

ENDOPHYTIC FUNGI: FUTURISTIC TOOL FOR BIOREMEDIATION

Abstract

The global concern of contamination of water and land with heavy metals has gotten more complicated. Given that increased metal concentrations in terrestrial and aquatic system constitute treat to mankind as well as to animals, this topic has gained tremendous attention of young researchers from all over the world. The metabolism and growth among most plants were impaired by high concentrations of heavy metals. Several traditional techniques have been employed to overcome the problem of heavy metals. However, these techniques have a number of disadvantages such as high cost, large energy requirements, and inappropriate conversion of heavy metals. Bioremediation is the most effective and promising method for treating heavy metals. Microorganisms have the capacity to minimize the toxic effects caused by heavy metals on plants. Despite their limited research to far, endophytic fungi is an effective source for shielding plants from the toxicity of heavy metals. All higher plants have endophytic fungi that live in their internal tissues asymptotically without having any negative consequences on the host. Endophytic mycoflora provide their host plant with advantages such as improved plant development, tolerance to biotic and abiotic stresses, and generation of significant and valuable pharmacological, medicinal, and therapeutical substances. Endophytes increase the effectiveness of bioremediation by lowering the toxicity of plants to heavy metals.

Keywords: Heavy metals, endophytic fungi, bioremediation.

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I. INTRODUCTION

There has been a significant concentration of heavy metals posing a significant threat to grassland and wildlife with the rapid growth of industrialisation and urbanisation. This is essential for preserving the purity of healthy soil and keeping it free from contaminants. Numerous strategies that are simple to implement, long-lasting, and practical from an economic standpoint have been devised. Different physiochemical techniques have been employed in the past to for the remediation of topsoil that previously has been contaminated with the heavy metals. However, they have significant drawbacks, such as the inability to remediate soil on a broad scale due to the higher expense and the variety of negative effects brought on by exposure to heavy metals. Bioremediation has demonstrated successful outcomes as a low-cost and environmentally benign method to address these issues. Microbe-based remediation, a cost effective and environment friendly methods for removing toxicants from polluted soils, has shown efficient in resolving these issues (Aishwarya S et al., 2014). It has been discovered that using microorganisms including bacteria and fungi remove heavy metals from soil in both economical and environmentally safe ways. Rhizospheric bacteria enhance soil stability and health, enabling plants to grow and develop continuously despite adverse situations. Algae, fungi, and bacteria are used in microbe-based bioremediation (Hassan et al., 2017).

II. HEAVY METAL

The environment has gotten worse as a result of the extension of numerous anthropogenic activities in recent years, that have led to an inflation of significant heavy metals in the soil. According to Su et al. (2014), there are main heavy metals that impose harmful effects in soil including arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), zinc (Zn), nickel (Ni), vanadium (V) and stannum (Sn). It is crucial to comprehend that the increase in heavy metal concentration can obtrude significant health risks by entering the food chain because it may have major repercussions. It is challenging to remediate heavy metal pollution after it has occurred in the soil.

1. Heavy Metal Uptake: Water, food, and air are the primary sources of heavy metal recruitment in plants and animals. As soon as heavy metals penetrate certain cellular compartments, they bond to them and disrupt a number of biological functions. Binding of heavy metals leads to the loss of catalytic activity of enzyme resulting into the formation of "new" metal-enzyme complex. This metal-enzyme complex can later bind to the sulfhydryl groups of varying enzymes which later limits the various biological metabolic reactions in plant system (Aprile et al., 2020). There are variable factors responsible for the heavy metals toxicity including the exposure duration, concentration, condition of plans and animals. The process of accumulation of heavy metals occurs when the concentration of harmful compounds in living things rises as the trophic level does. The trophic level is directly proportional to the concentration of heavy metals, i.e., higher the trophic level, the higher the concentration of heavy metals. According to Aprile and Bellis (2020), biomagnification is also defined as the gradual rise in a pollutant's concentration within a biological organism. Consequently, there has been a growing understanding that this sector need additional focus.

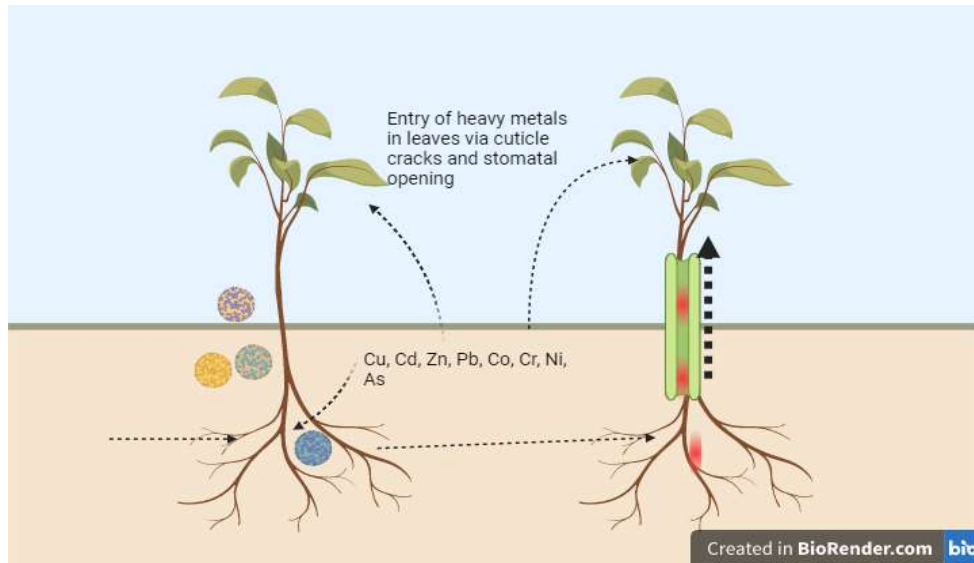


Figure 1: Heavy Metal Uptake by Plants

- 2. Characteristic features of Heavy Metal Contamination:** Since heavy metals are used in many different industries around the world, they pose a severe hazard to every nation (Yang and Sun, 2009). The environment is gradually harmed by heavy metal contamination, which has a long latency and the distinct quality of being colourless and odourless.. The content of heavy metals in soil can vary from less than one to as high as one lakh mg/kg, according to Long, Yang, and Ni (2002). But when a soil's concentration of heavy metals surpasses what the ecology can tolerate, the metals become activated. Wood (1974) first made the observation that heavy metal pollution behaves like chemical Time Bombs (CTBs). Self-purification methods such as dilution are ineffective for removing heavy metals. Dilution and self-purification techniques are not appropriate for the removal of heavy metals. Some polluted soil requires one or two hundred years to be remedied since the ex situ removal of heavy metals from soil is a laborious process (Wood, 1974). The contamination triggered by heavy metals either alone or in combination will always be amplified by the pollutants brought on by the heavy metals independently. According to research by Yong Shang et al. (2008), $Cu > Pb > Cu$ has the greatest impact on soil respiration.
- 3. Sources of Heavy Metals:** Heavy metals found in soil can originate from both natural and man-made sources. Water is less dense than heavy metals. Soil typically contains low levels of heavy metals due to the metals' natural cycle in the earth's crust. The composition of the Earth's crust determines the concentration of heavy metals in soil in areas that are not affected. Low concentrations are ideal for most heavy metals because life as we know it requires them. The primary cause of the heavy metal concentration exceeding the standard threshold is anthropogenic activity. Because of their many industrial, agricultural, residential, and technical applications, they are widely dispersed throughout the environment. Concerns regarding their potential effects on the environment and public health have been raised by this. The most common heavy metals are As, Cd, Cr, Pb, Hg, Ni, Zn, and Cu. Since they are not biodegradable in the natural world, they infiltrate the food chain. Excessive exposure to heavy metals in living things has various

negative effects, including death. Inhalation, ingestion, direct contact, and indirect contact are the ways that heavy metals enter humans (Smiljani et al., 2019). There are numerous ways that heavy metals can get into the soil. Both manmade activities and natural processes can result in the contamination of heavy metals (Alloway, 2013).

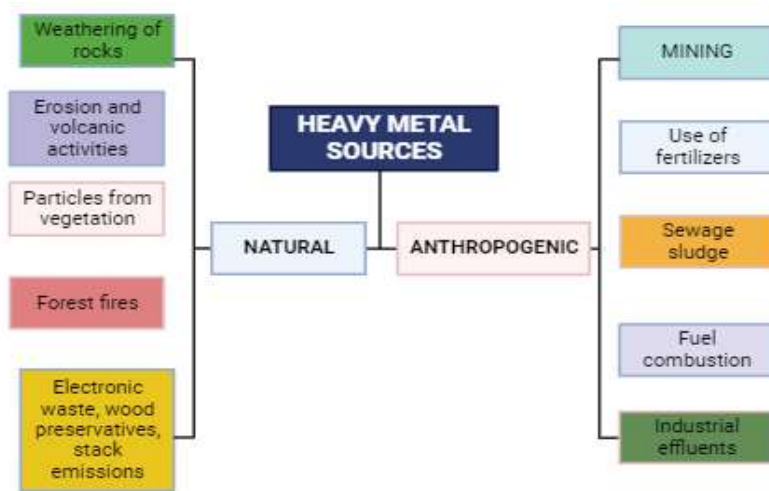


Figure 2: Sources of Heavy Metal Contamination

- **Natural Activities:** Heavy metals, which are classified as trace and infrequently dangerous, are added to unpolluted places via weathering of rocks, lithospheres, and pedogenic processes (Alloway, 2013; Yannagi, 2011). ..The 10 elements O, Si, Al, Fe, Ca, Na, K, Mg, Ti, and P make up more than 99 percent of the crust's overall composition. "Trace elements" are the remaining elements, with quantities not exceeding 1,000 mg/kg (0,1%). (Hawkeswarth & Kemp, 2006; Wuana & Okieimen, 2011; Yanagi, 2011). All soils naturally contain traces of metals. Therefore, contamination is not always indicated by the presence of metals in the soil.
- **Anthropogenic Sources:** The main cause of the high concentration of heavy metals in soil is human activity. There are several reasons why heavy metal and metalloid buildup occurs., including industrial wastewater, mining waste deposits, sanitary landfill sites, the improper disposal of high-metal waste, agricultural byproducts, the application of fertilizers and animal manures, sewage sludge, pesticide usage, irrigation with wastewater, residues from coal combustion, runoff from terrestrial ecosystems, as well as industrial and domestic discharges, accidental spills, and atmospheric deposition. In comparison to naturally occurring pedogenic or lithogenic heavy metals, those originating from anthropogenic origins in soil tend to be more mobile and bioavailable (Alloway, 2013; Wuana & Okieimen, 2011; He et al., 2015) Unlike heavy metals, which are more stable, organic pollutants are more persistent and pose a hazard to human health, the environment, soil and water quality, and ecological balance because they degrade naturally. Additionally, heavy metals can enter the food chain, leading to the proliferation of various diseases through contamination of land, water, and air, posing risks to both human and animal well-being (Mahurpawar, 2015).

Table 1: Toxicities Associated with Heavy Metals

Heavy Metals	Toxicities
Arsenic	Skin diseases, cancers and vascular diseases
Cadmium	Hepatotoxicity, kidney damage, insomnia
Copper	Wilson disease, liver damage
Mercury	Rheumatoid arthritis, defective circulatory system, neuronal damage
Lead	Fetal brain damage, kidney damage
Nickle	Skin diseases, nausea, asthma, coughing, lung diseases
Zinc	Lethargy, depression, neurological signs, increased thirst
Chromium	Diarrhea, headache, vomiting and nausea

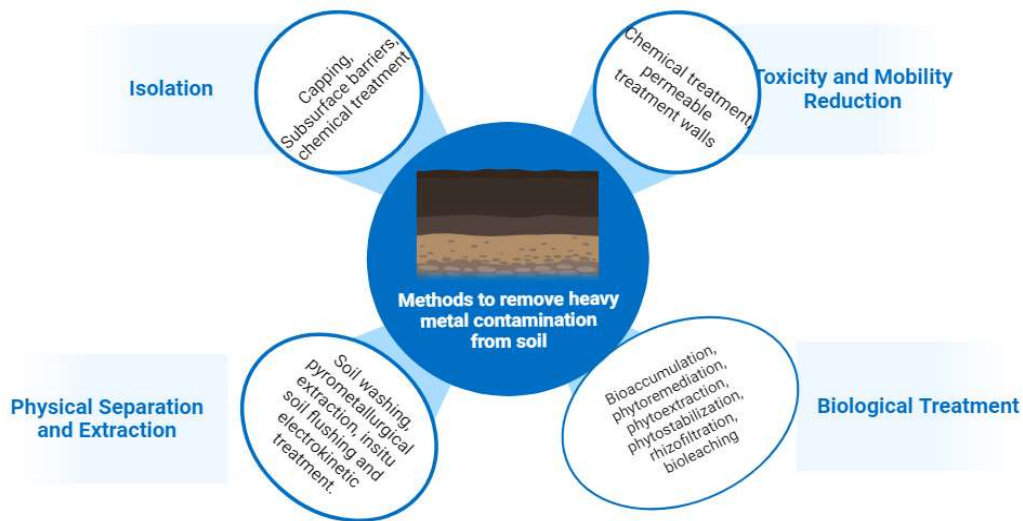


Figure 3: Methods to Remove Heavy Metal Contamination from Soil (Wuana and Okieimen, 2011).

By modifying their chemical composition or changing their chemical bioavailability, bacteria and fungi can counteract the harmful effects of heavy metals, metalloids, and radionuclides in an ecological and biochemically sound way. However, these limitations can be bypassed by plant-associated endophytes, allowing plants to absorb larger quantities of metals without facing negative effects.

III. BIOREMEDIATION

Biological methods are economical and environmentally responsible for the expulsion of harmful contaminants (Doble and Kumar, 2005). Bioremediation, phytoremediation, bioventing, bioleaching, bioaugmentation, and biostimulation are a few examples of biological processes employed. The most effective of these methods are bioremediation and phytoremediation. In contrast to physiochemical procedures, these strategies also maintain the soil's physical status (Beskoski et al., 2011). A biological method for heavy metal removal is called bioremediation (Boopathy 2000). Global worry surrounds the discharge of

heavy metals, pesticides, and phenolic waste into the environment as a result of human or natural practices. Because of its low cost and streamlined process, microbial-based treatment is ideal. Many techniques and procedures have been used to remove heavy metals via microbial metabolism. Hazardous waste can be mostly removed from the biosphere via a variety of bioremediation techniques and processes, such as phytoremediation improved by endophytic microbes and rhizoremediation. The mobility, solubility, degradability, and bioavailability of pollutants all affect how bioremediation works. Additionally, these elements have a significant impact on deterioration. As a result, understanding the mechanisms of efficient bioremediation depends on the detection of natural microbial processes (Stępniewska & Kuniar, 2013).

For remediation, a variety of physicochemical and conventional techniques have been used in the past, including soil burning, excavation, soil washing, landfilling, leaching, solidification, and soil flushing (Wuana and Okieimen 2011). Nevertheless, the physical and chemical characteristics of the soil may be adversely affected by these methods. They come with limitations, including high costs, labor intensiveness, harm to soil-dwelling microorganisms, and the generation of pollution-related issues. Moreover, these methods can alter the soil's physical and chemical composition without completely degrading heavy metals. Therefore, there is a growing need for innovative, cost-effective, and environmentally friendly approaches (Lambert et al., 2000; Ali et al., 2013). Modern technology for the remediation of heavy metals, which is both economically viable and eco-friendly, is in demand. For example, *Pseudomonas aeruginosa* and *Bacillus* spp. have been employed to alleviate Zn and Cu stress (Kumar et al. 2011). The significance of plant-microorganism partnerships has increased due to the potential of microorganisms to bioaccumulate heavy metals (Hadi and Bano, 2010).

1. Why Endophytic fungi?

Endo- indicates inside, and phyte- means plants in the word endophyte. De Bary first used the term "endophyte" in 1866. There are over 300,000 plant species on Earth and it is thought that at least one form of endophyte contributes to the planet's immense biodiversity (Strobel and Daisy, 2003). The fact that few plant-associated endophytic fungi have been examined suggests that there is a significant potential for discovering intriguing endophytes among the numerous plants in various niches and habitats. According to Petrini (1991), endophytic microorganism colonize plant tissues without showing any symptoms. These bacteria are found in the root cortex or xylem as well as in particular plant tissues. Furthermore, endophytes regularly enter plants through the apoplast or vascular systems (Stępniewska & Kuźniar, 2013).

2. Colonization of Endophytic Fungi: The interaction between plants and the soil's microcosm helps plants grow, deal with biotic and abiotic challenges, modulate their immune systems, and produce bioactives like polyketides, coumarins, isocoumarins, quinones, and anthrones, among other things. Several data indicate that endophytic fungi can support their host plants' defence mechanisms. The utilisation of endophytic fungi as biocontrol agents, which are capable of producing important bioactive compounds, is currently the focus of increasing research. Endophytic fungi are mitosporic and meiosporic microorganisms that are "quiescent infections" that exist asymptotically within the healthy plant tissues beneath the epidermal cell layers. It's also beneficial for plants when endophytic fungus colonise them. Plant immune system responses to endophytic fungal colonization are also beneficial. Over the course of long-term

development, plants have evolved a number of advantageous defense mechanisms against the invasion of endophytic fungus. Yan et al. (2019) claim that interactions between endophytic fungus and plants alter the way that plants react to both biotic and abiotic stresses.

When endophytic fungi interact with plants, they produce signals after sensing plant stimuli, which then cause the plants' immune systems to become active. Plants typically have a two-branch innate immune system that aids in cell communication and allows them to recognise signals from endophytes. This primary signalling initiates two separate pathways: one leads to MAMP-triggered immunity (MTI), in which plants identify the molecules produced by microorganisms (called effectors) through intracellular receptors; the other leads to effector-triggered immunity (ETI), in which plants identify the molecules produced by microorganisms (called MAMPs) through cell surface-localized pattern recognition receptors (PRRs).

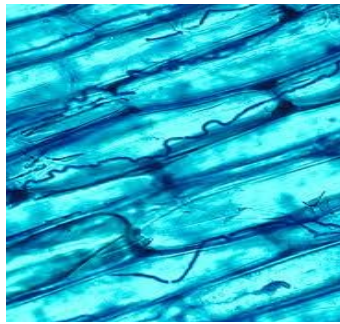


Figure 4: Growth of Endophytic Fungus inside Plant Tissue

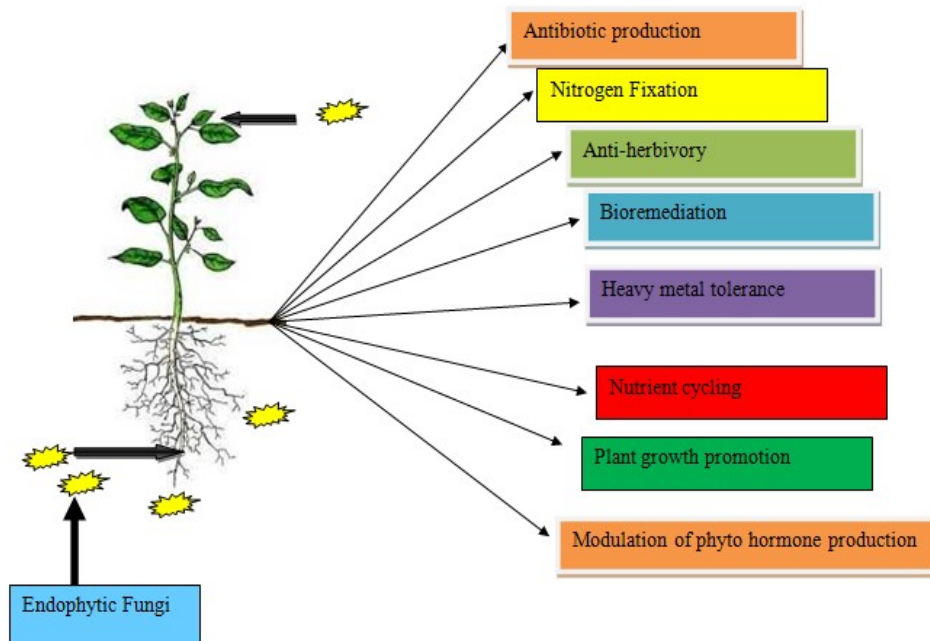


Figure 2: Different Properties Exhibited by Endophytic Fungi

- 3. Endophytic Fungi in Bioremediation:** Lately, endophytic fungi have demonstrated an increased degree of metabolic flexibility, leading to the release of several enzymes that aid in the breakdown of hydrocarbons. One workable method for the on-site treatment of contaminated soils is the use of endophytic fungi in bioremediation. The reason for this is that many endophytic fungi are capable of decomposing organic contaminants and are resistant to heavy metals. Filamentous fungi can be a beneficial and promising supplementary method in situations where bacterial cells are unable to form the necessary mycelia network for responding to contaminants (Aishwarya S et al., 2014).

Because of their wide range of processes that can break down complex compounds, degrade chemical pollutants, and promote heavy metal biosorption, endophytes have emerged as a promising resource for the removal of heavy metals (Xiao et al. 2010; Russell et al. 2011; Li et al. 2012c). Numerous endophytic fungi have the ability to break down both big and small organic molecules enzymatically. participate in the degradation of environmental pollutants, and contribute to the enhancement of the soil microenvironment (Krishnamurthy & Naik, 2017). As suggested by H-Y Li et al. (2012), endophytic fungi play a pivotal role in augmenting the ability of host plants to extract pollutants from soil, water, sediment, and the atmosphere. These fungi induce alterations in the morphology and physiological processes of the host plant, consequently conferring resistance to metal pollution. Per Barkey, Miller Summer (2003) and Kim et al. (2015), this resistance is probably caused by elements like a high surface-to-volume ratio, extracellular scavenging, and intracellular precipitation. The existence of a variety of resistance mechanisms exhibited by different fungi may explain the observed variations in metal tolerance (Iram et al. 2013). Notably, the polysaccharides chitin and cellulose, commonly found in fungi, contain functional groups including amino, carboxyl, hydroxyl, and sulfate, which exhibit a significant binding affinity for metals and hold considerable potential for heavy metal removal (Davis et al. 2003).

Endophytic fungi have gained considerable attention in bioremediation practices due to their extensive mycelial networks. In cases where bacteria may not develop the requisite mycelia network to respond effectively to pollutants, the use of filamentous fungi emerges as a promising solution or a valuable complement. This strategy works especially well when pollution levels are too high for bacteria to survive or when unicellular organisms have trouble physically obtaining poisons (Singh, Verma, & Gaur, 2013). Unlike bacteria, a considerable fraction of endophytic fungus display filamentous growth patterns, which allow them to utilize either exploitative or exploratory development methods. Additionally, they can create linear structures made of aggregated hyphae to facilitate environmental navigation (Deng & Cao, 2017).

According to a number of studies (Monnet et al. 2001; Sun et al. 2010; Zhang et al. 2010), some endophytic fungus may even help host plants flourish in soil contaminated with heavy metals. However, little is yet known about the variety of endophytic fungi found in environments contaminated with lead and zinc (Zhang et al., 2008; Guo et al., 2010; Xiao et al., 2010).

Because of their ability to sequester metals, microorganisms have attracted a lot of research (Wang and Chen, 2009). Heavy metal resistance has already been documented in *Aspergillus* sp., *Fusarium* sp., and *Humicola* sp. (Valix et al., 2001; Ezzouhri et al., 2009; Iram et al., 2013).

Numerous recent studies have demonstrated that endophytic fungi display a comparable pattern of resistance to multiple heavy metals, such as copper, zinc, and cadmium (Hong et al. 2010; Salvadori et al. 2013; Deng et al. 2014).

Endophytic fungi from Sarawakian wetlands can thrive in environments with high levels of heavy metals (up to 1000 ppm) (Choo et al., 2015). This was the first report on *Pestalotiopsis* sp. tolerance to a group of heavy metals including copper, chromium, zinc, and lead and has the ability of being used to screen possible biosorbents. A low cost, environmentally friendly, and efficient way to remove toxicants from polluted soils has been suggested, i.e., phytoremediation. However, there are still some significant drawbacks in phytoremediation of heavy metals, such as phytotoxicity. However, endophytes associated with plants can help to decrease the effect of phytotoxicity, allowing plants to accumulate more metals without experiencing an increase in toxic effects for plants.

Endophytic fungi exhibit a noticeable resistance to heavy metals under persistent metal stress and long-term exposure, according to H.-Y. Li et al. (2011). A majority of the endophytic fungal isolates tested for the resistance of lead and zinc. These growth-stimulating endophytic fungi can utilize the heavy metal as micronutrients. In order to facilitate phytoremediation in soils contaminated with heavy metals, it may be advantageous to inoculate these stress-adapted fungus into plants (Dodd & Thompson 1994; Zhang et al. 2008).

Endophytic fungus can be used for phytoremediation or bioremediation at contaminated sites (Li et al., 2010). Endophytic fungi more commonly colonised in areas that were contaminated with lead and zinc. The most prevalent endophytic fungus in the Pb-Zn polluted area were *Phoma*, *Alternaria*, and *Peyronellaea*. Pb²⁺ and/or Zn²⁺ tolerance has risen in them (Yang et al. 2012).

Compared to the bacterium *Pantoea* sp., *Pestalotiopsis* sp. exhibited a stronger resistance to copper; however, the bacterial resistance to copper reached only 200 ppm (Ozdemir et al., 2014). According to Congeevaram et al. (2007), fungi displayed greater tolerance to chromium, with resistance levels reaching up to 10,000 ppm. *Aspergillus niger* strains successfully withstood lead concentrations of up to 7,000 ppm (Faryal et al., 2007). Both studies isolated fungi from environments contaminated with heavy metals, highlighting the significant impact of environmental pressures on microorganisms, influencing their capacity to resist heavy metals and adapt for survival. Choo et al. (2014) identified endophytic fungi capable of withstanding high concentrations of heavy metals, demonstrating *Pestalotiopsis* sp.'s ability to tolerate various heavy metals, including Cu, Cr, Zn, and Pb. Further research will be required to comprehensively understand the mechanisms that enable endophytic fungi to thrive in environments with heavy metal concentrations of up to 1,000 ppm.

Strains of *Aspergillus flavus*, *A. niger*, *Fusarium solani*, and *Penicillium chrysogenum* were shown to be resistant to heavy metals like chromium and lead after screening soil samples from peri-urban agricultural districts. Most of these isolates exhibited resistance to Pb and Cr, with only a few capable of growth. Among the isolated strains, *Aspergillus niger* displayed the highest tolerance to Pb, with a minimum inhibitory concentration (MIC) of 600 mg/l, while *Aspergillus flavus* showed the highest

tolerance to Cr, with an MIC of 400 mg/l. These findings indicate their potential suitability as candidates for bioremediation purposes (Iram et al., 2013).

Spray foam, rigid foam insulation panels, microcellular foam gaskets and seals, high-resilience foam seating, and durable elastomeric wheels and tires are just a few applications for polymeric polyester polyurethane (PUR). Nevertheless, studies have indicated that PUR is biodegradable (Darby & Kalpan, 1968; Howard, 2002). A polyisocyanate and a polyol are condensed to create the polymer. As a result, a carbon polymer made up of many urethane connections is produced. The characteristics of the resultant polymer can differ from linear and rigid to branching and flexible depending on the type of the substitutions and variations in the distance between urethane links. Under liquid suspension, PUR is entirely opaque and milky white in appearance. According to Russell et al. (2011), this material is commercially manufactured for the production of textiles and textile coatings, just like other polyurethanes may be.

Because of the enzymes they create, both fungi and bacteria can break down PUR (Cosgrove et al., 2007; Crabe et al., 1994; Pathirana & Seal, 1984; Rowe & Howard, 2002). Soil fungus comprise the majority of the species examined for PUR-degrading activity. In buried PUR samples, fungi belonging to the genera *Alternaria*, *Aspergillus*, *Phoma*, *Penicillium*, *Plectosphaerella*, *Geomyces*, *Nectria*, and *Neonectria* have been discovered. The most commonly isolated PUR-degrading organism from these samples was *Geomyces pannorum* (Cosgrove et al., 2007). There are very few species known to be able to decompose PUR as their exclusive carbon source. As an example, *Aspergillus niger* has been shown to be capable of breaking down carbon sources, with results becoming apparent in as little as 30 days (Fillip, 1979). According to Russell et al. (2011), endophytic fungus have demonstrated a wide range of activities, indicating that they may be a useful source of biodiversity for research into processes related to bioremediation and the breakdown of polyester polyurethane.

There are two different ways that endophytic fungus can spread across plants: horizontal and vertical gene transfer. The phenomenon of horizontal gene transfer could suggest a significant level of phenotypic variation within the genus or could play a role in some endophytic fungi's ability to break down polyester polyurethane as their primary carbon source. For instance, *Pestalotiopsis microspora* frequently exhibit horizontal gene transfer. *Aspergillus niger* and *Penicillium* sp., on the other hand, are examples of fungal endophytes that have notable capacities for biosorbing Cr, Ni, and Cd from single and multi-metal solutions. This emphasizes the filamentous fungi from metal-contaminated environments' potential usefulness. The endophytic fungus *Microsphaeropsis* sp., which is obtained from *Solanum nigrum* L., a cadmium hyperaccumulator, produces a significant amount of biomass when grown in vitro. The endophytic fungus LSE10 has been shown in studies by Xiao et al. (2010) to be a useful biosorbent for cadmium detoxification. Furthermore, fungal populations from heavy metal-contaminated areas are more resilient to elevated metal concentrations, as reported by Chandrakar et al. (2014). Filamentous fungi that originated in uncontaminated environments also showed a commensurate level of resistance to metals. The tolerance and resistance of the isolates were determined by the test fungus significantly more so than by the isolation site. This variation could be the result of the fungi's tolerance and adaptation to heavy metals. *Aspergillus* sp. and *Fusarium* sp. are interesting candidates for more investigation into their ability to remove metals because of their high metal resistance to all studied metals.

According to Mukherje et al. (2014), *Aspergillus flavus* (ASC1) and *Aspergillus niger* (ASB3) exhibit the capacity to remove between 50% to 76% of arsenic from various arsenic-enriched media while also demonstrating tolerance to several other heavy metals, including Cd, Pb, Hg, Zn, and Cr. These two fungal strains hold promise for future applications in arsenic cleanup efforts in contaminated areas. Furthermore, Deng et al. (2014) reported that the endophytic fungus *Lasiodiplodia* sp. MXSF31, which was isolated from *Portulaca oleracea*, a plant that accumulates metals, exhibited resistance to zinc, lead, and cadmium. The endophytic fungus had strong ability to both biosorb and accumulate zinc, lead, and copper from solutions contaminated with metals. This improved the efficiency of rapeseed in removing metals from soils contaminated with different heavy metals. Consequently, a valuable source of microorganisms for bioremediation in water and soil contaminated with various heavy metals can be found among fungi associated with plants that accumulate multiple metals. Hyperaccumulating plants like *Alyssum bertoloni*, *Alnus firma*, *Brassica napus*, *Nicotiana tabacum*, *Thlapsi caerulescens*, *T. goesingense*, and *Solanum nigrum* have been found to harbor a multitude of metal-resistant endophytes.. However, numerous metal-resistant endophytes have also been found in plants that do not hyperaccumulate metals, including *Symplocos paniculata*, *Acacia decurrens*, and *Arabis hirsta* (Li et al., 2012). *Microspaeopsis*, *Mucor*, *Phoma*, *Alternaria*, *Peyronellaea*, *Steganosporium*, and *Aspergillus* are the metal-resistant endophytic fungus.

IV. OTHER APPLICATIONS EXHIBITED BY ENDOPHYTIC FUNGI

- 1. Endophytic Fungi in Agriculture:** Finding more interest in environmentally friendly alternatives to artificial fertilisers and pesticides is due to the numerous negative health impacts associated with their use. There have been reports of fungal endophytes producing beneficial substances including phytohormones, antimicrobials, and other agrochemical bioactive metabolites. Since it is known that endophytic and rhizosphere fungi help the host plant withstand a variety of biotic and abiotic challenges (nutrient depletion, droughts, etc.), they continue to be important natural resource reservoirs. The peripheral tissues of the plant, however, provide a chemically intricate microcosm that supports a wide array of microbes. The ability of *Epicoccum nigrum* to biocontrol bacterial and fungal plant diseases is also well documented (Lugtenberg et al. 2016).

As per Berardo et al. (2018) findings, *E. nigrum* exhibited biocontrol efficacy against the bacterial pathogen *Pseudomonas savastanoi* pv. *savastanoi* (Psv), responsible for causing olive knots, resulting in a significant reduction in psv growth and biomass. Furthermore, *Theobroma cacao* tissues containing the endophyte *Colletotrichum gloeosporioides* displayed antagonistic properties against the pathogen causing black pod rot. Various pathogens, such as *Phytophthora palmivora* (causing black pod rot), *Moniliophthora roreri* (causing frosty pod rot), and *M. perniciosa* (causing witches broom), have been identified in both field and in vitro studies. According to Park et al. (2019), *Trichoderma* sp. has been effectively employed as a Biological Control Agent (BCA) against plant pathogenic fungi, including *Botrytis cinerea*, *Fusarium* spp., *Pythium* spp., and *Rhizoctonia* spp. Notably, when in close proximity to pathogenic mycelium, the endophytic fungus *T. viride* displayed antagonistic behavior (Talapatra et al., 2017). Endophytic fungi play a pivotal role in agriculture by enhancing plant nutrition through the solubilization of essential nutrients like phosphorus, potassium, and zinc. Moreover, they produce phytohormones such as Indole acetic acids, gibberellic acids, and

cytokinins, as well as Fe-chelating compounds, hydrolytic enzymes, hydrogen cyanide, and ammonia, thereby contributing significantly to agricultural practices (Yadav & Yadav, 2018; et al., 2016; Saxena et al., 2016; Verma et al., 2017). Many endophytic fungal species from different genera have been isolated from different host plants, such as *Acremonium*, *Alternaria*, *Aspergillus*, *Berkleasium*, *Chaetomium*, *Cladosporium*, *Claviceps*, *Cryptococcus*, *Curvularia*, *Fusarium*, *Geomyces*, *Glomus*, *Leptospora*, *Metarhizium*, *Microdochium*, *Neotyphodium*, *Ophiognomonia*, *Paecilomyces*, *Penicillium*, *Phaeomoniella*, *Phyllosticta*, *Piriformospora*, *Rhizoctonia*, *Rhizopus*, *Rhodotorula*, *Talaromyces*, *Trichoderma*, *Wallemia*, and *Xylaria*.

- 2. Endophytic Fungus producing Secondary Metabolites:** Among the active secondary metabolites that fungus endophytes can produce are alkaloids, various amides, and other compounds containing nitrogen (Rustamova et al., 2020). Numerous types of secondary metabolites are produced by endophytic fungus. Antibacterial substances generated by *Periconia* sp., *Penicillium* microspore, *Phomopsis* sp., *Aspergillus clavatus*, *Phomopsis* sp., and *Fusarium* sp., respectively, include Periconicin A and B, Petacin, Phomol, Mullein, Brefeldin A, Uridine, and Cerebrocoide (Guo et al., 2000; Kim et al. The chemicals alternariol and alternariol-(9)-methyl ether, which are produced by the endophytic fungus *Pleospora tarda*, have been shown to have the strongest antiviral effects (Selim et al., 2018). Brefeldin A, which has been isolated from many fungal species such as *Curvularia*, *Alternaria*, *Phyllosticta*, *Penicillium*, and *Cercospora*, possesses antifungal, antiviral, anticancerous, and protein-transport inhibitory characteristics (Zabala et al., 2014). (Wang et al., 2002). *Podophyllum emodi* has a potent antimitotic and tubulin polymerase inhibitor called podophyllotoxin, which is applied topically to cure vaginal warts. But several of its semi-synthetic derivatives, such as teniposide, etoposide, and etoposide phosphate, which are inhibitors of topoisomerase II, are effective anticancer drugs (Stahelin & Wartburg, 1991; Baldwin & Osherhoff, 2005). The endophytic *Aspergillus versicolor* was isolated from the leaves of the *Eichhornia crassipes*, an Egyptian water hyacinth, and it produced aflaquinolone, a derivative of dihydroquinolone and a secondary metabolite. Ebada et al. (2018) claim that aflaquinolone has better antiproliferative qualities. *Fusarithioamide*, *pestalotiones*, and *koninginol B* from *Fusarium chlamydiosporium*, *Petalotiopsis theae*, and *Trichoderma koningiopsis*, respectively, are responsible for the antifungal, antibacterial, antioxidant, cytotoxic, and antimicrobial activities (Ibrahim et al., 2018; Guo et al., 2020; Shushuai et al., 2020).

V. CONCLUSION

Endophytic fungi, the concealed companions residing within plant tissues, have been recognized for their ability to thrive in contaminated soil, displaying metal tolerance and mitigating their detrimental effects. These endophytic fungi not only coexist with their host plants but also exhibit accelerated carbon metabolism, enhanced bioactive productivity, and appropriate growth. The innovative application of endophyte-assisted bioremediation technology holds promise for the removal of a wide range of environmental pollutants, including bio-hazardous contaminants, metals, metalloids, carcinogens, industrial effluents, inorganic pesticides, herbicides, hydrocarbon-based compounds, and chlorinated substances. Bioremediation, as an environmentally friendly approach, has proven effective in mitigating heavy metal pollution with minimal adverse impacts. However, the elimination of metal pollution through endophyte-assisted bioremediation approaches presents unique challenges

and is more time-consuming, albeit feasible. Previous studies have indicated that endophytic fungi may possess the capacity to break down metals, although this natural degradation process is relatively slow in addressing metal pollution.

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