laurentii* (Kuff.) X.Z. Liu, F.Y. Bai, M. Groenew & Boekhout *Candida maltosa* Komag.,	Six mine tailing sites in Itogon, Benguet	Wastewater with Cr, Cu, and Pb exceeding allowable standards	Cu and Pb adsorption capacity at 50 mg/L; *Nodulisporium* sp. Capable of treating Ni from wastewater	Gacho et al. (2019)

TABLE 10.1 Fungal isolates were tested for tolerance against metals and remediating ability.—cont'd

Species	Place of isolation	Substrate	Activity	Reference
Nakase & Katsuya) *Nodulisporium* sp. *Candida guilliermondii* (Castell.) Langeron & Guerra *C. lusitaniae* Uden & Carmo Souza	–	Banana and citrus peels	Tolerant to Cd concentrations; Cr absorption capacity	Casamorin et al. (2014)
Pleurotus ostreatus (Jacq.) P. Kumm.	Mandaluyong and Tagaytay	Soil	Adsorptive capacity for Pb and Mn in contaminated soils	Llarena and Solidum (2012)
Glomus sp. *Gigaspora* sp. *Acaulospora* sp. *Scutellospora* sp. *Entrophospora* spp.	–	MYKOVAM from BIOTECH, University of the Philippines Los Baños, Laguna	Enhanced seedling survival and tree growth in mined-out areas (Mogpog, Marinduque, Cu)	Aggangan et al. (2019)
AMF associated with ferns	Abandoned Copper mine in Mogpon, Marinduque	Soil	Effects comparable with commercially available AMF	Aggangan and Cortes (2018)
Coprinus comatus (O.F. Mull.) Pers.	–	Culture collection of the Center for Tropical Mushroom Research and Development, Nueva Ecija	Accumulated high levels of copper in its fruiting bodies	Dulay et al., (2015)
Trichoderma harzianum	Trichoderma microbial inoculant	Soil	Increased yield of rice in Cu-rich rice paddies	Cuevas et al. (2019)
Glomus etunicatum *Glomus* sp. *Gigaspora margarita*	–	MYKOVAM BIOTECH, University of the Philippines Los Baños, Laguna	In combination with carbonized rice hull, Improved nutrient uptake of *Paraserianthes falcataria* (L.) in copper-contaminated soil	Rollon et al. (2017)
Trichoderma spp.	Mt. Talipanan, Oriental Mindoro, La Mesa Ecopark Sorsogon province Las Piñas-Parañaque Ecotourism Park	Soil and leaf litter, marine substrates (seawater, seafoam, decayed seagrass, and seaweeds)	Moderate to high tolerance to Ni at 50–1200 ppm Ni uptake by 6 species range from 66% to 68%	De Padua (2021)

Aspergillus unguis and *Penicillium griseofulvum* were also used in consortia to degrade compounds containing Ni and Va (Cordero et al., 2015).

Microbial consortia present advantages, especially on higher metal scavenging capacity and resilience against environmental fluctuations (Mishra & Malik, 2014). In addition, different species may take advantage of unique optimum ranges so that the remediation process remains active across the tolerance spectrum. Interkingdom consortia, which contain fungi, bacteria, and other microorganisms, may also improve the process. Zhang et al. (2018) said that there is a synergistic division of resources or labor, enhanced tolerance of inhibitors or toxicants, antagonistic interactions that lead to the production of beneficial metabolites, and optimized efficiency and consortia robustness through assembled biotransformation.

At least two studies were recorded using fungal allies: *Salispilia tartarea*, an oomycete (Marcelo et al., 2018), and the myxomycetes *Acyria cinerea*, *Physarum album* and *P. pusillum* (Rea-Maminta et al., 2015). The limited studies among the potentials of fungal allies for remediation may lead to an opportunity for expanding future works.

4. Fungi as bioremediation agents for pesticides

The Philippines' steady pace in modernizing its agri-fishery sector has conventionally encouraged the practice of applying a diverse range of synthetic agrochemicals. However, its massive and indiscriminate use consequently created public health and environmental repercussions, including disruption of the ecosystems (Abreo et al., 2015), high rates of bioaccumulation (Tingson et al., 2018), and large-scale soil contamination (Navarrete et al., 2017). These detrimental events render a large group of beneficial nontarget organisms (Mahmood et al., 2016) vulnerable to the adverse effects of these chemicals, which disrupts soil quality and the pivotal process of pedogenesis (Samal & Mishra, 2021). In addition, the high cost of physical and chemical methods has necessitated the development of various bioremediation strategies in the country to remove contaminants effectively and sustainably, especially in pesticide-polluted areas (Abo-Amer, 2012; Carascal et al., 2017; Mercado et al., 2012; Poncian et al., 2019).

Among the most commonly used pesticide are several chemical subgroups, namely carbamates, pyrethroids, organophosphates, and organochlorines (Cubelo & Cubelo, 2021; Lu, 2010; Lu et al., 2010; Tirado & Bedoya, 2008). While rice is the largest consumer of pesticides in terms of volume (due to a larger production area), the pesticide application in high-value crops is more aggressive (Bajet, 2015). In an analysis by Lu (2010) on the brands of pesticide used in the largest vegetable producing area in the Philippines, Tamaron was the most prevalent type of pesticide used, an organophosphate pesticide. Consequently, pesticide fate is governed by transfer and degradation processes in any agricultural ecosystem, which physicochemical or biological agents can reduce upon reaching the soil, sediment, or water ecosystems. Following a schematic diagram (Fig. 10.2) adopted from Barik (1984), decomposition of xenobiotic compounds in such environments undergo photometabolism, oxidation, reduction, and hydrolysis, which are always driven by the changes of many physicochemical forces such as pH, temperature, ion concentration, and redox potential (Díaz, 2004).

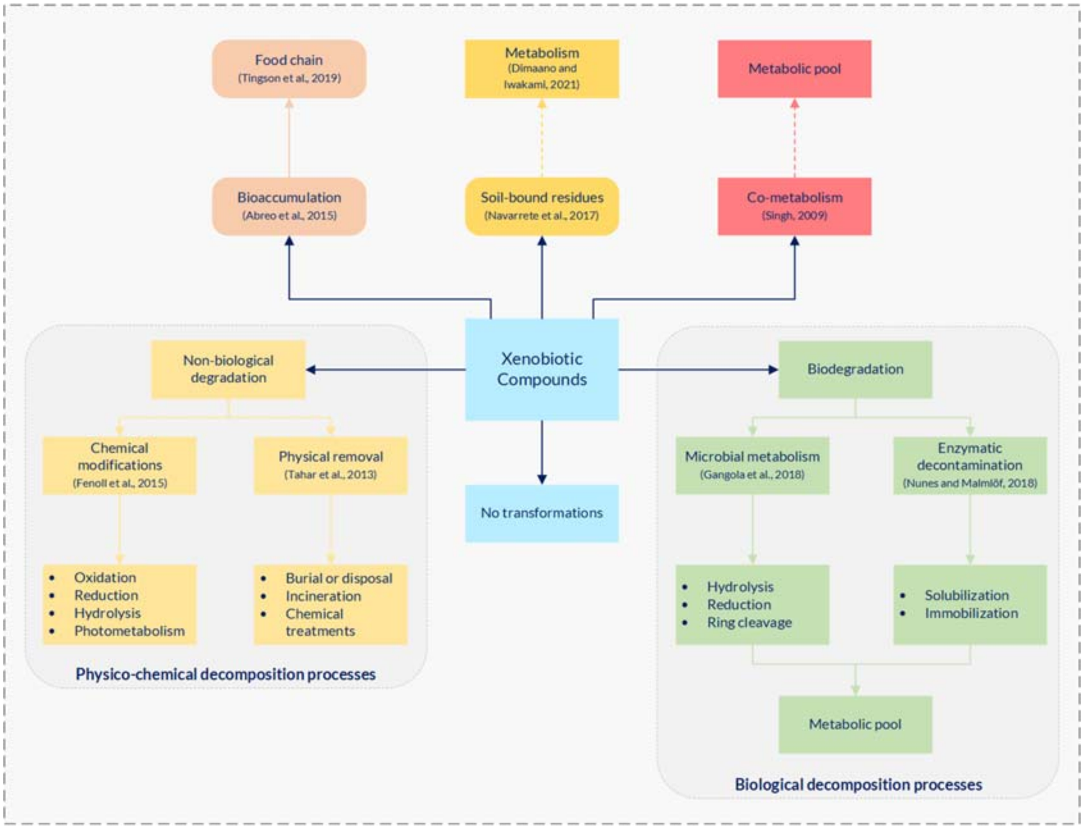

FIGURE 10.2 Fate of xenobiotic compounds in soil, aquatic, and microbial systems by Barik (1984). The diagram is grouped according to transfer and degradation processes; rounded rectangles indicate transfer while regular rectangles indicate degradation. Physico-chemical and biological degradation pathways were also highlighted. Moreover, selected case studies were included to highlight examples from each process. Studies conducted in the Philippines were used, whenever possible. *Adapted by permission from Springer Nature Customer Service Center GmbH: Springer* Insecticide Microbiology *Metabolism of Insecticides by Microorganisms, Sudhakar Barik, Copyright by Springer, Berlin, Heidelberg (1984).*

In the Philippines, mycoremediation studies of pesticide-polluted soil and water systems have not been extensively explored. However, renewed interests in recent years (Carascal et al., 2017; Mercado et al., 2012; Poncian et al., 2019) have advanced the understanding, applicability, and regard of the strategy in the country. The small fraction of fungal species documented in the Philippines with pesticide degradation potential (summarized in Table 10.2) belongs to the group of Ascomycetes found in the provinces of Batangas, Benguet, and Laguna.

Some fungal species were documented to degrade organochlorines, specifically butachlor (Carascal et al., 2017) and endosulfan (Mercado et al., 2012) pesticides. Organochloride pesticides are synthetic, making them recalcitrant, resistant to biodegradation, and characterized mainly by a slow breakdown rate (Jayaraj et al., 2016; Newton, 2018). The findings by

TABLE 10.2 Pesticide-degrading fungi isolated from contaminated sites with degradation potential of more than 50%.

Strain	Source	Degraded pesticide	Degradation potential	References
Acremonium crassum Petch 4PULB05 *Aspergillus fumigatus* Fresenius 8BINM03 *Fusarium* sp.1 9MATK02	Surface water, Lake Taal, Batangas	Butachlor (organochloride)	Degradation of up to 100 mg/L. No percentage data indicated	Carascal et al. (2017)
Aureobasidium sp. MATK04 *Lecythophora* sp. BINM02-1 *Phialemonium* sp.2 ALA03	Submerged wood, Lake Taal, Batangas	Butachlor (organochloride)	Degradation of up to 100 mg/L. No percentage data indicated	Carascal et al. (2017)
Aspergillus heteromorphus Batista & H. Maia strain SF-6390	Potato plantation, Mankayan, Benguet	Cypermethrin (pyrethroid)	About 20 mg/L 1-naphthol equivalent concentration indicating CES enzyme activity	Poncian et al. (2019)
Aspergillus sp. BDP3	Potato plantation, Mankayan, Benguet	Cypermethrin (pyrethroid)	About 58 mg/L 1-naphthol equivalent concentration indicating CES enzyme activity	Poncian et al. (2019)
Candida tropicalis (Castellani) Berkhout P601	Lowland rice field, Calamba, Laguna	Endosulfan (organochloride)	91.35% total endosulfan (100 mg/L) degradation in 14 days	Mercado et al. (2012)
Fusarium sp. BDP3	Potato plantation, Mankayan, Benguet	Cypermethrin (pyrethroid)	About 32 mg/L 1-naphthol equivalent concentration indicating CES enzyme activity	Poncian et al. (2019)
Neodeightonia subglobosa Booth IFM 63572	Surface water, Lake Taal, Batangas	Butachlor (organochloride)	94.68% degradation (100 mg/L) in 5 days using mycelial mat and 73.4% degradation (50 mg/L) in 5 days using mycelial balls	Carascal et al. (2017)
Penicillium sp. BDP1	Potato plantation, Mankayan, Benguet	Cypermethrin (pyrethroid)	About 35 mg/L 1-naphthol equivalent concentration indicating CES enzyme activity	Poncian et al. (2019)
Penicillium sp. BDP10	Potato plantation, Mankayan, Benguet	Cypermethrin (pyrethroid)	About 54 mg/L 1-naphthol equivalent concentration indicating CES enzyme activity	Poncian et al. (2019)
Penicillium sp. BDP12	Potato plantation, Mankayan, Benguet	Cypermethrin (pyrethroid)	About 30 mg/L 1-naphthol equivalent concentration indicating CES enzyme activity	Poncian et al. (2019)
Sclerotium hydrophilum Saccardo IFM 63573	Submerged wood, Lake Taal, Batangas	Butachlor (organochloride)	89.64% degradation (100 mg/L) in 5 days using mycelial mat and 55.6% degradation (50 mg/L) in 5 days using mycelial balls	Carascal et al. (2017)
Unidentified mold species P701	Lowland rice field, Calamba, Laguna	Endosulfan (organochloride)	About 65% total endosulfan (100 mg/L) degradation in 14 days	Mercado et al. (2012)

Carascal et al. (2017) pursued the mycodegradation of a widely used organochloride herbicide butachlor from the surface water and submerged wood collected in Taal Lake, Batangas. Among the best isolates with a significantly high growth capacity on butachlor as the sole carbon sources were *Neodeightonia subglobosa* Booth and *Sclerotium hydrophilum* Saccardo, which showed increased mycelial biomass and decreased butachlor concentration. Moreover, Mercado et al. (2012) showed the capacity of *Candida tropicalis* (Castellani) Berkhout to degrade α- and β-endosulfan, a cyclodiene organochlorine insecticide, in soil showing 91.35% total endosulfan degradation (93.85% for alpha-endosulfan and 90.29% for beta-endosulfan). Despite such efforts, the number of other popular organochloride pesticides used in the country (Cubelo & Cubelo, 2021; Lu, 2010) are still widely uncharacterized such as lindane, aldrin/dieldrin, heptachlor, DDT, heptachlor epoxide, and 4,4-DDE, which necessitates further studies on biodegradation and remediation strategies especially since the majority of these pesticides were reported to be present as residues.

Similarly, the Philippines' principal management approach for pests and diseases also depends on applying pyrethroids—a class of more than 1000 powerful, broad-spectrum insecticides. Compared to organochlorines, pyrethroids biodegrade in the environment easily (Ostrea et al., 2014). One of the main commercially available pyrethroids is cypermethrin. Poncian et al. (2019) reported that the carboxylesterase activity of several filamentous soil fungi from a potato plantation in Mankayan, Benguet is effective in cypermethrin degradation. In addition, the enzyme carboxylesterase in the study was examined as an indicator of pyrethroid degradation since this enzyme has the specific function to mediate pyrethroid cleavage (Cycoń & Piotrowska-Seget, 2016). Among the collected isolates, unidentified Ascomycete species, BDP3 and BDP10 exhibited the greatest carboxylesterase activity and were identified as the most viable candidates for mycoremediation. According to the authors, both unidentified species were likely related to species of *Aspergillus* or *Penicillium* based on morphology and close homology of their D1/D2 sequences. Parallel studies on other pesticide families like anthranilic diamides, neonicotinoids, and thiourea should likewise be pursued since they have been gradually gaining traction in the country's agricultural setting in recent years (Almarinez et al., 2020; Del Prado-Lu, 2015; Lu, 2011a, 2011b, 2012).

5. Fungi as biocontrol agents in agriculture

Although pesticide management and residue risk assessment on food safety is regulated by the Fertilizer and Pesticide Authority (FPA) in the country, challenges in pesticide residues in water (Navarrete et al., 2018; Varca, 2012) and soil (Lu, 2011a, 2011b) and other environmental concerns related to pesticide usage (Cubelo & Cubelo, 2021; Lu et al., 2010) in agriculture remains increasingly pervasive. To date, biological control involving fungal species as biological control agents (BCAs) forms part of one of the widely utilized disease management approaches in Philippine crop protection mechanisms.

Several studies have been carried out in the recent decade to identify effective biocontrol candidates for pre- and postharvest pest-disease management (Table 10.3). National scientist Romulo G. Davide III pioneered considerable progress in biocontrol, evidenced by his numerous contributions to nematology. Perhaps the earliest report in biocontrol was

TABLE 10.3 Documented fungal species and commercially available root inoculants, in the recent decade, with biological control potential against several zoo- and phytopathogens and their reported biological activity.

Strain/Biocontrol agent/Commercial inoculant	Source	Pest/disease and host	Target pathogen	Potential mode of action	References
Beauveria bassiana (Bals.-Criv.) Vuill.	Los Baños, Laguna	Mite infestation on papaya	*Tetranychus kanzawai* Kishida	Predation, hyperparasitism, and enzymatic activity	Sanjaya et al. (2013b, 2014, 2015, 2016)
	University of the Philippines Los Baños, Laguna	Asian corn borer infestation	*Ostrinia furnacalis* Guenée	Predation and hyperparasitism	Nicolas et al. (2013)
Ceratobasidium spp. TDC037, TDC241, TDC474	Banana farms in Mindanao	Fusarium wilt (FocTR4) on Cavendish variety of banana	*Fusarium oxysporum* f. sp. *cubense* (E.F. Smith) Snyder & Hansen	Competition, growth enhancement, antibiosis, and induced systemic resistance	Catambacan and Cumagun (2021)
Chaetomium globosum Kunze	Not indicated	Blast disease in rice	*Pyricularia oryzae* Cavara	Antibiosis (visualized using crude extracts)	Gandalera et al. (2013)
Exophiala sp. NLE 03	Needle leaves of *Casuarina equisetifolia* L. growing in Tagaytay City, Cavite	Fusarium wilt diseases on various crops	*Fusarium oxysporum* Schltdl., *F. solani* (Mart.) Sacc., & *F. moniliforme* J. Sheld	Competition, antibiosis, mycoparasitism, enzymatic activity, and induced systemic resistance	De Mesa et al. (2020)
Fusarium sp. CGP150	Mt. Apo rainforest, Davao	Fusarium wilt (FocTR4) on Cavendish variety of banana	*Fusarium oxysporum* f. sp. *cubense*	Antibiosis, enzymatic activity, mycoparasitism, and competition	Puig and Cumagun (2019)
Geotrichum sp. EF-ds104-16	Lowland rice fields of Nueva Ecija	Sheath blight in rice	*Rhizoctonia solani*	Mycoparasitism, antibiosis, and enzymatic activity	Donayre and Dalisay (2015)
Guignardia spp. NLE 08, NLE 09, NLE 11	Needle leaves of *Casuarina equisetifolia* growing in Tagaytay City, Cavite	Fusarium wilt diseases on various crops	*Fusarium oxysporum*, *F. solani*, *F. moniliforme*	Competition, antibiosis, mycoparasitism, enzymatic activity, and induced systemic resistance	De Mesa et al. (2020)

TABLE 10.3 Documented fungal species and commercially available root inoculants, in the recent decade, with biological control potential against several zoo- and phytopathogens and their reported biological activity.—cont'd

Strain/Biocontrol agent/Commercial inoculant	Source	Pest/disease and host	Target pathogen	Potential mode of action	References
Lasiodiplodia theobromae (Patouillard) Griffon & Maublanc	Banana farms in Mindanao	Fusarium wilt (FocTR4) on Cavendish variety of banana	*Fusarium oxysporum* f. sp. *cubense*	Competition, growth enhancement, antibiosis, and induced systemic resistance	Catambacan and Cumagun (2021)
Metarhizium anisopliae (Metschn.) Sorokīn	Los Baños, Laguna	Mite infestation on papaya	*Tetranychus kanzawai*	Predation, hyperparasitism, and enzymatic activity	Sanjaya et al. (2013a, 2013b, 2016)
	Department of Agriculture General Santos City, South Cotabato	Tick infestation on cows	*Rhipicephalus microplus* Canestrini	Hyperparasitism	Alagos et al. (2015)
Metarhizium flavoviride Gams & Rozsypal var. *flavoviride*	Los Baños, Laguna	Earworm infestation on corn	*Helicoverpa armigera* Hübner	Hyperparasitism	Belen et al. (2011)
Metarhizium rileyi (Farlow) Kepler, S.A. Rehner & Humber	Infested onion fields from San Jose City, Nueva Ecija	Fall armyworm infestation on corn	*Spodoptera exigua* Hübner	Hyperparasitism, antibiosis, and enzymatic activity	Montecalvo and Navasero (2021)
Metarhizium sp. AB001	Abaca aphid at Visayas State University, Southern Leyte	Mealworm infestation	*Tenebrio molitor* L.	Hyperparasitism	Pajar et al. (2013)
Metarhizium sp. UP001	BIOTECH, University of the Philippines Los Baños, Laguna	Mealworm infestation	*Tenebrio molitor*	Hyperparasitism	Pajar et al. (2013)
Paecilomyces lilacinus (Thom) Samson	Los Baños, Laguna	Mite infestation on papaya	*Tetranychus kanzawai*	Predation, hyperparasitism, and enzymatic activity	Sanjaya et al. (2013b, 2016)
Pestalotiopsis sp. CGP117	Mt. Apo rainforest, Davao	Fusarium wilt (FocTR4) on Cavendish variety of banana	*Fusarium oxysporum* f. sp. *cubense*	Antibiosis, enzymatic activity, and mycoparasitism	Puig and Cumagun (2019)

(*Continued*)

TABLE 10.3 Documented fungal species and commercially available root inoculants, in the recent decade, with biological control potential against several zoo- and phytopathogens and their reported biological activity.—cont'd

Strain/Biocontrol agent/Commercial inoculant	Source	Pest/disease and host	Target pathogen	Potential mode of action	References
Phyllosticta sp. NLE 06	Needle leaves of *Casuarina equisetifolia* growing in Tagaytay City, Cavite	Fusarium wilt diseases on various crops	*Fusarium oxysporum*, *F. solani* & *F. moniliforme*	Competition, antibiosis, mycoparasitism, enzymatic activity, and induced systemic resistance	De Mesa et al. (2020)
Plectosphaerella sp. NLE 02	Needle leaves of *Casuarina equisetifolia* growing in Tagaytay City, Cavite	Fusarium wilt diseases on various crops	*Fusarium oxysporum*, *F. solani*, & *F. moniliforme*	competition, antibiosis, mycoparasitism, enzymatic activity, and induced systemic resistance	De Mesa et al. (2020)
Ramalina farinacea (L.) Acharius	Guimaras, Iloilo	Caustic pathogens and weed infestation in several crops	Pathogenic microbes and weeds	Antibiosis (visualized using crude extracts)	Gazo et al. (2019)
Ramalina nervulosa (Müller Arg.) Abbayes	Guimaras, Iloilo	Caustic pathogens and weed infestation in several crops	Pathogenic microbes and weeds	Antibiosis (visualized using crude extracts)	Gazo et al. (2019)
Ramalina roesleri (Hochstetter ex Schaerer) Nylander	Brgy. Hoskyn, Jordan Guimaras, Iloilo	Caustic pathogens and weed infestation in several crops	Pathogenic microbes and weeds	Antibiosis (visualized using crude extracts)	Gazo et al. (2019)
Schizophyllum commune Fries	Mt. Apo rainforest, Davao	Fusarium wilt (FocTR4) on Cavendish variety of banana	*Fusarium oxysporum* f. sp. *cubense*	antibiosis, enzymatic activity, and mycoparasitism	Puig and Cumagun (2019)
Trichoderma asperellum Samuels, Lieckfeldt & Nirenberg	Banana farms in Mindanao	Fusarium wilt (FocTR4) on Cavendish variety of banana	*Fusarium oxysporum* f. sp. *cubense*	Competition, growth enhancement, and antibiosis	Catambacan and Cumagun (2021)
Trichoderma ghanense Yoshim. Doi, Y. Abe & Sugiy.	University of the Philippines Los Baños, Laguna	Root diseases in aerobic rice variety Apo	*Pythium arrhenomanes* Drechsler	Growth enhancement, antibiosis, enzymatic activity, and parasitism	Banaay et al. (2012)

TABLE 10.3 Documented fungal species and commercially available root inoculants, in the recent decade, with biological control potential against several zoo- and phytopathogens and their reported biological activity.—cont'd

Strain/Biocontrol agent/Commercial inoculant	Source	Pest/disease and host	Target pathogen	Potential mode of action	References
Trichoderma strain KA	Buguias, Benguet	Clubroot disease on crucifers	*Plasmodiophora brassicae* Woronin	Induced systemic resistance, growth enhancement, mycoparasitism, and competition	Bulcio and Nagpala (2014)
Trichoderma sp. CGP106	Mt. Apo rainforest, Davao	Fusarium wilt (FocTR4) on Cavendish variety of banana	*Fusarium oxysporum* f. sp. *cubense*	Antibiosis, enzymatic activity, and mycoparasitism	Puig and Cumagun (2019)
Trichoderma sp.	Central Luzon State University-RMCARES, Muñoz, Nueva Ecija	Not indicated (conducted in vitro)	*Fusarium verticillioides*	Mycoparasitism, antibiosis, and competition	Santos et al. (2017)
Xylaria sp. NLE 04	Needle leaves of *Casuarina equisetifolia* growing in Tagaytay City, Cavite	Fusarium wilt diseases on various crops	*Fusarium oxysporum, F. solani* & *F. moniliforme*	Competition, antibiosis, mycoparasitism, enzymatic activity, and induced systemic resistance	De Mesa et al. (2020)
SM EFds61-73, SM EF-ds68-129, and SM EF-ds375-97	Lowland rice fields of Nueva Ecija	Sheath blight in rice	*Rhizoctonia solani*	Antibiosis and enzymatic activity	Donayre and Dalisay (2015)
Commercial microbial inoculants used for biocontrol					
Bio-Quick composting inoculant containing spores of *Trichoderma harzianum*	Developed by BIOTECH, University of the Philippines Los Baños, Laguna	Fusarium wilt (FocTR4) on "Lakatan" variety of banana	*Fusarium oxysporum* f. sp. *cubense*	Induced systemic resistance, growth enhancement, and competition	Castillo et al. (2019)
BIOSPARK *Trichoderma* microbial inoculant containing strains of *T. ghanense* & *T. harzianum*	Developed by the University of the Philippines Los Baños, Laguna	Scale insect infestation on lanzones	*Unaspis mabilis*	Induced systemic resistance and growth enhancement	Silva et al. (2019)
		Clubroot disease on crucifers	*Plasmodiophora brassicae*	Growth enhancement and induced systemic resistance	Cuevas et al. (2011, 2012)

(*Continued*)

TABLE 10.3 Documented fungal species and commercially available root inoculants, in the recent decade, with biological control potential against several zoo- and phytopathogens and their reported biological activity.—cont'd

Strain/Biocontrol agent/Commercial inoculant	Source	Pest/disease and host	Target pathogen	Potential mode of action	References
MYKOVAM arbuscular mycorrhizal inoculant containing spores and chopped roots colonized by species of *Glomus* and *Gigaspora*	Developed by BIOTECH, University of the Philippines Los Baños, Laguna	Bacterial wilt disease in hot peppers	*Ralstonia solanacearum* (Smith) Yabuuchi	Growth enhancement, competition, antibiosis, and induced systemic resistance	Agoncillo (2018)
		Parasitic nematode infestation on tissue-cultured "Lakatan" variety of banana	*Radopholus similis* (Cobb) Thorne, & *Meloidogyne incognita* (Kofoid & White) Chitwood	Induced systemic resistance, growth enhancement, and competition	Aggangan et al. (2013)
VAMRI vesicular-arbuscular mycorrhizal root inoculant composed of chopped dried corn roots infected with *Glomus mosseae* (T.H. Nicolson & Gerd.) Gerd. & Trappe and/or *Glomus fasciculatum* (Thaxt.) Gerd. & Trappe	Developed by BIOTECH, University of the Philippines Los Baños, Laguna	Fusarium wilt (FocTR4) on "Lakatan" variety of banana	*Fusarium oxysporum* f. sp. *cubense*	Induced systemic resistance, growth enhancement, and competition	Castillo et al. (2019)
		Fungal onion root rot	*Sclerotium rolfsii* Sacc., *Fusarium oxysporum* & *Rhizoctonia solani*	Growth enhancement, induced systemic resistance, and antibiosis	Nepomuceno et al. (2019)

documented in a collaborative work by Cortado and Davide (1968) using nematode-trapping fungal species of *Dactylella*, *Arthrobotrys*, and *Harposporium* from rice straw compost and cow manure which showed how the fungi held nematodes in captivity. Subsequent pioneering works by Dr. Davide in 1979 on nematode biocontrol immediately followed upon discovering *Paecilomyces lilacinus* (Thom) Samson as a biocontrol agent against burrowing nematodes causing disease on tomato, potato, banana, and other agronomically important crops (Davide, 1988).

Renewed interest in studying nematophagous fungi have been recently reported by Aggangan et al. (2013) involving arbuscular mycorrhizal fungi (AMF) species of *Glomus* and *Gigaspora* from a soil-based mycorrhizal biofertilizer (under the product name MYKOVAM) which showed effectiveness in controlling nematode population and infestation with decreased galled-roots in tissue-cultured banana (var Lakatan) under screenhouse conditions. Additionally, Oclarit and Cumagun (2009) demonstrated the reapplication of *P. lilacinus* obtained from the original culture used by Villanueva and Davide (1984), Generalao and Davide (1986), Orolfo and Davide (1986) as an effective biocontrol agent against *Meloidogyne incognita* (Kofoid & White) Chitwood attacking tomatoes. Furthermore, Nicolas et al. (2013) reported the potency of a lepidopteran-associated *Beauveria bassiana* (Balsamo-Crivelli) Vuillemin obtained from the University of the Philippines Los Baños (UPLB), Laguna in suppressing the Asian corn borer *Ostrinia furnacalis* Guenée under field conditions. In another study, Santiago et al. (2001) initially documented the virulence of *Metarhizium anisopliae* (Metschnikoff) Sorokīn against the nymphs of the Oriental migratory locust *Locusta migratoria manilensis* Meyen, which have been causing major infestations in Central Luzon and Negros Island. In recent work, Alagos et al. (2015) reported the higher acaricidal capacity of *M. anisopliae* than *Trichoderma viride* Persoon against different developmental stages of cow ticks *Rhipicephalus microplus* Canestrini that were collected in General Santos City. Interrelated experiments by Sanjaya et al. (2016; 2013a; 2013b) evaluated the same virulence of *M. anisopliae* and other fungal isolates of *B. bassiana* and *P. lilacinus* against the red spider mite *Tetranychus kanzawai* Kishida. Other *Metarhizium* species were also explored in the studies of Belen et al. (2011), Pajar et al. (2013), and more recently by Montecalvo and Navasero (2021, 2020).

For the majority of it, the potential of *Trichoderma* spp. as a potent BCA has received the most attention as a fungal BCA because of the ability of some of its species to function not just as microbial antagonists of many phytopathogenic fungi but also as avirulent plant symbionts (Vinale et al., 2008). Cuevas et al. (2011, 2012) reported the potential economic benefits of using *Trichoderma* spp. on vegetable farmers' profit for the field control of clubroot disease of crucifers caused by *Plasmodiophora brassicae* Woronin. The growth-promoting activity and potential antibiotic activity of *T. ghanense* Yoshim. Doi, Y. Abe & Sugiyama isolate CDO (TgCDO) from UPLB, Laguna was also seen against the virulent *Pythium arrhenomanes* Drechsler (Banaay et al., 2012). Bulcio and Nagpala (2014) published results on soil incorporation of *Trichoderma* strain KA against the spread of clubroot infection in highland cabbages. Their research conducted in Buguias, Benguet further discovered that lime (CaO) combined with the isolate significantly reduced clubroot infection, hence lowered disease severity. In another study by Santos et al. (2017), a particular *Trichoderma* sp. from Nueva Ecija demonstrated antibiosis, mycoparasitism, and competition for space and nutrients as suppression mechanisms against *Fusarium verticillioides* (Saccardo) Nirenberg in vitro. Induced plant systemic resistance by *Trichoderma* Persoon was also documented by Silva et al. (2019) to increase lanzones (*Lansium domesticum* Corrêa) defense and resistance against the scale-insect *Unaspis mabilis* Lit & Barbecho. Results indicated that applying the *Trichoderma* microbial inoculant (under the product name BIOSPARK) in lanzones plants demonstrated better resistance when challenged by *U. mabilis* infestation.

In other studies, Castillo et al. (2019) documented the delayed disease progression of Panama wilt (causal organism: Tropical Race four of *Fusarium oxysporum* f.sp. *cubense* (E.F. Smith) Synder & Hansen) on young 'Lakatan' banana seedlings using the combined treatment of two commercial root inoculants, Bio-Quick and VAMRI. Puig and Cumagun (2019) also documented the antibiosis of five rainforest fungal endophytes from Mt. Apo in Davao on *Foc*TR4. Among the isolates, *Schizophyllum commune* Fries has efficient eradicative ability against *Foc*TR4 in the Cavendish variety GCTCV 219 through numerous lytic enzymes. This result was corroborated in a much recent work of Catambacan and Cumagun (2021), who also documented the antagonistic activity (antibiosis and competition) of five weed-associated fungal endophytes, *Lasiodiplodia theobromae* (Patouillard) Griffon & Maublanc, *Trichoderma asperellum* Samuels, Lieckfeldt & Nirenberg and three species of *Ceratobasidium* against *Foc*TR4 infecting the same banana variety.

Aside from bananas, rice (*Oryza sativa* L.) proves to be the most cultivated and highly valued commodity in Asia, especially in Southeast Asia. Because of this, intensive crop protection and heightened pest-disease management of rice are particularly fundamental in the Philippines. In biocontrol, Donayre and Dalisay (2015) performed bio-efficacy screenings in vitro of potential endophytic fungi of barnyard grass weed for biocontrol of the rice sheath blight pathogen, *Rhizoctonia solani* J.G. Kühn. Their findings revealed that *Geotrichum* sp. demonstrated the most effective antagonistic activity against *R. solani* by penetration, coiling and disruption of its hyphae. In another study, Gandalera et al. (2013) investigated the biocontrol of *Pyricularia oryzae* Cavara, the causative fungus of the rice blast disease. Using the crude ethanol extract of its antagonistic fungi *Chaetomium globosum* Kunze, the disease was significantly inhibited at a certain concentration purportedly by the bioactive molecules present in the extract. A study on the growth-promoting activity in seedlings of aerobic rice variety Apo and subsequent disease control activity through antibiosis of *Trichoderma ghanense* was also discussed previously (Banaay et al., 2012).

Meanwhile, De Mesa et al. (2020) isolated fungal endophytes from needle-leaf trees along Cavite and Batangas and tested their potential antagonistic activities against *Fusarium* pathogens. Several endophytes exhibited antagonistic activity against *F. oxysporum* Schltdl. on contact via the preventive, eradicative, and simultaneous approaches. However, the mechanism of action by which the isolates utilize remains to be ascertained. In another study, Nepomuceno et al. (2019) reported a reduction in disease incidence and severity of onion root rot and the potential of enhancing the biocontrol activity of AMF through coinoculation with plant growth-promoting microorganisms such as *Pseudochrobactrum asaccharolyticum* Kämpfer. In a related study, Agoncillo (2018) discussed the importance of applying the AMF inoculum at the early seedling stage of hot pepper to colonize its roots and protect it from entry by its pathogenic microorganism *Ralstonia solanacearum* (Smith) Yabuuchi. Meanwhile, in a unique study by Gazo et al. (2019), the fruticose lichen *Ramalina* collected within the Guimaras Island in Iloilo was tested for its potential antimicrobial and herbicidal activities. Effective antiproliferative activity of the crude acetone extracts of various *Ramalina* species was documented, attributed to their lichen acids. Finally, Pascual et al. (2004, 2000) explored the suppressive ability of the hypovirulent, binucleate *Rhizoctonia* sp. (Rhv7) against the virulent *Rhizoctonia solani* AG1-1A, which is the causative pathogen of the banded leaf and sheath blight on corn.

The efficiency of a particular biocontrol agent against potential, known, and emerging pathogens still greatly depends upon many influencing factors such as ecological/abiotic factors, host-agent-pathogen trophic interactions, suitable time of application, frequency of treatment, nature or technique of treatment, pathogen resistance, and persistence or population maintenance of the agent (Gang et al., 2013; Haïssam, 2011; Pascual et al., 2000; Seehausen et al., 2021; Thambugala et al., 2020). The same biocontrol agent can also demonstrate variable responses in vitro, in vivo, and *in planta* conditions (Besset-Manzoni et al., 2019; Padder & Sharma, 2011), making it complex to obtain consistent results for the same biocontrol agent in the field versus the laboratory applications. Despite the gaining popularity of several locally developed bio-pesticides (Javier & Brown, 2007), which are already commercially available, the majority of the potential BCAs documented in this review, albeit promising results, remain relatively underdeveloped and warrant further studies both in vitro and *in planta* before scaling up its possible applications. Additionally, reducing pathogen levels below the damage threshold should only constitute a portion of the overall control strategies in our integrated pest-disease management program. The proper and regulated use of pesticides (perhaps in reduced doses and in conjugation with compatible biotic organisms), stringent pesticide residue monitoring, a shift to more sustainable options, and other cultural practices should also be crucially considered if we hope to achieve both food security and safety and a sustainable environment.

6. Plastic degrading fungi in the Philippines

The 42nd annual scientific meeting of the National Academy of Science and Technology called on their resolution that single-use nonbiodegradable plastics should be phased out (NAST, 2019). The resolutions formulated the recommendations to support research and development efforts in biodegradable plastics.

As commonly applied, "plastic" refers to a group of synthetic polymers. Thermoplastics and thermosets are the two categories of plastics. Thermoplastics are polyethylene (PE), polyethylene terephthalate (PET), polystyrene (PS), polypropylene (PP), polyurethane (PUR), polyester polyurethane (PU), high-density polyethylene (HDPE), and low-density polyethylene (LDPE) (Wei & Zimmermann, 2017). PE has been utilized in making grocery bags, food packaging film, and toys; PET has been used for bottles for water and other drinks; PS has been used in making disposable food trays and laboratory plastic wares; PP for the creation of straws, car seats and container cups; HDPE has been used for shampoo containers, milk bottles and ice cream containers and LDPE has been used for food packaging film. Despite the importance of plastics, plastic pollution, mainly PE and PP, has been a major ecological challenge in the Philippines.

Based on the global estimates in 2015, 79% of plastic wastes ever produced accumulated in landfills, while 12% had been incinerated and only 9% had been recycled (Geyer et al., 2017). However, landfills and plastic waste incineration have environmental and health impacts. Therefore, one of the appropriate methods is plastic biodegradation. This is the process of converting organic carbon into biogas and biomass associated with the activity of a community of microorganisms (bacteria, fungi, and actinomycetes) capable of using plastic as a carbon source (Shah et al., 2008).

Some species of fungi are known to degrade plastics by utilizing plastic polymers as carbon and energy sources. In the Philippines, few studies of these organisms have been published that potentially degrade plastics (Table 10.4).

The genera *Aspergillus* and *Trichoderma* demonstrate the capability to degrade polyethylene (Swift, 1997). Previous studies reported that fungal species are degrading plastics in the Philippines. As early as 1997, a study on these organisms was done by (Cuevas and Manaligod, 1997) in a forest environment (Mount Makiling, Laguna). The study identified several fungal species such as *Chaetomium globosum* Kunze, *Trichoderma* sp., *Penicillium funiculosum* Thom, and *Aspergillus niger* Tieghem and reported potential plastic degrading ability. Plastic

TABLE 10.4 Fungal isolates from the Philippines with plastic-degrading ability.

Species	Plastic type	Source	References
Xylaria sp.	Polyester Polyurethane	Laguna	Urzo et al. (2017)
Xylaria sp.	Cellulose and lignin	Laguna	Cuevas and Manaligod (1997); Clutario and Cuevas (2001); Cuevas et al. (2008)
Aspergillus, *Penicillium*, and *Paecilomyces*	Low-density Polyethylene	Tondo, Manila	Vaghaye and Dogma (1998)
Phanerochaete chrysosporium Burdsall	Low-density Polyethylene and Oxybiodegarable	Culture Collection of BIOTECH, University of the Philippines Los Banos, Laguna	Gutierrez et al. (2018)
Xylaria sp.	Polystyrene	Mount Makiling, Laguna	Abecia et al. (2019)
Aspergillus sp.	Polyhydroxybutyrate	San Mateo and Carmona, Cavite	Tansengco and Dogma (1999)
Pleurotus ostreatus (Jacq.) P. Kumm	Polyethylene	Novaliches, Quezon City	Bermundo et al. (2019) (*unpublished*)

biodegradation showed physical holes in plastic sheets buried in soil and litter for 4 months. In the study of (Vaghaye and Dogma, 1998), fungal species of the genera *Aspergillus, Penicillium*, and *Paecilomyces* were isolated from the dumpsite in Smokey Mountain in Tondo, Manila. The ability of these fungi to degrade PE was determined by growing them in a mineral salt medium and 1% glucose (MSG) in shake flasks for 15 days at room temperature. Percent dry weight loss of plastic was monitored to determine the degradation activity of fungal isolates. Species of *Aspergillus* and *Penicillium* yielded significantly high weight losses of PE after the incubation period. Different combinations of fungal isolates were tested for the possible synergistic effect on the degradation of PE. The maximum synergism was among two species of *Aspergillus* and one of the *Penicillium* in MSG (2.8% weight loss) and between one species of *Aspergillus* and *Penicillium* in MS (1.2% weight loss). After 6 months of burial in soil, samples revealed possible biodegradation in natural soil conditions, as shown in microscopic examination. Moreover, a weight loss of 20.52% was also measured.

Tansengo and Dogma (1999) tested five fungal isolates for plastic degradation collected from the landfills in San Mateo, Rizal, and Carmona, Cavite. Scanning Electron Microscope (SEM) microphotograph revealed the attachment of the microbial cells and fungal mycelium and spores on the surfaces. Physical holes and cavities were noted due to the microbial degradation processes. In 2001, Clutario and Cuevas screened the fungal isolates on solid mineral medium (MM/S) by the clearance assay. They conducted the study to show the physical evidence of colonization of PE plastics strips by *Xylaria* sp. via SEM. The first reported crystal-like structure associated with plastic degradation was done by Urzo et al. (2017, pp. 572–580). The researchers implied that this could be a component of a novel mechanism of plastic degradation. From 18 test fungi, four had the potential for degrading PU. The identified four fungal isolates were *Lasiodiplodia theobromae* (Pat.) Griffon & Maubl., *Penicillium* *janthinellum* Biourge, *Fusarium verticillioides* (Sacc.) Nirenberg, and *Paecilomyces puntonii* (Vuill. Nann.). They were able to utilize DNA sequencing to identify the fungal species; however, they did not conduct tests to identify enzymes that can catalyze the lysis of recalcitrant synthetics polymers.

From the plastic bag in the forest soil of Mount Mailing, Laguna, fungal species formed surface biofilms, colonized and degraded PS (Abecia et al., 2019). They assessed the ability of local *Xylaria* sp. to grow and penetrate and damage the surface and structures of PE using SEM. Unpublished research work by Bemundo et al. (2019) screened *Pleurotus ostreatus* (Jacquin) P. Kummer as a potential agent for biodegradation of LDPE and HDPE. Results showed a segment of the plastic sheets depleted via an electronic single pan balance test in 1 month.

Gutierrez et al. (2018) studied the fungal biodegradation of so-called biodegradable plastics used in several establishments in Baguio City and Metro Manila utilizing the white rot fungus *Phanerochaete chrysosporium* Burdsall. This fungus was tested by incubating strips of biodegradable plastic with pure isolates in Petri dishes and determining their weight loss through time. The biodegradation was shown in the weight loss of plastics when incubated in the laboratory condition for specific periods using pure cultures of fungal species. The results indicated that pure fungal species gave the ability to break down plastics. The fungal species with more significant percent weight loss were found in LDPE over the oxybiodegarable (OBD) incubated. SEM analyses showed signs of degradation like holes, cracks, striations, and flakes on the surface of LDPE and OBD. Enzymes like amylases, cellulase peroxidase, and other ligninolytic enzymes are produced by this organism. This may potentially support the plastic degradation of several aromatic compounds of LDPE and OBD. Recently, a study enhancing the plastic-degrading ability of *Xylaria* sp. was conducted by (Cuevas et al., 2008). The promising result of the study was the production of albino fungal mutants that have better capability to degrade and utilize synthetic polymers. These mutants produced the wild-type (black-pigmented) xylarious fungus.

Most of the findings and insights of the previous studies focused on the identification and physical biodegradation of the fungal species for plastic degradation via light microscopy and SEM analyses. Results showed cracks, holes, and crystal-like structures at the surface of plastics used in the study. Essentially, biodegradation was shown in the surfaces of plastic sheet samples. Biomass was also measured in the previous studies, inferring the loss in weight as an indication of plastic biodegrading. Most fungal degrading plastics studies in the Philippines were conducted in terrestrial environments (soil landfills and forest environments). Whereas very few studies were conducted in freshwater and marine environments. Studies have recently isolated, identified, and screened potential fungi degrading plastic from collections done in diverse mangrove ecosystems (Apurillo et al., 2019; Calabon et al., 2018; Guerrero et al., 2018; Moron et al., 2018; Ramirez et al., 2020). Far from environmental conditions such as terrestrial and marine environments, most studies were based on selecting and testing fungal isolates in laboratory conditions. Moreover, most of the studies focused on LDPE types of plastics. A focus on PE and PP should be considered since these are mainly mismanaged plastics.

DNA sequencing has been utilized for identification and fungal diversity study in the Philippines (Urzo et al., 2017, pp. 572−580). However, the mechanism of fungal biodegradation is yet to be explored. Identifying enzymes and metabolic pathways responsible for plastic biodegradation is an interesting field. This is one of the major gaps of the previous studies on the potential application of fungi in plastic degradation. Essentially, a recent study by (Cuevas et al., 2008) used DNA mutation to enhance the capability to degrade the identified fungal species. The production of albino mutants was a promising result of the study. Hence, understanding the mutant's (albino) better capability of degrading plastic than wild type (black-pigmented) is important to gain more insights into the differences between two organisms. Studies on whether the potential fungal isolates and mutants from previous can completely degrade plastic could also be conducted. The study of long-term degradation to know how long plastics degrade is one of the research challenges since it will take time. Future studies may explore the duration of research from 6 months to several years. Comparison with other organisms such as bacteria is an interesting avenue to explore. These opportunities may help in the complete understanding of the fungal species degrading plastics. These studies may contribute to the application of the research and development of biodegradable plastics and the reduction of plastic pollution.

7. Mycoremediation of hydrocarbons

Current published mycoremediation studies in the Philippines are limited, and all are just exploratory researches dwelling on the isolation of fungi and bioassay of these locally isolated strains on hydrocarbons (Table 10.5). Philippines is a maritime gateway and has a high dependence on natural gas and coal to drive its domestic consumption (Rein & Cruz, 2008). The Philippines, as a source of hydrocarbons and the natural gas reservoir, has been explored as early as the 1800s, particularly in the waters off Palawan (Tamesis, 1981). These activities make the Philippines vulnerable to terrestrial and aquatic hydrocarbon pollution. For example, a high dissolved/dispersed petroleum hydrocarbon concentration was monitored in the waters near an offshore oil production site in Palawan. At the same time, contamination with DPPH along the western coast was also inferred to have come from the shipping activities in the area (Saramun & Wattayakorn, 2000).

Evaluation of the biosurfactant production of *Saccharomyces cerevisiae* (Desm.) Meyen 2031 from Nipa (*Nypa fruticans* Wurmb) sap from Bulacan, Philippines, was an offshoot of research conducted on the ethanol production of *S. cerevisiae* 2031 (Alcantara et al., 2010). This was the first report of a locally isolated *S. cerevisiae* strain with bioremediation potential, although there have been reported strains of *S. cerevisiae* with bioemulsifier and hydrocarbon-degrading potentials in other countries (Abioye et al., 2013; Cameron et al., 1988; Ilori & Adebusoye, 2008). The partially purified biosurfactant from this isolate emulsified aromatic hydrocarbon (benzene toluene and xylene) better than aliphatic hydrocarbons (pentane, hexane, hexadecane), suggesting that its biosurfactant activity is dependent on the hydrocarbon length (Alcantara et al., 2010). While the high emulsification indices of the biosurfactant showed that it is a promising candidate for bioremediation of petroleum-based pollutants, no further attempt was made to elucidate its mechanism of hydrocarbon emulsification.

The sinking of M/T Solar I off the coast of Guimaras Island on August 11, 2006, which caused the release of around 350,000 tons of bunker oil, posed a great concern on the environmental impacts of petroleum hydrocarbons, particularly the polycyclic aromatic

TABLE 10.5 Fungal strains isolated from hydrocarbon-contaminated sources with potential mycoremediation activities.

Strain	Source	Activity	Reference
Saccharomyces cerevisiae (Desm.) Meyen 2031	Nipa sap from Bulacan	Production of biosurfactant with emulsification activities on oils and hydrocarbons	Alcantara et al. (2010)
Phialophora sp. *Penicillium* sp. *Cladosporium* sp.	Baywalk, Manila Nasugbu, Batangas Calatagan, Batangas	Decolorization of Congo red and crystal violet	Torres et al. (2011)
Aspergillus sp. 1 *Aspergillus* sp. 2 *Aspergillus* sp. 3 *Penicillium* sp.	Coastal sediments from Ormoc City Port Area	Degradation of engine oil	Bitacura et al. (2012)
Ganoderma lucidum (Curtis) P. Karst. *Pleurotus florida* Singer	Not indicated	Utilization of diesel in growth medium	Enriquez (2015)
Aspergillus fumigatus Fresen. *Aspergillus cf. repens* (Corda) de Bary *Aspergillus niger* Tiegh. *Paecilomyces* sp. 1 *Penicillium* sp. 1	Sediments from the oil-contaminated beach and mangrove areas in Estancia and Batad, Iloilo	Degradation of TPH, PAH, and alkanes	Sadaba and Niego (2017)

hydrocarbons (PAH), on marine life (Uno et al., 2010). Two years after the incident, PAHs are still within detectable limits in the sediments and shellfishes in the affected areas. However, there was a significant decrease in the level of PAH (Pahila et al., 2010). To further determine the biological impacts of oil spills on the microorganisms, specifically the fungal community in the affected habitats, Sadaba and Sarinas (2010) conducted a 3-year (2006 and 2009) monitoring of the fungal composition in the contaminated sites. They observed an increase in fungal density in oil-contaminated sites in 2009, indicating a possible recovery and reestablishment of autochthonous fungal species. *Aspergillus* species dominated the isolates, possibly due to their ability to utilize hydrocarbons as energy sources (Asemoloye et al., 2020; Barnes et al., 2018). This assumption, however, was not further investigated.

Another oil spill incident in the Philippines occurred when the Power Barge 103 operated by the National Power Corporation (NAPOCOR) broke loose from its moor at the height of Typhoon Haiyan (locally as Typhoon Yolanda) on November 8, 2013. This caused the spillage of around 800,000L of bunker oil, which consequently contaminated the coastlines of Barangay Botongan in the town of Estancia, Iloilo, and neighboring areas (Joint UNEP/OCHA Environment Unit, 2013, pp. 1–16). Hydrocarbon-degrading fungi were isolated from the contaminated beach and mangrove areas of Batad and Estancia showed promising results in the degradation of total petroleum hydrocarbon (TPH), PHA, and alkanes either axenically or as consortia (Sadaba & Niego, 2017). The study showed that the efficiency of degradation of hydrocarbons either by single culture or as consortia depends on the complexity of the hydrocarbon involved. In this case, the more complex PAH was degraded efficiently by fungal consortia.

Strains of *Aspergillus* spp. isolated from coastal sediments in the port area of Ormoc City were also documented to be efficient in the degradation of hydrocarbons, this time using used engine oil as substrate (Bitacura et al., 2012). However, mean fat loss as the measure of the biodegradative abilities of the isolates was only determined by growing the isolates individually on the substrate. No attempt was made to evaluate their effects if grown in concert. Just like in the fungal strains collected by Sadaba and Niego (2017), the putative identification of the isolates was based on morphological and other phenotypic features. Enriquez (2015) also conducted a bioremediation study using diesel as the substrate. However, unlike the rest of the studies, which utilized filamentous fungi isolated from contaminated sites, he used the white rot fungi *Ganoderma lucidum* and *Pleurotus florida*. The mushrooms could tolerate and grow in the substrates with as high as 40% diesel content for *P. florida*. The use of white rot fungi as a bioremediator has been suggested by Reddy (1995), attributing their biodegradative potential to side reactions of their lignin-degrading enzyme systems. Moreover, the white rot fungus *Phanerochaete chrysosporium* Burdsall has been demonstrated to degrade bunker oil under nonlignocellulytic conditions attributed to the cytochrome P-450 enzyme system of this basidiomycete (Kanaly & Hur, 2006).

The hydrocarbon mycoremediation studies cited above focused on the degradation of PAH and oils. Torres et al. (2011) looked into the possibility of using marine-derived fungi to degrade synthetic dyes, which are hydrocarbon-derivatives (Jarman & Ballschmiter, 2012). *Phialophora* sp. was shown to decolorize Congo red. At the same time, species of *Penicillium* and *Cladosporium* were able to decolorize both Congo red and crystal violet, possibly due to the production of extracellular enzymes and biosorption activities.

8. Moving forward

The majority of the isolates presented in this review have only been tested in the laboratory. While this is necessary to ascertain their tolerance and mycoremediating ability, much needs to be done to validate their potentials in the field. Among those with established ability are the mycorrhizae due to their unique association with plants, and thus provides improved capacity for phytoremediation. It is likewise important that isolates remain viable so that follow-up researches may be done. A deposit in a mycological museum is a move forward.

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