academicJournals

Vol. 8(35), pp. 1679-1687, 18 September, 2013
DOI 10.5897/SRE2013.5605
ISSN 1992-2248 © 2013 Academic Journals
http://www.academicjournals.org/SRE

Scientific Research and Essays

*Review*

# Use of mycorrhiza in soil remediation: A review

**Chibuike, G. U.**

Department of Soil Science, University of Nigeria, Nsukka, Nigeria

Accepted 2 September, 2013

**Mycorrhiza-assisted remediation (MAR) is a sustainable method of remediation that uses natural organisms for soil remediation. It is a technique that not only ensures the removal of soil pollutants but also improves the structure of the soil and helps in plant nutrient acquisition. Thus, it helps in vegetation/revegetation of polluted soils after treatment. MAR can be used for the removal of both organic and inorganic soil pollutants. However, its efficiency may be influenced by the species and origin of the mycorrhizal fungi, the type of plants colonized, and the type and concentration of the pollutant. Various soil organisms interact with mycorrhizal fungi to improve the efficiency of MAR. However, more research is needed in order to fully understand the mechanisms of MAR.**

**Key words:** Mycorrhiza-assisted remediation (MAR), mycorrhiza, pollutants, soil remediation, soil organisms

## INTRODUCTION

Soil pollution has become a global problem due to increase in industrialization and mining activities. One major area that suffers from the impact of soil pollution is agriculture – crop production. Crops do not grow well on polluted soils because these soils contain toxic elements that hinder their growth. Soil remediation is therefore essential to not only create a healthy environment but also to increase the food demand of the ever increasing human population.

Soil remediation can be achieved via various methods. Some of these methods involve the physical excavation and transport of the polluted soil to landfills for disposal. Others involve the use of solvent extraction techniques, electrokinetic separation, chemical oxidation, soil stabilization/solidification and bioremediation (Bento et al., 2005; Gong et al., 2005; Collins et al., 2009; Roach et al., 2009). Each method has its own advantages and disadvantages and the choice of any method would depend on the type of pollutant to be remediated, the proposed use of the polluted site, available time and finance.

Mycorrhiza-assisted remediation (MAR) is an aspect of bioremediation that can be used for the treatment of both organic and inorganic pollutants. It has received much attention in recent years because it enhances the establishment/re-establishment of vegetation on the remediated soil and can equally be achieved at a reasonable cost even though it is relatively time consuming. This paper discusses the different mechanisms employed by mycorrhizal fungi for the treatment of both organic and inorganic soil pollutants. Interactions between mycorrhiza and other soil organisms were highlighted. Recommendations on the best approach to MAR were made after examination of various case studies.

## PROPERTIES OF POLLUTED SOILS

Soil properties are adversely affected by the presence of toxic elements. For instance, soils with high concentrations of heavy metals such as Cd, Pb and Zn show a decline in microbial biomass and nitrogen fixation (Fliessbach et al., 1994; Giller et al., 1998). However, the rate at which the soil is affected by these metals will depend on the soil's pH, temperature, organic matter, clay mineral and inorganic ion content (Bååth, 1989; Giller et al., 1998).

E-mail: chibuikeg@yahoo.com.

Organic pollutants affect soil properties in diverse ways. The hydrophobic nature of most organic pollutants influences soil physical properties such as water holding capacity (WHC) and hydraulic conductivity (HC). Trofimov and Rozanova (2003) reported a reduction in WHC and HC of soils polluted with petroleum hydrocarbon. On the other hand, increases in structural stability of hydrocarbon polluted soils have also been documented (McGill et al., 1981). Due to the structural composition of organic pollutants, the soils they come in contact with gain a high amount of organic carbon; this increases the activities of the microorganisms not affected by these pollutants (Tiquia et al., 2002; Trofimov and Rosanova, 2003; Robertson et al., 2007). However, continued growth of these organisms lead to depletion of soil nutrients which eventually results in poor plant growth (Xu and Johnson, 1997).

## SOIL REMEDIATION TECHNIQUES

Polluted soils can be treated on-site (*in situ* remediation) or they can be transported to another location for treatment (*ex situ* remediation) or disposal. The method adopted would depend on the proposed use of the site, the type of pollutants involved and the available resources. Soil remediation can be achieved by the physical excavation and transport of the polluted soil to landfills. Apart from the risk of pollutant dispersal during transport of polluted soils, this method is also time consuming and expensive (Bellandi, 1995). Scarcity of landfills also makes this method undesirable. Capping of the polluted soil with a surface layer that supports vegetation is another physical method of soil remediation. However, this method is temporal and most times complete soil remediation is not achieved (Smith and Hayward, 1993; Bellandi, 1995).

A more common method of soil remediation is the use of chemicals. This method has received much attention because it can be used for the treatment of soils polluted with organic and inorganic pollutants. It also achieves remediation within a relatively short time. However, chemical remediation is a rather expensive method of soil remediation and some chemicals may interfere with the soil's ability to support plant growth. Chemicals that have been used for soil remediation include oxidants such as ozone, $KMnO_4$, $H_2O_2$ and Fenton's reagent (Masten and Davies, 1997; Ferrarese et al., 2008). Chemical soil stabilizers such as lime and apatite have also been used for the remediation of polluted soils (Collins et al., 2009; Venäläinen, 2011).

Solvent extraction technique is a physical/chemical method that can be used for the removal of organic soil pollutants. It involves washing the soil with water and organic solvents. Solvents such as surfactants, cyclodextrins and vegetable oil have been used for the removal of pollutants via this method (Li and Chen, 2002; Gong et al., 2005; Viglianti et al., 2006). Electrokinetic separation is another physical/chemical method of soil remediation that can be used for both organic and inorganic pollutants when minimum disturbance of the surface soil is required (Wang et al., 2007). Thermal techniques such as soil incineration (*ex situ* treatment) and conductive heating (*in situ* treatment) can also be used for the removal of volatile and semi-volatile soil pollutants (Bellandi, 1995; Baker and Heron, 2004; Gan et al., 2009).

Another common method of soil remediation is bioremediation. It involves the use of organisms (microorganisms and/or plants) for the treatment of polluted soils. It is a generally accepted form of remediation because it involves the use of natural substances rather than the introduction of artificial chemicals/materials. Thus, it eliminates the risks associated with handling chemicals. It can also be used for the remediation of soils polluted with organic and inorganic pollutants (Salunkhe et al., 1998; Li et al., 2008). It is relatively cheap compared to most types of soil remediation techniques, even though complete soil remediation can be achieved within a longer time.

Phytoremediation (bioremediation that involves the use of plants) is widely used for the remediation of soils polluted with heavy metals (Ebbs et al., 1997; Bani et al., 2007). However, it can also be used to remediate soils polluted with organic pollutants (Aprill and Sims, 1990; Chaineau et al., 2000). Plants use various mechanisms for the remediation of polluted soils. Some of these mechanisms involve the accumulation of pollutants by plant structures (phytoextraction); reduction in pollutant mobility/bioavailability (phytostabilization); release of pollutants/metabolites into the atmosphere (phytovolatilization) and degradation of pollutants (phytodegradtion and rhizodegradation). Whichever mechanism is employed, complete remediation of polluted soils via phytoremediation takes a considerable amount of time to be accomplished (McCutcheon and Schnoor, 2003).

## MYCORRHIZA-ASSISTED REMEDIATION (MAR)

MAR is an aspect of bioremediation that uses mycorrhiza for the treatment of polluted soils. Mycorrhiza is the symbiotic association between fungi and the roots of vascular plants. The plant supplies the fungi with carbohydrate, while the fungi - known as mycorrhizal fungi - extends the surface area of the plant's roots and thus increases their ability to absorb more nutrients (especially phosphorus) and water from the soil. Mycorrhiza increases the plant's ability to resist diseases (Harrier and Watson, 2004). It also provides a stable soil for plant growth via production of glomalin - a substance that binds soil aggregates (Wright et al., 2007).

Mycorrhizal fungi are also able to detoxify toxic substances; hence they have been used for the remediation of both organic and inorganic pollutants in

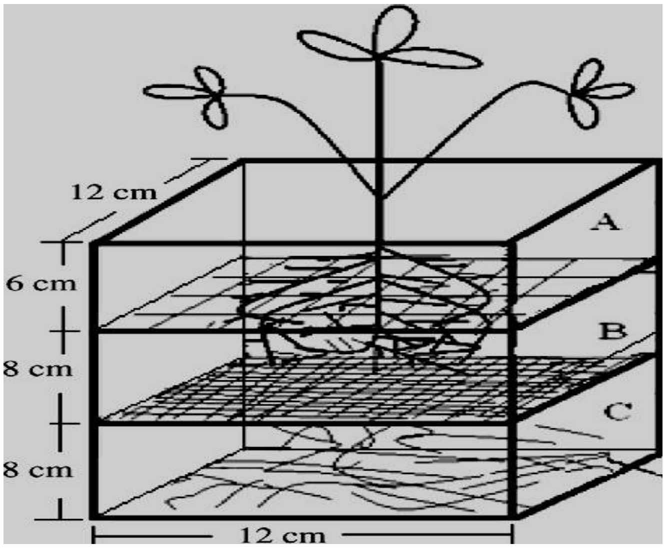


**Figure 1.** Area covered by mycorrhizal fungi hyphae. This figure shows how mycorrhizal fungi increase the surface area of plant roots and thus help in remediation. The ordinary plant root did not go farther than compartment B; however the fungi hyphae extended into compartment C (Adapted from Gao et al., 2010).

soils. Remediation of polluted soils can be done by the two common types of mycorrhizae – ectomycorrhiza (ECM) and arbuscular mycorrhiza (AM). However, AM is used in most remediation exercises because it colonizes almost all types of plants unlike ECM that colonizes mostly woody species.

Mycorrhiza cannot exist without a plant; therefore MAR can be described as a modified form of phytoremediation that exploits the benefits derived from mycorrhizal fungi. It uses some of the techniques of phytoremediation such as phytoextraction and phytostabilization. However, it is different from phytoremediation because remediation can be achieved at a faster rate since the area covered by plant roots - through the fungi hyphae - in MAR is larger than the area covered in phytoremediation (Gao et al., 2010) (Figure 1).

Rufyikiri et al. (2004) observed that MAR reduced the translocation of pollutants from the roots to the shoots of plants. Thus, MAR increases the secondary value of plants used for phytoremediation (especially phytoextraction) because the plants that would normally be harvested and incinerated could be used to check erosion on the remediated soil. Furthermore, as the fungi spores remain in the soil for up to six years (Nguyen et al., 2012), they easily colonize and support the growth of any crop planted on the soil after remediation. Thus, MAR ensures the rapid vegetation of remediated soils.

## REMEDIATION OF INORGANIC POLLUTANTS IN SOILS

Mycorrhizal fungi occur naturally in roots of plants growing on heavy metal polluted soils (Turnau, 1998). Thus, they have been used for the remediation of these soils; though in most cases, the fungi are inoculated in order to speed up the remediation process. The basic mechanisms of MAR employed in the remediation of inorganic pollutants are phytoextraction and phytostabilization (Table 1).

Studies have shown that soils polluted with various heavy metals including As, Cu, Cd, Pb, U and Zn can be remediated via MAR (Chen et al., 2005; Janouskova et al., 2006; Marques et al., 2006; Trotta et al., 2006; Wang et al., 2007; Chen et al., 2008). The ability of MAR to effectively remove heavy metals depends on the plant species the fungi colonizes. Chen et al. (2007) reported that the effect of MAR was significant when a legume (*Trifolium repens*) and two native plants (*Coreopsis drummondii* and *Pteris vittata*) were planted on a soil with high Cu concentration. On the other hand, using turf grass (*Lolium perenne*) did not produce significant results. Thus, it can be deduced that some phytoremediation plants have greater tolerance to heavy metals than others and would thus produce better results when used in MAR. The origin of the mycorrhizal fungi also determines the amount of heavy metal removed from a soil. Orłowska et al. (2012) found that fungi species isolated from polluted soil are able to accomplish more remediation than others introduced from a different source; this is mainly due to the high adaptability of the indigenous species.

Soils polluted with multiple heavy metals can be treated via MAR (Liao et al., 2003; Vogel-Mikus et al., 2005; Chen et al., 2006). This is achieved through phytoextraction with appropriate plant species. Vogel-Mikus et al. (2005) used MAR with *Thlaspi praecox* (Brassicaceae) for treatment of a soil polluted with Zn, Cd and Pb. It is widely known that most plants in the Brassicaceae family do not form mycorrhizal associations (Marschner, 1995). Some researchers have argued that their exudates may even be toxic to the mycorrhizal fungi (Cardoso and Kuyper, 2006). Thus, the work of Vogel-Mikus et al. (2005) indicates that there may be more species of the mycorrhizal fungi - which are yet to be discovered - that may have the ability to colonize these group of plants. MAR can also be used for the treatment of soils polluted with radionuclides such as $^{137}$Cs and $^{90}$Sr through phytoextraction as demonstrated by Entry et al. (1999); though the feasibility of this method under field conditions is yet to be determined.

There are conflicting reports about the use of MAR. Joner and Leyval (1997) observed that uptake of Cd by *Trifolium subterraneum* was not significantly influenced by the mycorrhizal status of the plant. Similarly, Diaz et al. (1996) reported that at lower concentrations of Pb and Zn, plants inoculated with *Glomus mosseae* and *Glomus macrocarpus* accumulated an equal or greater amount of these metals compared to the control. However, at higher concentrations of these metals, the control accumulated

**Table 1.** MAR of inorganic pollutants in soils.

| Pollutant | Mechanism | Reference |
|---|---|---|
| As | Phytoextraction, Phytostabilization | Trotta et al., 2006; Dong et al., 2008; Leung et al., 2010; Orłowska et al., 2012 |
| Cd | Phytostabilization | Janouskova et al., 2006 |
| Cu | Phytostabilization | Cheng et al., 2007; Wang et al., 2007 |
| Pb | Phytostabilization | Chen et al., 2005 |
| U | Phytostabilization | Chen et al., 2008 |
| Zn | Phytoextraction | Marques et al., 2006 |
| As and U | Phytoextraction | Chen et al., 2006 |
| $^{137}Cs$ and $^{90}Sr$ | Phytoextraction | Entry et al., 1999 |
| Cu and Cd | Phytoextraction | Liao et al., 2003 |
| Zn, Cd and Pb | Phytoextraction | Vogel-Mikus et al., 2005 |

**Table 2.** MAR of organic pollutants in soils.

| Pollutant | Mechanism | Reference |
|---|---|---|
| Atrazine | Phytoextraction and Biodegradation | Huang et al., 2007 |
| DDT | Phytoextraction and Biodegradation | Wu et al., 2008 |
| *p, p'*- DDE | Phytoextraction | White et al., 2006 |
| Fluorene and Phenanthrene | Phytostabilization and Biodegradation | Gao et al., 2010 |
| Phenanthrene and Pyrene | Phytostabilization and Biodegradation | Gao et al., 2011 |
| Anthracene, Chrysene, Dibenz(a,h)anthracene | Biodegradation | Joner et al., 2001 |
| Anthracene, Phenanthrene, Fluoranthene, Chrysene, Benzo[a]anthracene, Benzo[k]fluoranthene, Dibenzo[a,h]anthracene, Benzo[g,h,i]perylene | Phytoextraction and Biodegradation | Binet et al., 2000 |

more of these metals than plants inoculated with *G. mosseae*, but this was not so for the *G. macrocarpus* plants which accumulated similar or higher amounts of metal compared to the control. Some other researchers have shown that heavy metals can inhibit mycorrhizal activities (Chao and Wang, 1990; Del Val et al., 1999). The above experiments indicate that MAR of soils polluted with heavy metals may be influenced by the concentration of the metal and the species of the mycorrhizal fungi used for remediation. Thus, when using MAR, appropriate fungi species should be selected. Determining the tolerable limits of the fungi species before they are used for MAR will also ensure that good results are produced. Addition of a layer of non-contaminated soil to the polluted soil before use of MAR may reduce the concentration of these pollutants and thus enhance MAR. Studies have shown that combining MAR with other methods of remediation such as addition of soil amendments like phosphate rock and organic materials enhances the remediation of soils polluted with heavy metals (Leung et al., 2010; Alguacil et al., 2011).

## REMEDIATION OF ORGANIC POLLUTANTS IN SOILS

The mechanisms involved in MAR of soils polluted with organic pollutants are similar to that of inorganic pollutants except that for most organic pollutants e.g. polycyclic aromatic hydrocarbons (PAHs), remediation is also accomplished through biodegradation (Binet et al., 2000; Gao et al., 2011) (Table 2). Mycorrhizal fungi favour the activities of some soil microorganisms (Harrier and Watson, 2004). Thus, the amount of pollutants remediated via MAR is increased due to activities of these microorganisms.

The rate of pollutant removal by MAR may be influenced by the structure of the organic pollutant. Pollutants with high molecular weight and hence low water solubility are degraded (or are taken up by plants) at a slower rate than those with lower molecular weight. This is evident in the work of Gao et al. (2010) where the remediation of fluorene and phenanthrene with AM were compared. The authors observed that due to the lower molecular weight of fluorene, its translocation by the fungal hyphae was greater than that of phenanthrene; thus fluorene was easily removed from the soil.

Soils polluted with organic pollutants can also be remediated through the other mechanisms of MAR – phytostabilization and phytoextraction (White et al., 2006; Gao et al., 2010). However, phytostabilization is mostly used on soils with low concentrations of pollutants. MAR of organic pollutants can be accomplished through the combination of two mechanisms (Table 2). Reductions in the rate of organic pollutant translocation from the root to the shoot of plants used in MAR have been recorded (Huang et al., 2007; Wu et al., 2008).

MAR does not always support the removal of organic pollutants from soil. Genney et al. (2004) and Joner et al. (2006) attributed this negative result to the mineral nutrient status of the polluted soil. They argued that the absence of nutrients (especially N and P) hinders the activities of the fungi and thus their ability to assist in remediation is adversely affected. Based on above finding, one may be tempted to add fertilizers in order to aid the remediation process. However, this should be done with caution as excess P hinders mycorrhizal fungi activities (Smith and Read, 2008). It is better to add organic materials since they release these nutrients at a slower rate than the mineral fertilizers. The above researchers (Genney et al., 2004; Joner et al., 2006) used ECM for the remediation of soils polluted with recalcitrant organic pollutants such as chrysene, anthracene and fluorene. Other researchers have used ECM for the remediation of soils polluted with easily biodegradable pollutants such as 3-chlorobenzoic acid and effective remediation was accomplished (Heinonsalo et al., 2000; Dittmann et al., 2002). Thus, this further accentuates the fact that the efficiency of MAR depends on the type of pollutant and the fungi species. AM fungi adapt in a wide variety of soils and have achieved the expected results in various remediation studies (Joner et al., 2001; Joner and Leyval., 2003; Huang et al., 2007). Therefore, various species of AM fungi could be employed for the remediation of soils polluted with organic pollutants to ensure effective clean-up of the polluted soils. Combining MAR with other remediation methods such as introduction of other microorganisms or surfactants that facilitate biodegradation would also aid in the removal of organic pollutants (Alarcón et al., 2008; Wu et al., 2008; Yu et al., 2011; Xiao et al., 2012).

## INTERACTION BETWEEN MYCORRHIZA AND OTHER SOIL ORGANISMS: EFFECTS ON SOIL REMEDIATION

Mycorrhizal fungi interact with some other beneficial soil organisms in order to achieve complete clean-up of polluted soils. These organisms include earthworms, and various species of bacteria and fungi (Table 3).

### Earthworms

Earthworms are important soil organisms that contribute to the maintenance of soil properties. They are known to survive in soils with high concentrations of heavy metals because they are able to accumulate these metals into their tissues (Morgan et al., 1989). They have the ability to increase metal availability in soil (Cheng and Wong, 2002) and thus, they have been used to improve the efficiency of phytoremediation (Ma et al., 2002).

Interaction between earthworm and mycorrhiza results in rapid remediation of heavy metal contaminated soils. Yu et al. (2005) reported a rapid colonization rate of rye grass by mycorrhizal fungi as a result of earthworm activities. This interaction significantly increased the amount of Cd removed from the soil. The authors linked this result to the production of phytohormones by earthworms which may have stimulated mycorrhizal infection. Earthworms also contribute to the effective dispersal of the fungi propagules through their feeding habits. Gange (1993) showed that earthworm casts contain more than ten times the number of infective mycorrhizal propagule in surrounding soils. On the other hand, earthworms may also contribute to the disconnection of mycorrhizal fungi from plant root as they feed and burrow through the soil (Ma et al., 2006). The combined effect of earthworm and mycorrhiza on soil remediation is complex; the mechanism involved in this relationship is not fully understood. However, Lebron et al. (1998) argue that the relationship depends on the plant species the fungi colonizes.

### Microorganisms

Most microorganisms used for the remediation of organic pollutants have the ability to biodegrade these pollutants; hence, when they are used together with mycorrhiza, remediation is faster and more efficient. Both the filamentous fungus, *Cunninghamella echinulata* and the bacterium, *Sphingomonas paucimobilis* have been used in conjunction with AM for the remediation of a soil polluted with petroleum hydrocarbon (Alarcón et al., 2008). The authors reported that the combined use of these microorganisms resulted in the highest amount of pollutant degradation compared to when the microorganisms were not used simultaneously. Another soil bacterium capable of remediating polluted soils is *Bacillus subtilis*. It does this by producing biosurfactants which are capable of enhancing biodegradation of organic pollutants (Cameotra and Bollag, 2003; Xiao et al., 2012). *Bacillus subtilis* also enhances mycorrhization of plant roots by increasing the growth of the fungi hyphae. Thus, when both microbes are used for remediation, greater amounts of the pollutant are removed at a faster rate than with ordinary MAR (Xiao et al., 2012).

*Acinetobacter* is known for its ability to biodegrade PAHs (Kanaly and Harayama, 2000). Miya and Firestone (2001) reported that biodegradation of PAH by *Acinetobacter* can be stimulated by root exudates. Therefore, since mycorrhizal fungi ensure the production of more root exudates - through extended root growth, combining both organisms would enhance the removal of PAH from polluted soils. Yu et al. (2011) reported that more PAH was removed from a polluted soil through the

**Table 3.** Soil remediation via interaction between mycorrhiza and other soil organisms.

| Organism | Pollutant | Mechanism | Reference |
|---|---|---|---|
| *Acinetobacter sp*. | Phenanthrene and Pyrene | Biodegradation and Phytoextraction | Yu et al., 2011 |
| *Bacillus subtilis* | Phenanthrene | Biodegradation and Phytoextraction | Xiao et al., 2012 |
| Earthworm | Cd | Phytoextraction | Yu et al., 2005 |
| Earthworm and *Rhizobium* | Pb/Zn mine tailings | Phytostabilization | Ma et al., 2006 |
| *Fusarium concolor* and *Trichoderma koningii* | Cd and Pb | Phytoextraction | Arriagada et al., 2004, 2005, 2007 |
| *Sphingomonas paucimobilis* and *Cunninghamella echinulata* | Crude oil | Biodegradation | Alarcón et al., 2008 |

combined use of *Acinetobacter* and mycorrhiza.

A number of saprobes have the ability to biodegrade soil pollutants; thus they have been used in several remediation studies (Wainwright, 1992; Arriagada et al., 2004; Madrid et al., 2005). *Fusarium* sp. and *Trichoderma* sp. are two saprobes that have been used in conjunction with MAR for the remediation of soils polluted with heavy metals (Arriagada et al., 2004, 2005, 2007). These studies show that the combined effect of these fungi in MAR resulted in the removal of larger amounts of pollutants compared to when they were not combined. The interaction between these fungi species is not well understood. However, the amount of pollutant removed depends on the species of saprobe and mycorrhizal fungi used for remediation (Arriagada et al., 2007).

Due to the extensive root system of leguminous plants, they have been used in many phytoremediation studies (Palmroth et al., 2002; Smith et al., 2006). Therefore, *Rhizobium*, the nitrogen fixing bacterium in the root nodules of legumes can be found in most soils remediated with legumes. *Rhizobium* improves the growth of mycelia in mycorrhizal fungi, while the fungi supplies phosphorus that aids nitrogen fixation (Ma et al., 2006). Therefore, this symbiotic association between these organisms indirectly enhances the remediation of polluted soils.

## Advantages of MAR

1. MAR enhances the vegetation/revegetation of a soil after clean-up. This is basically because of the other benefits (that is, increased nutrient and water uptake, disease resistance and soil stabilization) derived from mycorrhizal fungi.
2. It is achieved through a natural process and thus is perceived to be environmentally friendly.
3. Remediation is carried out *in situ*, thus eliminating the risks involved in transporting polluted soils to other locations for treatment.
4. It is used for the remediation of a wide range of pollutants (both organic and inorganic).
5. It achieves complete soil remediation, since the fungal spores can remain in the soil for a long time. Thus, they colonize any introduced plant and continue the remediation process.
6. It is assumed to be relatively cheaper and easier to accomplish compared to other methods of soil remediation (such as chemical and thermal remediation), since it does not require sophisticated technologies.
7. It can be safely combined with other remediation techniques to achieve the desired results. For instance, MAR can be combined with chemical remediation whereby the chemicals are used to achieve faster remediation while MAR helps to restore the soil properties for better crop establishment.

## Disadvantages of MAR

1. It is a relatively slow method of remediation. It may take months for complete soil remediation to be accomplished.
2. Some species of mycorrhizal fungi are pollutant-specific. Thus, the wrong species may be used for a particular pollutant and the desired results may not be obtained.
3. Its efficiency depends on the type of plant used. Some plants do not form mycorrhizal association; hence, remediation may not be accomplished when these plants are used.

## RESEARCH NEEDS

1. MAR has been used to remove several soil pollutants. However, in few other cases, effective soil remediation was not achieved (Joner et al., 2006). The reason for these negative results is not well understood. It has been attributed to the nutrient status of the soil. However, more research is needed in order to arrive at a definite conclusion so as to enhance the efficiency of MAR.
2. Most MAR have focused on the use of AM fungi. Some other researchers who used ECM did not achieve the expected result (Joner et al., 2006). More research is therefore needed in order to discover other species of ECM fungi that can be used for soil remediation because

this group of fungi colonize tree species that control erosion; thus, they indirectly reduce further soil degradation.

3. MAR has been improved by interactions between the fungi and other soil organisms. There are millions of other soil organisms whose interaction with mycorrhizal fungi has not been explored. There is need to focus research in this area so that MAR would be achieved at a faster rate.

4. Studies on the use of MAR for the treatment of soils polluted with both organic and inorganic pollutants are rare in literature. Therefore, both laboratory and field trials should be conducted to ascertain the efficiency of MAR for this type of soil pollution. Incorporating various species of mycorrhizal fungi may be one way of achieving this.

## CONCLUSION

The benefits derived from mycorrhizal fungi make MAR a suitable method for the clean-up of soils whose intended use is crop production. MAR effectively detoxifies both organic and inorganic pollutants. However, the efficiency of this method of remediation depends on the species and origin of the fungi used, the type of plant colonized, and the type and concentration of the pollutants. Combining MAR with other methods of remediation help improve its efficiency. However, more research is needed in order to harness the benefits of this method of soil remediation.

### REFERENCES


Alarcón A, Davies FT Jr, Autenrieth RL, Zuberer DA (2008). Arbuscular mycorrhiza and petroleum-degrading microorganisms enhance phytoremediation of petroleum-contaminated soil. Int. J. Phytoremed. 10:251-263.

Alguacil MM, Torrecillas E, Caravaca F, Fernandez DA, Azcon R, Roldan A (2011). The application of an organic amendment modifies the arbuscular mycorrhizal fungal communities colonizing native seedlings grown in a heavy-metal-polluted soil. Soil Biol. Biochem. 43:1498-1508.

Aprill W, Sims RC (1990). Evaluation of the use of prairie grass for stimulating polycyclic aromatic hydrocarbon treatment in soil. Chemosphere 20:253-265.

Arriagada CA, Herrera MA, Garcia-Romera I, Ocampo JA (2004). Tolerance to Cd of soybean (*Glycine max*) and eucalyptus (*Eucalyptus globulus*) inoculated with arbuscular mycorrhizal and saprobe fungi. Symbiosis 36:285-299.

Arriagada CA, Herrera MA, Ocampo JA (2005). Contribution of arbuscular mycorrhizal and saprobe fungi to the tolerance of *Eucalyptus globules* to Pb. Water Air Soil Pollut. 166:31-47.

Arriagada CA, Herrera MA, Ocampo JA (2007). Beneficial effect of saprobe and arbuscular mycorrhizal fungi on growth of *Eucalyptus globules* co-cultured with *Glycine max* in soil contaminated with heavy metals. J. Environ. Manage. 84:93-99.

Bååth E (1989). Effects of heavy metals in soil on microbial processes and populations: A review. Water Air Soil Pollut. 47:335-379.

Baker RS, Heron G (2004). *In-situ* delivery of heat by thermal conduction and steam injection for improved DNAPL remediation. Proceedings of the 4th International Conference on Remediation of Chlorinated and Recalcitrant Compound, Monterey, CA, May 24-27, 2004. Battelle, Columbus, OH.

Bani A, Echevarria G, Sulçe S, Morel JL, Mullai A (2007). In-situ phytoextraction of Ni by a native population of *Alyssum murale* on an Ultramafic site (Albania). Plant Soil 293(1):79–89.

Bellandi R (1995). Innovative Engineering Technologies for Hazardous Waste Remediation. New York: Van Nostrand Reinhold.

Bento FM, Camargo FAO, Okeke BC, Frankenberger WT (2005). Comparative bioremediation of soils contaminated with diesel oil by natural attenuation, biostimulation and bioaugmentation. Bioresour. Technol. 96:1049-1055.

Binet P, Portal JM, Leyval C (2000). Fate of polycyclic aromatic hydrocarbons (PAH) in the rhizosphere and mycorrhizosphere of ryegrass. Plant Soil 227:207-213.

Cameotra SS, Bollag, JM (2003). Biosurfactant-enhanced bioremediation of polycyclic aromatic hydrocarbons. Crit. Rev. Environ. Sci. Technol. 33:111-126.

Cardoso IM, Kuyper TW (2006). Mycorrhizas and tropical soil fertility. Agric. Ecosyst. Environ. 116:72-84.

Chaineau CH, Morel JL, Oudot J (2000). Biodegradation of fuel oil hydrocarbons in the rhizosphere of maize. J. Environ. Qual. 29:569-578.

Chao CC, Wang YP (1990). Effects of heavy-metals on the infection of vesicular–arbuscular mycorrhizae and the growth of maize. J. Agric. Assoc. China 152:34-45.

Chen BD, Zhu Y-G, Smith FA (2006). Effects of arbuscular mycorrhizal inoculation on uranium and arsenic accumulation by Chinese brake fern (*Pteris vittata* L.) from a uranium mining impacted soil. Chemosphere 62:1464-1473.

Chen BD, Zhu Y-G, Duan J, Xiao XY, Smith SE (2007). Effects of the arbuscular mycorrhizal fungus *Glomus mosseae* on growth and metal uptake of four plant species in copper mine tailings. Environ. Pollut. 147:374-380.

Chen B, Roos P, Zhu Y-G, Jakobsen I (2008). Arbuscular mycorrhizas contribute to phytostabilization of uranium in uranium mining tailings. J. Environ. Radioactiv. 99:801-810.

Chen X, Wu C, Tang J, Hu, S (2005). Arbuscular mycorrhizae enhance metal lead uptake and growth of host plants under a sand culture experiment. Chemosphere 60:665-671.

Cheng JM, Wong MH (2002). Effects of earthworms on Zn fractionation in soils. Biol. Fertil. Soils 36:72-78.

Collins CD, Lothian D, Schifano V (2009). Remediation of soils contaminated with petrol and diesel using lime. Land Contam. Reclam. 17(2):237-244.

Del Val C, Barea JM, Azcon-Aguilar C (1999). Diversity of arbuscular mycorrhizal fungus populations in heavy-metal-contaminated soils. Appl. Environ. Microbiol. 65(2):718-723.

Diaz G, Azcon-Aguilar C, Honrubia M (1996). Influence of arbuscular mycorrhizae on heavy metal (Zn and Pb) uptake and growth of *Lygeum spartum* and *Anthyllis cytisoides*. Plant Soil 180:241-249.

Dittmann J, Heyser W, Bucking H (2002). Biodegradation of aromatic compounds by white rot and ectomycorrhizal fungal species and the accumulation of chlorinated benzoic acid in ectomycorrhizal pine seedlings. Chemosphere 49:297-306.

Dong Y, Zhu YG, Smith FA, Wang Y, Chen B (2008). Arbuscular mycorrhiza enhanced arsenic resistance of both white clover (*Trifolium repens* Linn.) and ryegrass (*Lolium perenne* L.) plants in an arsenic-contaminated soil. Environ. Pollut. 155:174-181.

Ebbs SD, Lasat MM, Brady DJ, Cornish J, Gordon R, Kochian LV (1997). Phytoextraction of cadmium and zinc from contaminated soil. J. Environ. Qual. 26(5):1424-1430.

Entry JA, Watrud LS, Reeves M (1999). Accumulation of $^{137}Cs$ and $^{90}Sr$ from contaminated soil by three grass species inoculated with mycorrhizal fungi. Environ. Pollut. 104:449-457.

Ferrarese E, Andreottola G, Oprea IA (2008). Remediation of PAH-contaminated sediments by chemical oxidation. J. Hazard. Mater. 152:128-139.

Fliessbach A, Martens R, Reber HH (1994). Soil microbial biomass and microbial activity in soils treated with heavy metal contaminated sewage sludge. Soil Biol. Biochem. 26:1201-1205.

Gan S, Lau EV, Ng HK (2009). Remediation of soils contaminated with polycyclic aromatic hydrocarbons (PAHs). J. Hazard. Mater. 172:532-549.

Gange A (1993). Translocation of mycorrhizal fungi by earthworms during early succession. Soil Biol. Biochem. 25:1021-1026.
Gao Y, Cheng Z, Ling W, Huang J (2010). Arbuscular mycorrhizal fungal hyphae contribute to the uptake of polycyclic aromatic hydrocarbons by plant roots. Bioresour. Technol. 101:6895-6901.
Gao Y, Li Q, Ling W, Zhu X (2011). Arbuscular mycorrhizal phytoremediation of soils contaminated with phenanthrene and pyrene. J. Hazard. Mater. 185:703-709.
Genney DR, Alexander IJ, Killham K, Meharg AA (2004). Degradation of the polycyclic aromatic hydrocarbon (PAH) fluorene is retarded in a Scots pine ectomycorrhizosphere. New Phytol. 163:641-649.
Giller KE, Witter E, McGrath SP (1998). Toxicity of heavy metals to microorganisms and microbial processes in agricultural soils: A review. Soil Biol. Biochem. 30:1389-1414.
Gong Z, Alef K, Wilke B-M, Li P (2005). Dissolution and removal of PAHs from a contaminated soil using sunflower oil. Chemosphere 58:291-298.
Harrier LA, Watson CA (2004). The potential role of arbuscular mycorrhizal (AM) fungi in the bioprotection of plants against soil-borne pathogens in organic and/or other sustainable farming systems. Pest Manage. Sci. 60:149-157.
Heinonsalo J, Jorgensen KS, Haahtela K, Sen R (2000). Effects of *Pinus sylvestris* root growth and mycorrhizosphere development on bacterial carbon source utilization and hydrocarbon oxidation in forest and petroleum-contaminated soils. Can. J. Microbiol. 46:451-464.
Huang H, Zhang S, Shan X, Chen B-D, Zhu Y-G, Bell, JNB (2007). Effect of arbuscular mycorrhizal fungus (*Glomus caledonium*) on the accumulation and metabolism of atrazine in maize (*Zea mays* L.) and atrazine dissipation in soil. Environ. Pollut. 146:452-457.
Janouskova M, Pavlikova D, Vosatka M (2006). Potential contribution of arbuscular mycorrhiza to cadmium immobilization in soil. Chemosphere 65:1959-1965.
Joner EJ, Leyval C (1997). Uptake of $^{109}$Cd by roots and hyphae of a *Glomus mosseae*/*Trifolium subterraneum* mycorrhiza from soil amended with high and low concentrations of cadmium. New Phytol. 135:353-360.
Joner EJ, Leyval C (2003). Rhizosphere gradients of polycyclic aromatic hydrocarbon (PAH) dissipation in two industrial soils, and the impact of arbuscular mycorrhiza. Environ. Sci. Technol. 37:2371-2375.
Joner EJ, Johnsen A, Loibner AP, Szolar OHJ, Portal JM, Leyval C (2001). Rhizosphere effects on microbial community structure and dissipation and toxicity of polycyclic aromatic hydrocarbons (PAHs) in spiked soil. Environ. Sci. Technol. 35:2773-2777.
Joner EJ, Leyval C, Colpaert JV (2006). Ectomycorrhizas impede phytoremediation of polycyclic aromatic hydrocarbons (PAHs) both within and beyond the rhizosphere. Environ. Pollut. 142:34-38.
Kanaly RA, Harayama S (2000). Biodegradation of high-molecular-weight polycyclic aromatic hydrocarbons by bacteria. J. Bacteriol. 182:2059-2067.
Lebron L, Zou XM, Lodge DJ (1998). Disturbance VA mycorrhizae by earthworm in a pasture and a forest in Puerto Rico. Second International Conference on Mycorrhiza, Uppsala, Sweden, 5–10 July 1998.
Leung HM, Wu FY, Cheung KC, Ye ZH, Wong MH (2010). Synergistic effects of arbuscular mycorrhizal fungi and phosphate rock on heavy metal uptake and accumulation by an arsenic hyperaccumulator. J. Hazard. Mater. 181:497-507.
Li J-L, Chen B-H (2002). Solubilization of model polycyclic aromatic hydrocarbons by non-ionic surfactants. Chem. Eng. Sci. 57:2825-2835.
Li X, Li P, Lin X, Zhang C, Li Q, Gong Z (2008). Biodegradation of aged polycyclic aromatic hydrocarbons (PAHs) by microbial consortia in soil and slurry phases. J. Hazard. Mater. 150:21-26.
Liao JP, Lin XG, Cao ZH, Shi YQ, Wong MH (2003). Interactions between arbuscular mycorrhizae and heavy metals under sand culture experiment. Chemosphere 50:847-853.
Ma Y, Dickinson NM, Wong MH (2002). Toxicity of Pb/Zn mine tailings to the earthworm *Pheretima* and the effects of burrowing on metal availability. Biol. Fertil. Soils 36:79-86.
Ma Y, Dickinson NM, Wong MH (2006). Beneficial effects of earthworms and arbuscular mycorrhizal fungi on establishment of leguminous tress on Pb/Zn mine tailings. Soil Biol. Biochem. 38:1403-1412.
Madrid F, De La Rubia T, Martinez J (2005). Effect of Phanerochaete flavido-alba on aromatic acids in olive oil mill waste waters. Technol. Environ. Chem. 51:161-168.
Marques APGC, Oliveira RS, Rangel, AOSS, Castro PML (2006). Zinc accumulation in *Solanum nigrum* is enhanced by different arbuscular mycorrhizal fungi. Chemosphere 65:1256-1263.
Marschner H (1995). Mineral Nutrition of Higher Plants (2nd Ed.). Academic Press, London.
Masten SJ, Davies SHR (1997). Efficacy of in-situ ozonation for the remediation of PAH contaminated soils. J. Contam. Hydrol. 28:327-335.
McCutcheon SC, Schnoor JL (2003). Phytoremediation: Transformation and Control of Contaminants. New Jersey: Wiley-Interscience Inc.
McGill WB, Rowell MJ, Westlake DWS (1981). Biochemistry, ecology, and microbiology of petroleum components in soil. In Paul EA, Ladd JN (eds) Soil Biochemistry (Vol. 3), New York: Marcel Dekker, pp. 229-296.
Miya RK, Firestone MK (2001). Phenanthrene biodegradation in soil by slender oat root exudates and root debris. J. Environ. Qual. 30(6):1911-1918.
Morgan JE, Norey CG, Morgan AJ, Kay J (1989). A comparison of the cadmium-binding proteins isolated from the posterior alimentary canal of the earthworms *Dendrodrilus rubidus* and *Lumbricus rubellus*. Comparative Biochem. Physiol. 92C:15-21.
Nguyen NH, Hynson NA, Bruns TD (2012). Stayin' alive: survival of mycorrhizal fungal propagules from 6-yr-old forest soil. Fungal Ecology [Online]. Available from: http://dx.doi.org/10.1016/j.funeco.2012.05.006. [Accessed 13/12/2012].
Orłowska E, Godzik B, Turnau K (2012). Effect of different arbuscular mycorrhizal fungal isolates on growth and arsenic accumulation in *Plantago lanceolata* L. Environ. Pollut. 168:121-130.
Palmroth MRT, Pichtel J, Puhakka JA (2002). Phytoremediation of subarctic soil contaminated with diesel fuel. Bioresour. Technol. 84:221-228.
Roach N, Reddy KR, Al-Hamdan AZ (2009). Particle morphology and mineral structure of heavy metal-contaminated kaolin soil before and after electrokinetic remediation. J. Hazard. Mater. 165:548-557.
Robertson SJ, McGill WB, Massicotte HB, Rutherford PM (2007). Petroleum hydrocarbon contamination in boreal forest soils: A mycorrhizal ecosystems perspective. Biol. Rev. 82:213-240.
Rufyikiri G, Huysmans L, Wannijn J, Hees MV, Leyval C, Jakobsen I (2004). Arbuscular mycorrhizal fungi can decrease the uptake of uranium by subterranean clover grown at high levels of uranium in soil. Environ. Pollut. 130:427-436.
Salunkhe PB, Dhakephalkar PK, Paknikar KM (1998). Bioremediation of hexavalent Cr in soil microcosms. Biotechnol. Lett. 20(8):749-751.
Smith DL, Hayward WM (1993). Decommissioning of a resource conservation and recovery act treatment, storage, and disposal facility: A case study of the interim stabilization of the 216-A-29 ditch at the Hanford site. Waste Manage. 13:109-116.
Smith MJ, Flowers TH, Duncan HJ, Alder J (2006). Effects of polycyclic aromatic hydrocarbons on germination and subsequent growth of grasses and legumes in freshly contaminated soil and soil with aged PAHs residues. Environ. Pollut. 141:519-525.
Smith SE, Read DJ (2008). Mycorrhizal Symbiosis (3$^{rd}$ Ed.). Academic Press, New York.
Tiquia SM, Lloyd J, Herms DA, Hoitink HAJ, Michel FC Jr (2002). Effects of mulching and fertilization on soil nutrients, microbial activity and rhizosphere bacterial community structure determined by analysis of TRFLPs of PCR-amplified 16S rRNA genes. Appl. Soil Ecol. 21:31-48.
Trofimov SY, Rozanova MS (2003). Transformation of soil properties under the impact of oil pollution. Euras. Soil Sci. 36:S82-S87.
Trotta A, Falaschi P, Cornara L, Minganti V, Fusconi A, Drava G, Berta G (2006). Arbuscular mycorrhizae increase the arsenic translocation factor in the As hyperaccumulating fern *Pteris vittata* L. Chemosphere 65:74-81.
Turnau K (1998). Heavy metal content and localization in mycorrhizal *Euphorbia cyparissias* from zinc wastes in southern Poland. Acta Societatis Botanicorum Poloniae 67(1):105-113.
Venäläinen SH (2011). Apatite ore mine tailings as an amendment for

remediation of a lead contaminated shooting range soil. Sci. Total Environ. 409:4628-4634.

Viglianti C, Hanna K, Brauer C, Germain P (2006). Removal of polycyclic aromatic hydrocarbons from aged-contaminated soil using cyclodextrins: Experimental study. Environ. Pollut. 140:427-435.

Vogel-Mikus K, Drobne D, Regvar M (2005). Zn, Cd and Pb accumulation and arbuscular mycorrhizal colonisation of pennycress *Thlaspi praecox* Wulf (Brassicaceae) from the vicinity of a lead mine and smelter in Slovenia. Environ. Pollut. 133:233-242.

Wainwright M (1992). The impact of fungi on environmental biogeochemistry. In Carrol GC, Wicklow DT (eds) The Fungal Community, Marcel Dekker, New York pp. 601-618.

Wang FY, Lin XG, Yin R (2007). Inoculation with arbuscular mycorrhizal fungus *Acaulospora mellea* decreases Cu phytoextraction by maize from Cu-contaminated soil. Pedobiologia 51:99-109.

Wang J-Y, Huang X-J, Kao JCM, Stabnikova O (2007). Simultaneous removal of organic contaminants and heavy metals from kaolin using an upward electrokinetic soil remediation process. J. Hazard. Mater. 144:292-299.

White JC, Ross DDW, Gent MPN, Eitzer BD, Mattina MI (2006). Effect of mycorrhizal fungi on the phytoextraction of weathered *p*, *p*-DDE by *Cucurbita pepo*. J.Hazard. Mater. B137:1750-1757.

Wright SF, Green VS, Cavigelli MA (2007). Glomalin in aggregate size classes from three different farming systems. Soil Till. Res. 94(2):546-549.

Wu N, Zhang S, Huang H, Shan X, Christie P, Wang Y (2008). DDT uptake by arbuscular mycorrhizal alfalfa and depletion in soil as influenced by soil application of a non-ionic surfactant. Environ. Pollut. 151:569-575.

Xiao X, Chen H, Si C, Wu L (2012). Influence of biosurfactant-producing strain *Bacillus subtilis* BS 1 on the mycoremediation of soils contaminated with phenanthrene. Int. Biodeter. Biodegrad. 75:36-42.

Xu JG, Johnson RL (1997). Nitrogen dynamics in soils with different hydrocarbon contents planted to barley and field pea. Can. J. Soil Sci. 77:453-458.

Yu X, Cheng J, Wong MH (2005). Earthworm-mycorrhiza interaction on Cd uptake and growth of ryegrass. Soil Biol. Biochem. 37:195-201.

Yu XZ, Wu SC, Wu FY, Wong MH (2011). Enhanced dissipation of PAHs from soil using mycorrhizal ryegrass and PAH-degrading bacteria. J. Hazard. Mater. 186:1206-1217.