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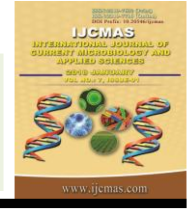

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Phytoremediation and Carbon Sequestration Potential of Agroforestry Systems: A Review

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A B S T R A C T

Agroforestry constitute major chunk of share in replenishing atmosphere, sequestering carbon, and remediating contaminated soils. Phytoremediation is emerging as an alternative agriculture-based technology because word remediation of metal polluted sites can be brought about utilizing the plants to uptake and store contaminants in them. Conventional procedures for cleaning up heavy-metal- contaminated sites (*i.e.* excavation, dredging, and chemical leaching) are all expensive and destructive for the natural environment. An alternative to these physical remediation methods is the use of plants to remove pollutants from soil and water through their root systems, an approach known as phytoremediation. Once extracted, plants may sequester the pollutants in their tissues and/or convert them to less toxic forms. Agroforestry systems are a better climate change mitigation alternatives than oceanic, and other terrestrial options because of the secondary environmental benefits such as helping to attain food security and secure land tenure in developing countries, increasing farm income, restoring and maintaining above-ground and below-ground biodiversity, corridors between protected forests, as CH_4 sinks, soil conservation and. maintaining watershed hydrology.

Introduction

Contaminants of concern are both inorganic and organic compounds (heavy metals, radionuclides, nitrate, phosphate, inorganic acids, and organic chemicals) from sources including waste materials, explosives, pesticides, fertilizers, pharmaceuticals, acidic deposition, and radioactive fallout. Soil, surface water, and groundwater may become contaminated with hazardous compounds as a consequence of natural activities (e.g., geologic erosion and saline seeps) and human activities (e.g., industry, agriculture, wastewater treatment, construction, and mining). Pollutants may be traced to a particular source, point source, or result from a large area, nonpoint source. Both in situ and ex situ remediation methods have been employed to remove contamination, most relying on physical and chemical processes. In situ methods include volatilization via air venting, leaching with a surfactant, vitrification (contaminants are solidified with an electric current) and isolation and containment with physical barriers (Sparks, 1995). Ex situ methods include excavation followed by thermal treatment, chemical extraction, and/or solidification (encapsulation) prior to disposal in a landfill. Phytoremediation, the use of plants to bioremediate contaminated soil, water, and air, has emerged as a more cost effective, noninvasive, and publicly acceptable way to address the removal of environmental contaminants (Boyajian, 1997). An overview of phytoremediation, including phytofiltration and rhizofiltration, phytoextraction, phyto immobilization, phytostabilization and phytodegradation, and rhizodegradation, is presented in this review. Biotechnological advances in phytoremediation are also discussed. These modern tools provide insight into processes important to phytoremediation and allow for the optimization of phytoremediation, improving its commercial viability.

Rhizofiltration and phytofiltration

Phytofiltration or rhizofiltration is the use of plants to remove contaminants from water. The plant can take up contaminants into the biomass, thus removing the pollutant. Rhizofiltration is a form of phytoremediation, which refers to the approach of using hydroponically cultivated plant roots to remediate contaminated water through absorption, concentration, and precipitation of pollutants (Raskin and Kumar, 1994). Pilon-Smits *et al.,* (1999) identified several species, including parrot's feather (*Myriophyllum brasiliense*), iris-leaved rush (*Juncus xiphioides*), cattail (*Typhalati folia*), saltmarsh bulrush, and Scirpusrobustus, that showed great potential for Se phytoremediation in wetlands. De Souza *et al.*, (1999) determined that bacteria in the rhizosphere of Indian mustard (Brassica juncea) were necessary to achieve the best rates of plant Se accumulation and volatilization of selenate. A novel phytofiltration technology has been proposed by Sekhar *et al.*, (2004), which could be used to remove and recover lead (Pb) from wastewaters. This technology uses plant based biomaterial from the bark of the plant commonly called Indian sarsaparilla (Hemidesmusindicus). The target of their research was polluted surface water and groundwater at industrially contaminated sites. Rhizofiltration of lead-contaminated water has also been investigated by Schulman, Salt, and Raskin (1999).

Phytostabilization and Phytoimmobilization

Phytostabilization results in the elimination of the availability of toxic metals in soil through complexing with metals by certain plants (Gwozdz and Kopyra, 2003). This process does not remove the contaminant from the soil, but it does reduce the inherent hazard of the contaminant (Li *et al.,* 2000). Phytoimmobilization is a remediation technology in which plants are used to remove contaminants from soil through plant uptake and subsequently the contaminants are released from decomposing plant materials and are then immobilized in either a mineral-amended soil or a geomat (mineral-containing mat). This strategy is being evaluated at the Savannah River Site in Aiken, S.C., by researchers who are investigating indigenous plants that have the natural ability to accumulate high concentrations of contaminants (Knox *et al.,* 2001).

Hyperaccumulation and phytoextraction

Phytoextraction, the ability of plants to take up inorganic (primarily metal) contaminants from soil is becoming a more widely-used remediation technology (McCutcheon and Schnoor, 2003). The most common route of chemical uptake into plants is through the root via an aqueous phase. Ions and organic molecules move to roots from soil and sediment through plant transpiration (ion transport from the soil water into the root occurs simultaneously with water transport), diffusive transport, and microbial facilitated transport (Committee on Bioavailability of Contaminants in Soils and Sediments, 2003). The plasma membrane serves as a barrier to uptake; chemicals need to cross the plasma membrane into the cytoplasm of the root cells. Different mechanisms have been identified which control chemical uptake by plants. Some chemicals can enter root tissue by altering pH through efflux of hydrogen (H+) ions, resulting in an electrochemical gradient that facilitates transport of cations and anions. This mechanism is termed a proton pump and requires cellular energy in the form of adenosine triphosphate (ATP). Most divalent cations are absorbed through ion channels. Ion channels can also mediate uptake and release potassium ions (K+). There is also evidence for carrier-mediated active transport of K+, SO_2− 4, NO− 3, and Mg^{2+} that uses ATP as an energy source (Marschner, 1995). For metals, another possible mechanism of uptake is transport of metal-chelate complexes. Whenever there is a metal deficiency, plants produce and release chelating agents into the rhizosphere. The complexed metal form is then transported into the plant through a transport protein specific for that metal (Kochian, 1993; Von Wiren, Marschner, and Romheld, 1996).

Phytodegradation and rhizodegradation

Degradation of a compound refers to its breakdown into smaller constituents, or its transformation to a metabolite. It is important to identify, quantify, and understand the significance of metabolites formed during remediation because of their potential unknown toxicities and availabilities to biota. Rhizodegradation, or transformation of the contaminant in the rhizosphere, can occur in soil organisms such as fungi or bacteria, or via enzyme exuded from microorganisms or plants.

Phytodegradation

Methods for studying phytodegradation can involve growing plants in soils, nutrient media in hydroponic systems, or utilization of tissue preparations (Bhadra *et al.,* 2001). In a hydroponic system, the solution is treated with a known concentration of the contaminant in question, and plant uptake, metabolism, and exudation are studied.

Rhizodegradation

The rhizosphere, with myriad species of microorganisms from many taxa, is a perfect example of biodiversity. While any individual species is usually capable of producing one or more enzymes that can carry out a biotransformation reaction, a consortium of microbes in the root zone of a plant can carry out many and varied types of enzymatic transformations (Anderson, Guthrie, and Walton, 1993).

Degradation is influenced by variable factors

Phytodegradation and rhizodegradation proceed via enzymatic activity; there are numerous other variables that influence the process, including soil temperature, moisture, pH, organic matter content, and aeration, all of which can affect the proliferation of microorganisms in the soil, which in turn will affect biodegradation. There are also factors from the biological perspective that can modify the contaminant and it degradates in a phytoremediation setting. It is crucial to understand the physical, chemical, and biological processes, as well as interactions between them, before we can optimize conditions for phytoremediation or have confidence in making predictions about the potential extent or rate of cleanup from a phytoremediation approach to a given soil-contamination situation.

Transformation pathways

Transformation of contaminants can occur through a variety of pathways. In this case, we will discuss the metabolism and cometabolism of pesticides, as example compounds. Plants and soil microorganisms, including bacteria and fungi, contain many similar enzymes for detoxification or transformation of xenobiotics. One major difference between microorganisms and higher plants is that microbes are much more likely to mineralize a contaminant (Hoagland *et al.*, 2001) or use it as a nitrogen source (Assaf and Turco, 1994).

Improving phytoremediation with biotechnology

Transfer of metabolic functions from microorganisms to plants

Exploitation of the inherent detoxification mechanisms of plants

Transfer of metabolic functions from mammals to plants

Carbon sequestration potential in agroforestry systems

Management of trees in agro-ecosystems such as agroforestry, ethno forests, and trees outside forests can mitigate greenhouse gas (GHG) emissions under the Kyoto Protocol. Agroforestry systems are a better climate change mitigation option than oceanic, and other terrestrial options because of the secondary environmental benefits such as helping to attain food security and secure land tenure in developing countries, increasing farm income, restoring and maintaining above-ground and below-ground biodiversity, corridors between protected forests, as CH_4 sinks, maintaining watershed hydrology, and soil conservation. Agroforestry also mitigates the demand for wood and reduces pressure on natural forests. Promoting woodcarving industry facilitates long-term locking-up of carbon in carved wood and new sequestration through intensified tree growing. By making use of local knowledge, equity, livelihood security, trade and industry, can be supported. There is need to support development of suitable policies, assisted by robust country-wide scientific studies aimed at better understanding the potential of agroforestry and ethno forestry for climate change mitigation and human well-being.. It has the ability to enhance the resilience of the system for coping with the adverse impacts of climate change. Agroforestry systems offer important opportunities of creating synergies between both adaptation and mitigation actions. Various authors have carried out studies to estimate carbon stocks in different agroforestry systems in India. Agroforestry systems have the potential to provide significant mitigation options but they require proper management that influences the amount of carbon sequestered. The role of agroforestry practices in climate change mitigation in India can be realized to its full potential by overcoming various technical, financial and institutional barriers. Agroforestry, the practice of introducing trees in farming has played a significant role in enhancing land productivity and improving livelihoods in both developed and developing countries. Although carbon sequestration through afforestation and reforestation of degraded natural forests has long been considered useful in climate change mitigation, agroforestry offers some distinct advantages. The planting of trees along with crops improves soil fertility, controls and prevents soil erosion, controls water logging, checks acidification and eutrophication of streams and rivers, increases local biodiversity, decreases pressure on natural forests for fuel and provides fodder for livestock.

Table.1 Detailed information about different tree species

Potential	Cultivation	Suitable for	Contamination	Productivity	Remediation potential	Uses
Species	**method**	**production in**	**constraints**			
		Renfrewshire				
Willow	Short	Yes – known to	Can grow on	Fast growing (can	Ecosystem restoration,	Biomass –
(Salix spp.)	rotation	grow in Scotland.	contaminated soils;	sequester more	phytoremediation	fuel and fibre
	coppicing –	Flood resistant	resistant to Cd, Cu,	carbon than	(phytoextraction,	
	rotation 3-5		Zn, Ni, Pb, Fe.	softwoods in a	phytodegradation, rhizofiltration	
	years		Cultivars/	growing season);	phytostabilisation), reduction in	
			genotypes vary in	easily propagated.	water/ wind erosion. High	
			resistance	Yield 7-12 oven-dried	accumulator of metals, e.g. Cd	
					and Zn. Can remediate many	
					organic compounds, e.g. oil	
Poplar	Short	Yes – known to	Can grow on	Yield very site-	Hyper accumulator of metals,	Biomass –
(Populus	rotation	grow in Scotland	contaminated soils	dependent and can	e.g. Cd and Zn,	fuel and fibre
spp.)	coppicing –			out-perform willow on	(phytoaccumulation) and	
	rotation 4-5			some sites	promotes phytostabilisation in	
	years				rhizosphere	
Elephant	Short	Grows well in	Unknown -more	Higher yields on	May reduce nutrient loss from	Biomass
Grass	rotation	England; not	research required	moisture retentive	soils by uptake and storage in	
(Miscanthu	cropping –	known in Scotland.		soils which warm up	rhizomes, decreasing pollution	
s	annual	Wide range of soil		quickly in spring.	of water environment (not	
giganteus)	harvesting	types		Yield 12-15 oven	usually applicable to brownfield	
	of grass			dried tonnes /ha (15-	sites); reduction in soil erosion.	
				18t fresh/ha)		

Potential	Cultivation	Suitable for	Contamination	Productivity	Remediation potential	Uses
Species	**method**	**production in**	**constraints**			
		Renfrewshire				
Aspen	Short	Yes – known to	American (Populus	Fast growing; easily	High accumulator of metals, e.g.	Biomass,
(Populus	rotation	grow in Scotland.	tremula) and	propagated Yield –	Cd and Zn, (phytoaccumulation)	Timber
tremula)	forestry -	Only native poplar	European (Populus	mean annual	and promotes phytostabilisation	(though little
	tree	grows under range	tremuloides)	increment 4-12m^3/ha/	in rhizosphere	production in
		of climatic	known to grow on	yr (same as		Scotland);
		conditions (stunted	contaminated soils,	sycamore/ ash/ birch)		higher wood
		when stressed)	and shale quarries,			density than
			coal spoil, low pH,			poplar
			heavy metals,			
			PAHs.			
Birch	Short	Yes – known to	Can grow on	Fast growing Yield –	Uptake of Ca, Cu and Mn	potential
(Betula)	rotation	grow in Scotland.	contaminated soils	mean annual	reported	veneer,
	forestry (8-	Pioneer species,		increment 4-12m^3/ha/		plywood,
	20 years	rapidly colonise		yr (same as		biomass/
	rotation)	open ground		sycamore/ ash/		landscaping ?
		following		poplar)		
		disturbance				
Hazel	Woodland,	Yes – grows in	Can grow on	Fast growing (similar	Unknown	Nut
(Corylus	orchard,	Scotland.	contaminated soils	to birch)		production;
avellana)	tree belts					amenity value,
						biodiversity,
						potential
						biomass?
Oak	Woodland,	Yes – grows in	Can grow on	Slow growing	Unknown	Amenity
(Quercus)	tree belts,	Scotland.	contaminated soils			value,
	long-term					biodiversity
	forestry					(lesser extent
						timber
						production)

Transformation Pathways

No.	Process	Mechanism	Contaminant
1	Phytoextraction	Hyper-accumulation	Inorganics
2	Phytovolatilization	Volatilization by leaves	Organics/Inorganics
3	Rhizofiltration	Rhizosphere accumulation	Organics/Inorganics
4	Phytotransformation	Degradation in plant	Organic
5	Phytostabilisation	Complexation	Inorganic

Transgenic plants and phytoremediation

S.no	Pollutant(s)	Transgenic	Gene source	Foreign gene or DNA	Reference
1	Cd	*B. juncea*	*E. coli*	gshI	Zhu *et al.*, 1999b
2	Cd	*B. juncea*	*E. coli*	gshII	Zhu *et al.*, 1999a
3	Cd, Pb	*A. thaliana*	S. cerevisiae	YCF1	Song *et al.*, 2003
4	Cd, Cu, Pb	*B. Juncea*	*E. coli*	gshI	Bennett *et al.*, 2003
5	Hg(II)	*Arabidopsis*	Bacteria	merA	Heaton *et al.*, 1998
6	Hg (II)	*L. tulipifer*	Bacteria	merA	Rugh *et al.*, 1998
7	MeHg	*A. thaliana*	*E. coli*	merApe9	Rugh *et al.*, 1996
8	MeHg	*A. thaliana*	Bacteria	merBpe	Bizily *et al.*, 1999
9	MeHg	*A. thaliana*	Bacteria	merA, merB	Bizily *et al.*, 2000
10	MeHg	*Arabidopsis*	Bacteria	merB	Bizily *et al.*, 2003
11	PMA	*N. tabaccum*	Bacteria	merA, merB	Ruiz *et al.*, 2003
12	ACET, ME	*Populus*	Bacteria		Gullner *et al.*, 2001
13	GTN, TNT	*N. tabaccum*	Bacteria		French *et al.*, 1999
14	PCP	*N. tabaccum*	*C. versicolor*		Iimura *et al.*, 2002
15	As	*B. napus*	*E. cloacae*		Nie *et al.*, 2002

It also has the ability to enhance the resilience of the system for coping with the adverse impacts of climate change.

The effectiveness of agroforestry systems in storing carbon depends on both environmental and socio-economic factors; in humid tropics, agroforestry systems have the potential to sequester over 70 Mg/ha in the top 20 cm of the soil. The carbon storage capacity in agroforestry varies across species and geography. Further, the amount of carbon in any agroforestry system depends on the structure and function of different components within the systems put into practice. The fact that agroforestry systems can function as both source and sink of carbon has been presented in literature. There is also clear evidence to suggest that the type of agroforestry system greatly influences the source or sink role of the trees. For example, agri-silvicultural systems where trees and crops are grown together are net sinks while agro silvipastoral systems are possibly sources of GHGs. Practices like tillage, controlled burning, manuring, application of chemical fertilizers and frequent soil disturbance can lead to significant emissions of GHGs. According to the IPCC agroforestry systems offer important opportunities of creating synergies between both adaptation and mitigation actions with a technical mitigation potential of 1.1-2.2 PgC in terrestrial ecosystems over the next 50 years. Additionally, 630 Mha of unproductive croplands and grasslands could be converted to agroforestry representing a carbon sequestration potential of 391,000 MgC/yr by 2010 and 586,000 MgC/yr by 2040. The carbon in the aboveground and belowground biomass in an agroforestry system is generally much higher than the equivalent land use without trees (i.e. crop land without any trees).The estimates of potential for carbon storage in different kinds of agroforestry systems are provided In Southeast Asia, agri-silvicultural systems have the capacity to store 12-228 MgC/ha in humid tropical lands and 68-81 MgC/ha in dry lowlands. Highest potential for carbon storage can be observed for North American silvi pastoral systems with a range of 90-198 MgC/ha. The potential to sequester carbon in aboveground components in agroforestry systems is estimated to be 2.1×10^{9}MgCyear^{-1} in tropical and 1.9×10^{9} MgCyear^{-1} in temperate biomes. Agroforestry systems can have indirect effects on carbon sequestration as it helps decrease pressure on natural forests that are the largest sinks of terrestrial carbon, they also conserve soils and thus enhance carbon storage in trees and soils. Effects of agroforestry practices on the soil carbon pool indicated a rate of increase by 2-3 MgC/ha/yr. Estimations of carbon sequestration potential in various studies report an estimated potential of 6.3GtC and 0.7-1.6 GtC. The carbon sequestration potential of agroforestry systems has been established theoretically; however field measurements to validate these concepts are limited. The inherent variability in the estimates of potential carbon storage in agroforestry systems and the lack of uniform methodologies has made comparisons difficult. Few studies of specific agroforestry practices have proved potential for carbon sequestration.

Phytoremediation is a fast developing field, since last ten years lot of field application were initiated all over the world, it includes Phytoremediation of Organic, Inorganic and Radionuclides. This sustainable and inexpensive process is fast emerging as viable alternative to conventional remediation methods, and will be most suitable for a developing country like India. Most of the studies have been done in developed countries and knowledge of suitable plants is particularly limited in India. In India commercial application of Phytoremediation of soil Heavy metal or Organic compounds is in its earliest phase. Fast growing plants with high biomass and good metal uptake ability are needed. In most of the contaminated sites hardy, tolerant, weed species exist and phytoremediation through these and other non-edible species can restrict the contaminant from being introduced into the food web. However, several methods of plant disposal have been described but data regarding these methods are scarce. Composting and compaction can be treated as pre-treatment steps for volume reduction, but care should be taken to collect leachate resulting from compaction. Between the two methods that significantly reduce the contaminated biomass, incineration seems to be least time consuming and environmentally sound than direct burning or ashing.

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