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Short communication

Sustainable clean-up technologies for soils contaminated with multiple pollutants: Plant-microbe-pollutant and climate nexus

Vishal Tripathi[a], Leonardo F. Fraceto[b], P.C. Abhilash[a,*]

[a] Institute of Environment & Sustainable Development, Banaras Hindu University, Varanasi, India
[b] Department of Environmental Engineering, São Paulo State University – UNESP, Sorocaba, SP, Brazil

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ABSTRACT

Soil is a vital life supporting system of the Planet Earth. However, it has been estimated that around 25% the global soils are highly degraded and 44% are moderately degraded mainly due to the pollution of metals and metalloids, persistent organic pollutants, pesticides, radionuclides etc. Additionally, the pollution due to new and emerging pollutants such as antibiotics, disinfectants, flame retardants, nanoparticles etc pose an additional threat to the homeostasis of the soil system. Therefore, sustainable management of contaminated soils are essential for maintaining the ecosystem services. Though chemical and physical methods are widely pursued for the remediation of contaminated soils, phytotechnolgies (plant-based clean-up technologies) are outweighed and often preferred as a clean and carbon-neutral solution for the remediation and sustainable management of the contaminated soils. Apart from that, plant-based clean-up also provide phytoprodcuts such as biomass, biofuels and other industrially important chemicals for bio-based entrepreneurial activities during remediation. However, phytoremediation does not give desired results in soil contaminated with mixed/multiple pollutants. Furthermore, it is unclear that how changing climate will affect the plant-microbe interactions and pollutants behaviour in the soil system. Moreover, there is only limited information available on the plant-microbe-pollutants nexus under changing climate. Therefore, the present work is aimed to (i) address the difficulties in remediation of soils contaminated with multiple pollutants (ii) delineate the plant-microbe-pollutant and climate nexus and (iii) identify the key sustainability indicators for evaluating the remediated system.

1. Soil remediation: the need of the hour

The past few decades have seen an upsurge in the anthropogenic activities leading to the unprecedented pollution of the biosphere. Rapid industrialization, urbanization and intensive agricultural activities have resulted in the release of large amount of heavy metals, pesticides, radionuclides, petroleum hydrocarbons etc. Moreover, the advancement in pharmaceutical, biomedical, electronics and materials science etc have lead to the pollution of the ecosystems with new and emerging pollutants such as antibiotics, antiepileptics, analgesics, anti-inflammatories, lipid regulators, betablockers, diuretics, contrast media, cosmetics, psycho-stimulants, disinfectant, antidepressants, plasticisers and phthalates, wood preservatives, paint additives, nanoparticles etc. (Table 1.) (Abhilash and Singh, 2009; Jamil et al., 2009a,b; Srivastava et al., 2011; Vijgen et al., 2011; Srivastava et al., 2013; de Oliveira et al., 2014; Bakshi et al., 2014; Dubey et al., 2014; Tripathi el al., 2014a,b, 2015; Gavrilescu et al., 2015). Most of these contaminants are resistant to chemical, pholytic, hydrolytic and biological means of degradation so that they would persist in the receiving system for a very long period of time. Since soil is a major sink of these pollutants, the contamination of the soil system poses a serious threat to human existence as it provides food, fibre, fodder and other basic necessities to human beings. Moreover, it also support biodiversity and regulate all biogeochemical cycling in nature. Unfortunately, around 25% of the global soils are highly degraded and 44% are moderately degraded (FAO, 2011) and the growing body of evidences suggest that the number is steadily increasing. So there is an urgent need to clean-up the contaminated soils for maintaining their homeostasis. For example, European Environmental Agency (EEA) has estimated that there are 3 million contaminated sites in Europe, out of which, around 250,000 sites are highly contaminated and need immediate remediation (EEA, 2007; Gillespie and Philp, 2013). Moreover, by 2050, the number of contaminated sites needing remediation may increased by >50%

* Corresponding author at: Institute of Environment & Sustainable Development, Banaras Hindu University, Varanasi 221005, India. Tel.: +91 9415644280.
E-mail address: pca.iesd@bhu.ac.in (P.C. Abhilash).

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Table 1
List of common and emerging pollutants.

Type of pollutants	Examples
Metals and metalloids	As, Ni, Cd, Hg, Pb, Mn, Cr, Mg etc.
Persistent organic pollutants	Aldrin, chlordane, dieldrin, dioxins, endrin, endosulfans, heptachlor, mirex, toxaphane, chlordecone, HCB, α-, β-, γ- HCH, PCB, DDT, PCDF, PBDE, HBCD etc.
Petroleum hydrocarbons	Hexane, benzene, toluene, xylenes, naphthalene etc.
Organophosphorus pesticides	Chlorpyrifos, dichlorvos, dimethoate, malathion, parathion, parathion-methyl, phenthoate, phorate etc.
Carbamate insecticides	Aldicarb, aminocarb, carbaryl, carbofuran, carbosulfan, fenoxycarb, methiocarb, methomyl etc.
Herbicides	2,4-D-, atrazine, simazine, glyphosate etc.
Radionuclides	Uranium, thorium, plutonium, strontium, caesium etc.
New and emerging pollutants	Antibiotics, antiepileptics, analgesics, anti-inflammatories, lipid regulators, betablockers, diuretics, contrast media, cosmetics, psycho-stimulants, disinfectant, antidepressants, plasticisers and phthalates, wood preservatives, paint additives etc.
Nanoparticles	Carbon nanotubes, TiO_2, SiO_2, fullerenes, metal-phosphates, aluminosilicates, silver nanoparticles, ZnO nanoparticles etc.

(EEA, 2007). Although the remediation efforts are progressing, only 80 000 have been successfully cleaned up in Europe during the last 30 years (Gillespie and Philp, 2013). Similarly, more than 66, 0000 sites are already demarked by the United States Environmental Protection Agency (US EPA, 2013) for multipurpose phytoremediation. However, there is no official documentation of the number of contaminated sites in developing countries. Although developed countries have suitable technological frameworks for the onsite clean-up of contaminated sites, no such efforts are available in developing countries and even they do not have such policies or any methodical frame works for the onsite remediation of contaminated sites (Doberl et al., 2013; Tripathi et al., 2014a,b). Therefore there is an urgent need to design suitable policy frame works based on green and clean technologies for the immediate remediation and management of contaminated soils in developing nations.

In this context, plant-based clean-up technologies (phytotechnologies) are gaining popularity as a clean and sustainable technology for the remediation of contaminated soils (Peuke and Rennenberg, 2005). Apart from the removal of pollutants from soils, phytoremediation also provides additional benefit such as soil quality improvement, soil carbon sequestration and phyto-biomass for fiber, biomass and biofuel production (Abhilash et al., 2012). However, the successes of plant-based technologies are limited by many factors. For instance, phytoremediation often does not show the desired results when the polluted sites are co-contaminated with multiple pollutants. Similarly, phytoremediation is also governed by pollutant behaviour, microbial interactions, edpahic and climatic conditions. However, recent studies proved that changing climate will affect the plant-microbe interactions in the soil system. Furthermore, the warming climate may also alter the mobility, leaching, global transport, bioavailability, volatilization, fate and behaviour of the chemical pollutants present in the soil system (Lamon et al., 2009; Miraglia et al.,2009; Tripathi et al., 2015). Most importantly, there is a paucity of information regarding the indicators for assessing the sustainability of a remediated soil sites. Therefore, the present work is aimed to address three important challenges in plant-based clean-up technologies such as (i) the difficulties in remediation of soils contaminated with multiple pollutants (ii) the plant-microbe-pollutant and climate nexus and (iii) identifying key sustainability indicators for the remediation of contaminated soil system

2. Phytoremediation of soils contaminated with multiple pollutants

Several microbial and plant species are being tested for the remediation of the soil pollutants (Macek et al., 2000; Chiang et al., 2006; Glick 2010; Abhilash et al., 2009; Abhilash et al., 2013a,b; Kcil et al., 2015). However, the success of any phytoremediation technology depends upon the three important factors such as (i) inherent nature of the plant species (ii) microflora present in the soil and (iii) physico-chemical properties of the pollutant itself (Fig. 1.) Globally, most of the soils are either contaminated with organic or inorganic pollutants or a mixture of both (Wang et al., 2010). According to USEPA, more than 67% of the polluted sites are co-contaminated with heavy metals and organic pollutants (USEPA, 2004). As a result, the remediation of the soils contaminated with mixed pollutants is a difficult task as the organic and inorganic compounds differ in their properties and

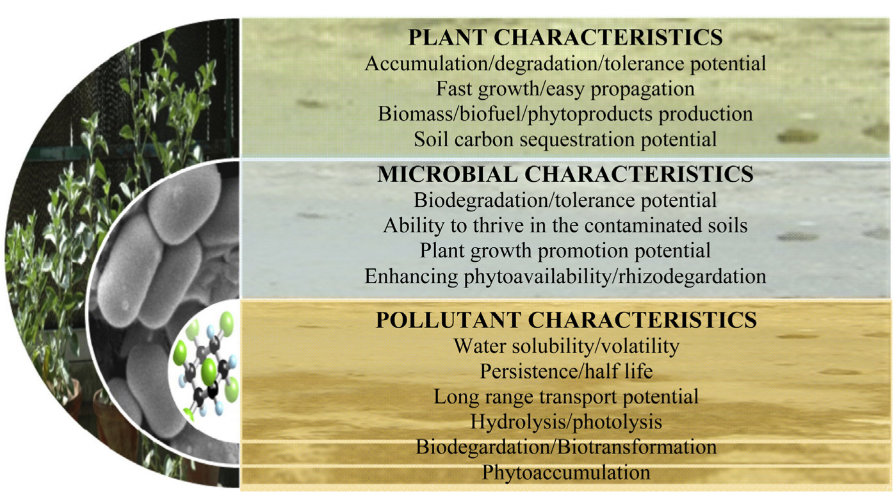

Fig. 1. Plant-microbe-pollutant nexus play a key role in the phytoremediation of contaminated soils.