PHYTOREMEDIATION OF ORGANIC AND INORGANIC COMPOUNDS IN A NATURAL AND AN AGRICULTURAL ENVIRONMENT: A REVIEW

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Abstract. Phytoremediation is currently an area of trending research due to its huge potential as a sustainable substitute for traditional methods of restoring contaminated sites. It is a profitable and ecological alternative to mechanical and chemical remediation techniques used worldwide. An increase in soil, water, and air pollution has severely disturbed an ecosystem functions and poses a huge threat to the natural and agricultural environment as well as public health. Remediation of the contaminated environment is one of the paramount concerns of the world. Hence this article deliberates on the general problems of pollutants linked to phytoremediation techniques of organic and inorganic contaminants, especially agrochemicals, petroleum, and explosive compounds. The paper also reviews a systematic assessment of the recent progress in the phytoremediation of contaminants in a natural and agricultural environment. Additionally, we highlight the benefits and limitations of phytoremediation along with a brief clarification of the resilient mechanistic removal of contaminants by a three-phase method. Finally, the perspective of biotechnological approaches in remediation is also suggested; taking into consideration the future of synergistic remediation approaches and genetically improved plants to enhance phytoremediation.

Keywords: *hyperaccumulation, pollutant, phytoextraction, phytotransformation, phytovolatilization*

Introduction

Phytoremediation is a term related to ecological restoration technology that takes plants as the main source. Therefore, phytoremediation can be explained as using plants (shrubs, trees, aquatic plants, and grasses) and associated microorganisms for the elimination, degradation, or separation of contaminated sites in an environment (Ossai, 2019; Chirakkara, 2015; Bruneel, 2019). Different approaches have been employed to remediate contaminated sites, but phytoremediation is well-thought-out as a possible alternative, effective, ecologically friendly, and best likened to other outmoded physicochemical methods (Burges et al., 2018; Rajput et al., 2019).

During the process of phytoremediation, compounds that can be remediated include (i) organic waste (ii) metals (iii) inorganic substances (iv) agrochemicals (v) metalloids (vi) radiochemical elements (vii) petroleum hydrocarbons (viii) explosives and (ix) chlorinated solvents (Cristaldi et al., 2017; Misra, 2019; Abdel-Shafy and

Mansour, 2018). The key sources of organic and inorganic pollutants occur naturally but others are a result of the use of fuels, solvents, and pesticides. Several organic and inorganic compounds are harmful and connected to health issues worldwide (Dixit et al., 2015; Li et al., 2017). These pollutants are on the rise within the environment through several activities in agriculture (pesticides, herbicides), industry (chemicals, petrochemicals), spillage (fuel, solvents), wood processing, and military activities (explosives, chemical weapons), etc. (Tripathi et al., 2020). Many contaminants within the agricultural soils can cause a substantial amount of damage to plant growth, soil ecological functions, and human health (Cai et al., 2019; Ngole-Jeme and Fantke, 2017). For instance, nitrobenzene impedes soybean seed growth and initiate genotoxicity in the cells of its root tip (Guo et al., 2010). There are also varied contaminants generally in soils or areas to be remediated, which contain trace elements and organic chemicals. Even though this is still a herculean task, many groups have faced action recently on contaminated soil phytoremediation (Gutiérrez-Ginés et al., 2014; Xu et al., 2019).

The extreme pressures from organic and inorganic waste and the magnitude of contamination have caused widespread concern as intentional or unintentional exposure of these materials poses a major threat to the environment and public health (Cristaldi et al., 2017; Rajput et al., 2019). Also, the events and mishaps of these contaminations worldwide have drawn the attention of the general public. Progressively, more people are alarmed and as a result, researchers are in search of the most effective remedies to curb these pollutions. The Soil Pollution Prevention and Control action plan by countries like China in 2016 was estimated to cost US$90 billion, aiming to utilize and develop effective remediation methods (Hou and Li, 2017). Conversely, these approaches do have some disadvantages such as high cost in operation and mobilizing contaminated material to the site of treatment which intensifies the risk of secondary contaminations.

Many techniques have evolved in the past decades intending to restore sanity to our environment and a wide acknowledgment of these methods is on the basis that it is an environmentally friendly method and a cheaper approach to get rid of contaminants. Currently, the extent of studies that have employed phytoremediation techniques to clean and reduce environmental pollution is increasing (Dixit et al., 2015; Rodriguez-Narvaez et al., 2017). However, despite several reports by many authors on the issue of remediation, there is still missing information regarding materials on the possible antagonistic or synergistic effects of diverse contaminants and their cross-accumulation or detoxification in both natural and agricultural environment.

Here, we:

- Provide an overview of phytoremediation of contaminants from agrochemicals (pesticides/fertilizers), petroleum compounds, explosive compounds, and inorganic compounds.
- Discuss the challenges in phytoremediation methods and also try to suggest an improvement in the biotechnological approaches for future research perspectives to enhance the phytoremediation of organic and inorganic pollutants.

This paper, we believe will provide a critical and extensive review of studies in natural and agricultural environment specifically in addressing the recent literature regarding remediation of organic and inorganic compounds.

Phytoremediation techniques

Phytoremediation has great promising as a natural on-site treatment with solar energy capable of treating the land and a vast area of moderately contaminated sites. Contrasting other kinds of remediation, plants grown for ornamental purposes in gardens and landscaping projects have become an important tool in recent years (Liu et al., 2018; Dodangeh et al., 2018; Cheng et al., 2017; Ranieri et al., 2016). Besides being attractive to the environment, some of these ornamental plants accumulate or decompose pollutants when they grow in soil polluted by heavy metals and organic pollutants (Liu et al., 2018). Just like heavy metals, an organic pollutant in plants is remediated by several natural biophysical and biochemical processes. Trees with large roots and high transpiration rates, such as *Populus* (*Populus spp.*) or *Willow* (*Salix spp.*), are well-known in the phytoremediation process (Srivastav et al., 2018). Such plants have a multiplicity of effects on these toxic compounds. They can be fixed, stored, volatilized, and converted to varying degrees (or even mineralized) or a combination of the processes which are conditional on the particular compound, environmental conditions, and plant genotypes. Phytoremediation remains a widely used method; however, if a cautious selection of the best appropriate plants and proper agronomic methods are not used appropriately, there could be a lack of control and plant availability. The mechanism that plants use to promote remediation (*Fig. 1*) includes plant extraction, plant degradation, plant stabilization, plant volatilization, and rhizosphere decomposition.

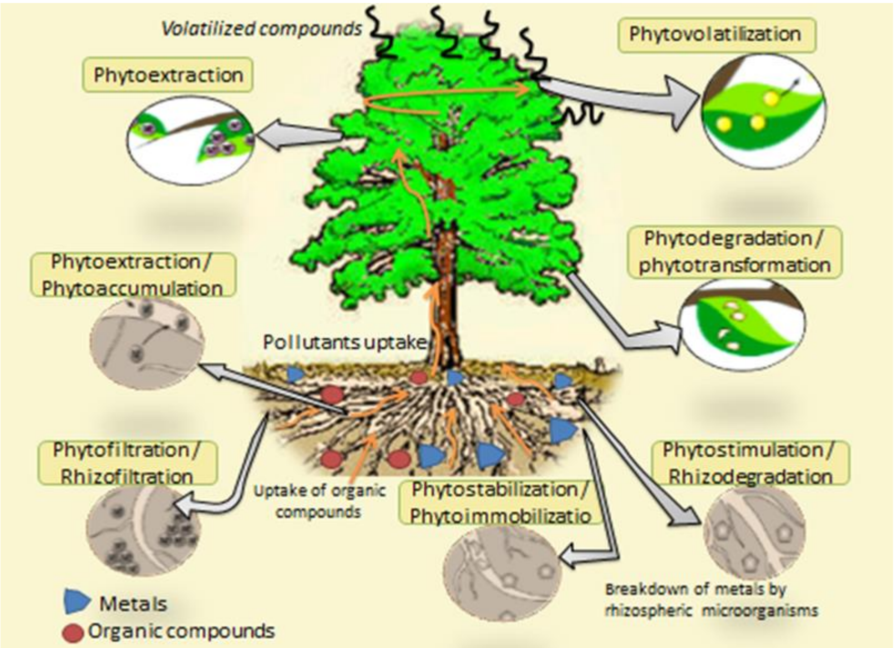

***Figure 1.** Presentation of phytoremediation of organic and inorganic pollutants from a contaminated environment (adapted from Favas et al., 2014; Avensblog, 2020)*

Phytodegradation (phytotransformation)

Phytodegradation (also known as phytotransformation) involves the uptake of organic contaminants to be decomposed (metabolized) or mineralized in plant cells by certain enzymes. These include nitroreductase (through the decomposition of nitroaromatic compounds), dehalogenase (through the decomposition of chlorinated solvents and pesticides), and volatile enzymes (involved in the decomposition of aniline) (Kumar et al., 2018). Plant species such as Populus and Sage are illustrations of plants with these enzyme systems (Leung et al., 2019; Feng et al., 2017). For instance, Chen et al. (2016) reported that the Armoracia rusticana possess the ability to degrade benzophenone within its tissues. These green plants are classified as the biosphere 'green liver'. Also, a current study employed phytotransformation for organic compounds like insecticides, chlorinated solvents, herbicides, inorganic nutrients, and munitions (Kumar et al., 2018).

Phytostabilization (phytoimmobilization)

Phytostabilization or phytoimmobilization is an in situ technology whereby toxic compounds are integrated into the root cell wall lignin to form non-toxic substances, hence decreasing the existence of pollutants in the natural and agricultural environment (Khalid et al., 2017; Mahar et al., 2016). Metals are precipitated in insoluble forms under the direct action of root exudate and subsequently enter the soil medium. The main challenge relating to this technique is the avoidance of the concentration of pollutants and suppressing their dispersion in soil (Favas et al., 2014; Ali et al., 2013; Fan et al., 2017). Studies conducted by Khalid and coworkers (Khalid et al., 2017) have referenced a great number of examples of plants grown for this purpose which are but not limited to species of the genera *Haumaniastrum*, *Eragrostis*, *Ascoliepis, Gladiolus*, and *Alyssum*. These plant species can also contribute to phytostabilization owing to their capability to release a greater number of chelating agents. Other research studies (Lebrun et al., 2018) showed that in phytoimmobilization, unclean soil is covered with vegetation that is resistant to high applications of harmful elements, thereby limiting soil erosion and the leaching of pollutants within groundwater. These substances immobilize pollutants, inhibiting their uptake and reducing their mobility in soil. As a result, plants with stabilizing potential play an essential role in polluted areas of agricultural production and vegetation restoration (Eskander and Saleh, 2017; Saha et al., 2017). It is reported (Eskander and Saleh, 2017), that these substances were known to immobilize pollutants, prevent absorption, and thereby decrease their movement in the soil. This accounts for why plants with phytostabilization potential are very valuable for mining, waste, and vegetation restoration in contaminated sites. Similarly, Yadav and colleagues (Yadav et al., 2018) have also revealed that phytostabilization is very useful in removing inorganic contaminants, from soil contaminated with Arsenic (As), Copper (Cu), Lead (Pb), Zinc (Zn), Cadmium (Cd), Chromium (Cr) and other metals in their sediments.

Phytovolatilization

Phytovolatilization is the capability of some green plants to engross certain metals/metalloids and later release them through vaporization. Some ions groups like IIB, VA, and VIA in the periodic table (especially mercury (Hg), selenium (Se), and As) are being taken by the roots, transformed into non-toxic forms and later volatilized into the atmosphere (Limmer and Burken, 2016). Conversely, the disadvantage of phytovolatilization lies in the fact that toxic compounds discharged into the atmosphere can undergo precipitation and re-deposit back into the environment, as this will give rise to other toxic substances (Nikolić and Stevović, 2015). Examples of plant species from studies (Ali et al., 2013; Mani and Kumar, 2014) include *Stanleya pinnata* and *Astragalus bisulcatus* or transgenic plants (with bacterial genes) such as *Liriodendron tulipifera, Brassica napus, Arabidopsis thaliana,* or *Nicotiana tabacum*. This method can also be applied to tackle organic compounds and other heavy metals like Se and Hg.

Phytoextraction (phytoaccumulation, phytoabsorption or phytosequestration)

This mechanism refers to the absorption of pollutants by roots, followed by displacement and accumulation in air particles. Phytoextraction technology as reviewed by Parmar et al. (2015) involves the eradication of contaminants from soil, groundwater, or surface water by living plants. This technique according to research by Sarwar et al. (2017) is mainly engaged in the remediation of soils polluted by metals (Cd, Nickel (Ni), Cu, Zn, Pb), however, it could also be used for other elements (such as Se, As) and organic compounds. This method favors hyperaccumulator species (which will be discussed in this paper) that can maintain a great absorption of exact metals in their air portions (0.01-1% dry weight, depending on the metal) (Parmar, 2015). Phytoaccumulation, also called phytoextraction or hyperaccumulation, reported by Xiao et al. (2017) uses cationic pumps and sorption to remove metals, salts, and organic compounds from the soil by absorbing water available to plants. The process commences by sowing the metal-accumulating plant in metal-polluted soil and coupled with extensive agricultural practices. Many authors (Van der Ent et al., 2013; Xiao et al., 2017; Reeves et al., 2018) have proposed *Elsholtzia splendens, Alyssum bertolonii, Thlaspi caerulescens* and *Pteris vittata* as known examples of hyperaccumulating plants of Cu, Ni, Zn/Cd, and As respectively. Several plant species near metal mining areas as stated by Saxena et al. (2020) thrived in soils heavily contaminated with metals, hence for remediation of contaminated areas, it is necessary to select the kind of plants which can absorb and transport metals in various conditions. However, some soils are highly contaminated hence the elimination of metals through this method will save an uncertain amount of time.

Phytofiltration

This technique uses plants to absorb distillate and/or precipitate contaminants, especially radioactive elements, and heavy metals, from the environment through the root structure or further submerged organs. In this process, Parmer and Singh (Parmar, 2015) reviewed that plants are stored in a hydroponic system through which wastewater passes and is “filtered” by the roots (rhizofiltration) or other structures that can absorb and concentrate pollutants (hyperaccumulators) or tolerate pollutants for the best results. Phytofiltration remediates metallic substances like Cu, Ni, vanadium (V), Cr, Pb, including other radionuclides such as caesium (Cs), strontium (Sr) and uranium (U). Nevena et al. (Cule et al., 2016) in an experiment used the ornamental plant (*Canabis indica*) to remediate Pb in wastewater. Their findings showed that the removal rate was 81.16% higher. The authors (Cule et al., 2016) supported the idea that terrestrial plants are most appropriate for rhizofiltration than aquatic plants and that *C. indica* is best used in rhizofiltration methods or floating islands for treatment of water polluted with Pb. Zhang et al. (2005) researched on the efficiency of Cu removal from contaminated water by *Elsholtzia argyi* and *Elsholtzi splendens* in hydroponics. Their results demonstrate that *Elsholtzia argyi* showed better Cu phytofiltration (removal rate of 50-90%) than *Elsholtzi splendens* (removal rate of 45-80%), which was linked with better capability to higher Cu concentrations and translocation to shoots. One could infer that various physicochemical properties of plant species are factors in the choice of plant for phytofiltration. This technology is capable of dealing with industrial discharge, agricultural runoff, and mine drainage. Several authors have indicated some promising examples of such plants as *Brassica juncea*, *Helianthus annus*, *Fontinalis antipyretica*, *Phragmites australis*, and some species of *Salix*, *Populus*, *Lemna*, and *Callitriche* (Van der Ent et al., 2013; Bonanno and Cirelli, 2017; Favas and Pratas, 2016; Tatar et al., 2019).

Rhizodegradation (phytostimulation)

Rhizodegradation or phytostimulation is the breakdown of organic compounds in the soil through the microbial activity of the root (rhizoshere) (Echereme, 2018). This is improved biodegradation of contaminants by a particular plant species root-associated fungi and bacteria (Ali et al., 2013; Khalid et al., 2017). There are free-living, symbiont mycorrhizal fungi that are associated with plant roots and are significantly more beneficial for the production and biochemical availability of nutrients such as cobalt (Co), Cu, Zn, Ni, nitrogen (N), phosphorus (P), potassium (K), sulphur (S) and Calcium (Ca) through the extensive hyphal network (Sarwar et al., 2017). In research by Jiang et al. (2017), it was demonstrated that bacterial species, for instance, *Pseudomonas*, *Acinetobacter*, *Bacillus*, and *Cupriavidus* improved their environmental adaptability and was resistant to Pb, Cd, and Cu in rhizospheric soil around the plant. The authors deduced that *Boehmeria nivea* L. (known to be evolving around chemical refineries) was improved by increased concentrations of the particular microorganisms (Jiang et al., 2017). Also, the plants themselves can release biodegradable enzymes. The microbial association in the rhizosphere is heterogeneous due to the changing spatial distribution of nutrients, but species of the genus *Pseudomonas* are the organisms largely connected with the root (Ali et al., 2013; Singh and Singh, 2016; Salem et al., 2018). The death of plants ought to be considered and agronomic methods must be used to reduce it by timely planting in the growing period, digging a hole in diameter, and feasibly filling it with unpolluted plant soil, for better survival of trees, thus bringing a greater efficiency of phytoremediation.

Phytodesalination

According to literature, this is a recently informed remediation approach that removes saline from internal salts. Studies have reveals that the efficacy of *Suaeda maritima* and *Sesuvium portulacastrum* in eradicating and accumulating sodium chloride (NaCl) from highly salty soil, has demonstrated to be very effective (Ali et al., 2013; Kumar et al., 2019b). Phytodesalination may possibly occur in parallel with phytoremediation of heavy metal contaminated soils in arid regions, increasing the prospect of this process. Halophytes (salt-tolerant plants) have been suggested (Padmavathiamma, 2014) to naturally adjust to cope with environmental stresses, such as heavy metals and other organic contaminants (Padmavathiamma, 2014). Iniyalakshimi (Iniyalakshimi, 2019) also found that *S. portulacastrum*, which has high sodium and chloride absorption ability may be a possible candidate for reducing secondary salinization due to irrigation with sodium-rich industrial wastewater (Fan et al., 2019). Taken together, this indicates that *S. portulacastrum* (SpSOS1 and SpAHA1) coordinates to alleviate salt toxicity by cumulating the efficiency of Na + extrusion to maintain K + homeostasis and defend the plasma membrane from oxidative harm induced by salt stress. In a current study (Lastiri-Hernández et al., 2020), the capacity of halophytes species namely; *Bacopa monnieri* (L.), *Sesuvium verrucosum* Raf. and *Wettst* was assessed to increase their chemical properties in saline soil for 240 days in a field. It was also reported that the association of these plants has a phytodesalination ability of 1.21 t Naþ ha1 and this served to prepare the conditions for the crop growth (Lastiri-Hernández et al., 2020). This technology involves an enzymatic breakdown of pollutants, relevant for soil, groundwater, or surface water, and sediment sludges. This process is an impressive kind from phytoextraction, even though it has its drawbacks. Some of these drawbacks could include the duration of the process, the properties of the soil (salinity, sodicity and porosity), the number and the initial weight of the plant species.

Phytoremediation of organic contaminants

Currently, phytoremediation is offered as a cost-effective method to remove many kinds of organic contaminants such as petroleum products, aromatic hydrocarbons (BTEX), chlorinated solvents, explosives, and cyanides as aforementioned (Hattab-Hambli et al., 2020).

Furthermore, one of the largest environmental disasters was in the Gulf of Mexico, which had a major impact on the ecosystem and human health (Sandifer et al., 2017; Singleton et al., 2016; Schaum et al., 2010; Han and Clement, 2018; Babcock-Adams et al., 2017; Eklund et al., 2019). Crude oil kills small invertebrates, destroying soil biological life thereby rendering such polluted soils habitable to only anaerobic bacteria. Phytoremediation, as a natural, solar energy-driven in situ method, has great potential for treating soils and large areas of moderately contaminated areas. Plants are carefully selected and appropriate agronomic methods are used to properly manage phytoremediation of organic pollutants (Schwitzguébel, 2017). Phytoremediation can restore, balance a stressful environment due to the natural, synergistic relationships between plants, microorganisms, and the environment. Further, during the in-situ phytoremediation process, organic matter, nutrients, and oxygen are added to the soil through the metabolic processes of plants and microorganisms, thereby improving the quality and texture of the clean area (Schwitzguébel, 2017; Wiszniewska et al., 2016).

Phytoremediation of agrochemicals

The predominant misuse of agrochemicals over several years has polluted the agricultural and natural environment. These chemicals cause various damages to agricultural lands, various water bodies, and other land-dwelling organisms.

Various organic compounds (OCs), for example, organochlorine pesticides (OCPs) and other agrochemicals are extremely toxic and persistent in the environment (Sun et al., 2018).

The potential use of alfalfa, tomato, sunflower, and soybean species to remove endosulfan from the soil was studied by Mitton et al. (2016). Their research results showed that, except soybean, the phytoextraction rate of all other species at 60 days increased with the decrease of soil pesticide levels. Sunflower plants had the highest phytoextraction rate (2.23%), followed by tomato (1.18%), soybean (0.43%), and alfalfa (0.11%). In additional research (Zhao, 2018), the dissemination of dichloro diphenyl trichloroethane (DDT) residues in agricultural soils in southwestern Ontario, Canada, was also studied to determine the degree of degradation of tomato plants. The DDT concentration in tomato fruits was 211.75 ug/kg, which was lower than the prescribed value. Consequently, tomato fruits are eligible and valued, and may be a potential choice for future field research. In a study (Qu et al., 2017) involving atrazine-contaminated lake sediments, spiked watermilfoil (*Myriophyllum spicatum*), and curled algae (*Potamogeton crispus*) were opened to 0.10 mg atrazine kg-1 soil at a decreased rate of 76.15% and 75.65% respectively in comparison to Atrazine's decline of 46.3% non-cultivated soil.

To correct these contaminations, researchers have essentially used consortia of various bacterial strains, such as atrazine and deisopropylrazine (Fan and Song, 2014) via rhizodegradation/phytostimulation of agrochemicals from agricultural environment. From a biotechnological point of view, bacterial strains can also be used to decompose certain pesticides, such as the one Myresiotis et al. (2012) used to remediate the soil contaminated with hydrochloride, metribuzin, acidobenzolar-S-methyl, propamocarb, thiamethoxam and napropamide. Phytoremediation of pesticides is affected by some factors. Their low bioavailability in soils might confine the attainment of this technology.

Large numbers of plants have been tested to proficiently accumulate pesticides and some of these plants are listed in *Table 1*. The capacity of these plants to uptake pesticide residues varies greatly between plant species (Handford et al., 2015; Romeh, 2015). These plants are widely used because of their significant role in agriculture and gardening and as a result of these good prospects for the accumulation of innumerable organic pollutants, they are therefore generally considered phytoremediation plants (Singh and Singh, 2017).

Significant interactions can occur between different pollutants in a polluted environment. When there is soil-to-plants absorption, the accumulation potential is affected by various plant properties such as water absorption potential and root depth/structure (Eevers et al., 2017). When pesticides are trapped in plant root tissues, they can be immobilized in the roots or transferred to an aerial portion of the plant where the analytes can be stored, metabolized, or evaporated (Eevers et al., 2017). In general, the objective of effective phytoremediation is not only phytoaccumulation but also the degradation of pollutants in plant tissues as this can be done with or without endophytic bacteria.

Phytoremediation of explosive compounds

After World War II, the commissioning and removal of weapons at military factories brought about the pollution of the agricultural environment and other biological systems with explosives like 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1, 3,5 triazine (RDX) and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetraazocin (HMX) (Taylor, 2017; Srivastava, 2015; Sheehan et al., 2020; Aguero and Terreux, 2019). These compounds are the most widely distributed organic explosive contaminates found in nature. The use of explosives during military exercises and operations leads to large-scale environmental pollution, in which case the ecological balance is disturbed (Ndibe et al., 2018). As a consequence of their manufacturing and disposal practices, these explosives with their transformation products are major pollutants in soils, ground and surface waters worldwide. For instance, ammunition contamination in the 1920s in Verdun, France, still posed a danger to public health (Rylott and Bruce, 2019; Gorecki et al., 2017).

Table 1. *Phytoremediation of pesticide by certain plant species from previous studies*

Plant species	Agrochemical	Formula	Molecular weight (g/mol)	References
Castor bean/castor oil plant (*Ricinus communis*)	Aldrin,	$C_{l2}H_5Cl_6$	364.92	Rissato et al., 2015
	Chlordane, Chlorpyrifos,	$C_{10}H_6Cl_8$	409.78	
	Dichlorodiphenyldichloroethylene (DDE)	$C_9H_{11}Cl_3NO_3PS$	350.59	
	Diclofop methyl, Dllieldrin	$C_{l4}H_5Cl_4$	318.03	
	Endrin	$C_{16}H_{14}Cl_2O_4$	341.2	
	Hexachloro-cycohexane (HCH)	$C_{l2}H_5Cl_6O$	380.91	
	Heptachlor, methoxychlor	Cl2H, Cl_6O	380.91	
		$C_6H_6Cl_6$	290.83	
		$C_{1O}H_5Cl_7$	373.32	
	DDT	$C_{l4}H_9C_{l5}$	354.49	Huang et al., 2011; Rissato et al., 2015
Maize/corn (*Zea mays*)	Dichloro diphenyl dichloroethane (DDD)	$C_{l4}H_{lO}C_{14}$	320.05	Bogdevich and Cadocinicov, 2010
	DDE	$C_{l4}H_5Cl_4$	318.03	
	DDT	$C_{l4}H_9C_{l5}$	354.49	
	Endosulfan	$C_9H_6Cl_6O_5S$	406.92	Mukherjee and Kumar, 2012
	Endosulfan sulphate	$C_9H_6Cl_6O_5S$	406.92	Somtrakoon et al., 2014; Somtrakoon, 2014
	Hexachloro-cycohexane (HCHs)	$C_6H_6Cl_6$	290.83	Alvarez et al., 2015; Bogdevich and Cadocinicov, 2010
Chinese violet cress (*Orychophragmus violaceus* L. O. E. Schulz)	DDD	$C_{l4}H_{lO}C_{14}$	320.05	Sun et al., 2015
	DDE	$C_{l4}H_5Cl_4$	318.03	
	DDT	$C_{l4}H_9C_{l5}$	354.49	
	HCHs	$C_6H_6Cl_6$	290.83	
Common sunflower (*Helianthus annus*)	Azoxystrobin	$C_{22}H_{17}N_3O_5$	403.4	Romeh, 2015
	DDD, DDE, DDT	$C_{l4}H_{lO}C_{14}$ $C_{l4}H_5Cl_4$ $C_{l4}H_9C_{l5}$	320.05 318.03 354.49	Mitton et al., 2014
Common yarrow *(Achillea millefolium)*	DDT	$C_{l4}H_9C_{l5}$	354.49	Moklyachuk et al., 2012
Sweet flag – Calamus (*Acorus calamus*)	Atrazine	$C_8H_{14}ClN_5$	215.68	Wang et al., 2012
Welsh onion/bunching onion/long green onion/Japanese bunching onion/spring onion (*Allium fistulosum*)	Phoxim	$C_{12}H_{15}N_2O_3PS$	298.3	Wang et al., 2011
Love-lies-bleeding (*Amaranthus caudate*)	Glyphosate	$C_3H_8NO_5P$	169.07	Al-Arfaj et al., 2013
Field mustard/Turnip rape/bird rape/Keblock (*Brassica campestris*)	Endosulfan	$C_9H_6Cl_6O_3S$	406.92	Mukherjee and Kumar, 2012
Broadleaf plantain/white man's foot/Greater plantain (*Plantago major*)	Azoxystrobin	$C_{22}H_{17}N_3O_5$	403.4	Romeh, 2015
	Chlorpyrifos	$C_9H_{11}Cl_3NO_3PS$	350.59	Romeh and Hendawi, 2013
	Cyanophos	$C_9H_{10}NO_3PS$	243.22	Romeh, 2014a,b

Source (common English name): https://en.wikipedia.org/wiki/ (accessed on April 7, 2020)

Explosives are sensitive to a xenobiotic, and their survival in an environment is dangerous for living organisms; as they can migrate through aboveground soils, polluting groundwater (Taylor, 2017). Despite the devastating effects of pollution on environmental and human health, the global market for explosives was forecast to grow from $ 23.8 billion in 2017 to $ 31.2 billion by 2022, therefore lucrative, clean-up methods are required instantly (BCC, 2018). There are innumerable practices connected with the conversion of explosive pollutants by plants. RDX has been described (Hannink et al., 2002) to have minor toxicity than TNT. Additionally, it can translocate within plants, and consequently, these compounds can be stored in various parts of the plants.

In the USA (Virginia Commonwealth University), a study by Via et al. (2016) was conducted to investigate the impacts of explosives polluted soils using ecological metrics in an experimental minefield on vegetative communities. Their results showed that RDX and TNT contaminated plots had shifted in dominant functional traits, suggesting an influx of more tolerant species as a result of new tolerant species filling open niches in contaminated plots (Via et al., 2016). In another study (Kiiskila et al., 2015), many agricultural and ornamental important plants were examined for their capability to remediate TNT and RDX in barley (*Hordeum sativum*), Soybean (*Glycine max*), alfalfa (*M. sativa*), chickpea (*Cicer arietinum*), maize (*Zea mays*), sunflower (*Helianthus annuus*), pea (*Pisum sativum*), and ryegrass (*Lolium multiflorum*) species. Furthermore, Das (2017) reported the two most effective species for TNT uptake-*Eurasian watermilfoil*, *Myriophyllum spicatum*, and vetiver grass as well as *Chrysopogon zizanioides*. For RDX phytoremediation, reed canary grass, rice, and fox sedge showed good promise, although degradation of RDX in the plant tissue is limited (Kiiskila et al., 2015). Conversely, there are limitations to this new technology. It is only effective when treating shallow soils, ground, and surface waters. Plants can also efficiently remove pollutants only close to the root zone since phytotoxicity is also a drawback to this methodology.

Phytoremediation of petroleum compounds

Economic growth and industrialization have led to increased emissions of petroleum hydrocarbons (PHC) and trace elements (TE). Due to their tenacity in an environment and various toxicological effects on living things, they are well-thought-out to be the greatest toxic pollutants in the world (Marchand, 2018). Most chemical contaminated soils are linked with the release of petroleum products into the environment. The intensification of global oil and gas activities, including oil exploration, drilling, production, land storage, and transportation has also increased the menace of crude oil spills and outflows (Okotie et al., 2018). Due to health problems, these water bodies and land contaminated with crude oil are often not suitable for domestic and agricultural uses (Tang and Angela, 2019a).

However, the exploration of crude oil has brought economic development, especially in developing countries (like Ghana, Nigeria, Niger etc.), but the natural and agricultural environment in these countries has also been damaged by the negative effects of these oil industries (Ngene et al., 2016). For instance, water resources in the Niger Delta are no longer fit for human drinking, but oil exploration in Nigeria cannot be stopped as 90% of Nigerian foreign currency earnings come from crude oil exploration (Okotie et al., 2018; Adekola et al., 2017; Siakwah, 2018). In addition to the detrimental effects of the oil industry in our environment, various reports (Ramirez et al., 2017) points out its negative impacts on human health as well. These are psychological problems initiated by crude oil leakage, respiratory tract irritation, and blood disorders (Ramirez et al., 2017; Taheri et al., 2018). Sylvia reported that contaminated sites pose a risk to human life owing to severe health complications caused by unreceptive health effects from introduction to oil-soil contamination (Adipah, 2019).

Phytoremediation is said to be a slowly developing process that can clean the environment for a long time. This method is also influenced by external parameters, including type and leaching of pollutants, soil chemistry, and photosynthesis (Lim et al., 2016) and water-related effects on conservation and weather conditions. Exposure of plants to organisms and pollutants for a longer period reduces their ability to uptake contaminants (Zabbey et al., 2017). In current research by Viesser et al. (2020), three bacteria were isolated namely; *Bacillus thurigiensis*, *Bacillus pumilus*, and *Rhodococcus hoagie*. These were able to use petroleum hydrocarbons as the sole carbon during vitrodegradation assays. The authors found that *R. hoagii* had the highest efficacy of petroleum consumption, attaining 87% of degradation after only 24 h of cultivation.

Another experiment (Heidari et al., 2018) was conducted to study the effect of oil-contaminated soil on *Echinacea purpurea* with four concentrations of crude oil. The results depicted that this plant has a possibility for removing TPHs, up to 45.5% at 1% crude oil contamination. The authors further reported that *E. purpurea* is a widely - spread species that can be commendably used for phytoremediation of ≤ 10000 mg kg^{-1} crude oil-contaminated soil. Other studies suggested that the faster-growing flora (e.g. grass species) are plants that effectively restore polycyclic aromatic hydrocarbons (PAH) in contaminated soil (Srivastav et al., 2018; Kumar et al., 2019a). The adsorption properties of TPH ought to be investigated as it aids to reduce the concentration of organic material in the soil. Thorough remedial studies have to be carried out not only to assess the effectiveness of the repair but also to investigate and implement the potential for secondary pollutants.

These studies demonstrate that agricultural lands with low rates of oil contamination allow the growth of plants. Furthermore, previous studies in phytoremediation of contaminants have not focused so much on petroleum hydrocarbons rather all attention has been on heavy metals remediation (Tang and Angela, 2019b), hence further studies must be focused on this area.

Inorganic contaminants

Inorganic materials belong to man-made environmental activities, for instance, smelting, mine drainage, chemical, and metallurgical processes, and also natural processes. These sources release inorganic pollutants usually in the form of minerals such as metals, salts, and natural substances (Masindi and Muedi, 2018; Fayiga et al., 2018). Heavy metal contaminants are usually brought about by human activities, but natural and biological contaminations are also common such as erosion and volcanic activity, mining pollution over time; which causes toxic particles release in vegetation nutrients and forest (Banunle, 2018). These contaminants are poisonous since they sometimes accumulate in the food chain (Masindi and Muedi, 2018). Pb, Co, Cd and other toxic heavy metals cannot be biodegraded, so they can be distinguished from other pollutants, but they can accumulate in plants, even if the concentration is relatively low, it can cause various diseases and diseases. Higher levels of essential and non-essential heavy metals in the soil may inhibit plant growth and cause toxic symptoms in most plants (Ochonogor, 2014). Several remediation techniques for inorganic compounds are known in literature but phytoremediation stands out.

Phytoremediation of inorganic contamination

Phytoremediation of inorganic contaminants comprises three technologies, plant extraction (similarly known as phytoextraction/phytoaccumulation), root filtration (rhizofiltration), and plant stabilization (phytostabilization) (Chirakkara et al., 2016; DalCorso et al., 2019). In phytoextraction as aforementioned, heavy metals within the soil are absorbed by the roots of the plants, transferred to the ground part, and accumulated in the soil. The contaminants do not decompose, but remain in roots and/or plant tissue (Chandra et al., 2017). After harvesting plant parts containing inorganic contaminants, it is advisable to keep them in a safe place for discarding. It is reported according to some authors (Banunle, 2018; Sharma, 2018) that the amount of contaminated plant material treated is relatively small compared to the amount of contaminated soil treated with in situ remediation techniques. There are differences in rhizofiltration from the phytoaccumulation, as this is applied to contaminants dissolved in shallow, underground, or wastewater (Chirakkara et al., 2016).

In the process of rhizofiltration of plant root, inorganic contaminants will be adsorbed in the roots or deposited on the roots (Makombe, 2018; Makombe and Gwisai, 2018). The fixation of pollutants in the root zone by the effects of soil chemistry, microbiology, and physics are also referred to as phytostabilization (Touceda-González et al., 2017). Some soils are so severely contaminated hence metals removal using plants would take an impractical expanse of time. Therefore, the normal practice is to select drought-resistant, fast-growing fodder or plants which will be able to grow in metal-contaminated and nutrient-deficient soils.

Hyperaccumulation process by some plant species

The remediation techniques noted here is plant extraction (phytoextraction), identified as phytoaccumulation, where residues of pollutants are taking by plant roots and transferred to other parts of the plant. Some metals are more deadly than others (e.g. arsenic, cadmium is less toxic) for instance cobalt, nickel, chromium, mercury, and selenium are very toxic even in small quantities (Masindi and Muedi, 2018). Plant extraction according to Rascio and Navari-Izzo (2011) can be accomplished by removing high concentrated contaminants from the soil, such as using hyperaccumulators; uptake of low concentrations of extracts while maintaining high growth status as in *Populas sp*. (Nissim et al., 2018). Subsequently, phytostabilization removes contaminants and reduces their leaching from the soil by reducing crop roots. Roots can also be an important material for transforming harmful metals into low-toxic forms (Ali et al., 2013). Additionally, damage to plants depends on the microorganisms that come with the root system and the enzymes that are secreted by the root to clear the germs and then remove them by absorption and transpiration.

The roots that accumulate higher concentrations of iron in each tissue are higher; and so, their habitat is acknowledged as hyperaccumulators (Srivastav et al., 2018). Qatari plants reported in recent studies by Al-Thani (2019) are the most candidates for active phytoremediation of contaminated compounds of such nature. Considering that monitoring is employed, *Phragmites australis*, *Typha domingensis*, *Amaranthus spp.*, *Nerium oleander*, and *Ricinus communis* are noted as important species of plant for successful ecological remediating and conserving a healthy environment (Al-Thani, 2019). *Table 2* summarizes some examples of plant species and their metal accumulation capabilities that have been tested for phytoremediation studies. In general, different methods of phytoremediation have potent characteristics which make them suitable for diverse soil and water pollution remediation. These methods of study are delimited by duration, nonetheless it supports the capability of selected phytoremediation plants to be considered (Tang and Angela, 2019a). For phytoremediation through phytoaccumulation, the shoot must be obtained after uptake. The shoot can be burned or otherwise destroyed (Valipour et al., 2015).

Table 2. *Some plant species used in the hyperaccumulation of metals and their accumulation capacity*

Plant species	Family	Polluted medium	Metals	Metal accumulation capacity (mg kg^{-1}DW)	Phytoremediation mechanism and metal accumulation compartment	References
Blue stool (*Noccaea caerulescens*)	Brassicaceae	Water	Pb	1,700–2,300	Rhizofiltration (aerial parts/root)	Dinh et al., 2018
Hemp (*Cannabis sativa L.*)	Cannabaceae	Soil	Cd	151	Phytoextraction (aboveground plant parts	Ahmad et al., 2016
Madwort (*Alyssum markgrafii*)	Brassicaceae	Soil	Ni	4,038	Phytoextraction (aboveground plant parts)	Salihaj et al., 2018
Hemp (*Cannabis sativa L.*)	Cannabaceae	Soil	Cu	1,530	Phytoextraction (aboveground plant parts)	Ahmad et al., 2016
Southern cone marigold (*Tagetes minuta*)	Asteraceae	Water	As	380.5	Phytoextraction (shoots)	Salazar, 2014
Johnson grass (*Sorghum halepense L.*)	Poaceae	Soil	Pb	1,406.80	Phytostabilization (reduction in rhizosphere)	Salazar, 2014
Water/red birch (*Betula occidentalis*)	Betulaceae	Soil	Pb	1,000	Phytoextraction (shoots)	Koptsik, 2014
Alpine pennygrass (*Thlaspi caerulescens*)	Brassicaceae	Soil	Cd	5,000	Phytoextraction (shoots)	Koptsik, 2014
Sunflower (*Helianthus annuus*)	Asteraceae	Soil	Pb	5,600	Phytoextraction (shoots)	Koptsik, 2014
Alpine pennygrass (*Thlaspi caerulescens*)	Brassicaceae	Soil	Ni	16,200	Phytoextraction (shoots)	Koptsik, 2014
Black mustard (*Brassica nigra*)	Brassicaceae	Soil	Pb	9,400	Phytoextraction (shoots)	Koptsik, 2014
Alfalfa/lucerne (*Medicago sativa*)	Fabaceae	Soil	Pb	43,300	Phytoextraction (shoots)	Koptsik, 2014

Benefits and limitations of phytoremediation technology

Phytoremediation does not only have advantages but also disadvantages that need to be considered when using this technique. Economically it is cost advantageous, but tracking results can be time-consuming and more of these are elaborated in *Table 3*. Choosing the technique that can recover multiple pollutants at once is tough (Srivastav et al., 2018). The concentration of contaminants and the occurrence of extra toxins should not exceed the tolerance of the plants used. It is not easy to choose plants that effectively remove various impurities. In applying this technique, these limitations and the likelihood of these pollutants entering the food chain should be considered.

Table 3. *Benefits and limitations of the phytoremediation technology of compounds (Dhanwal et al., 2017; Ashraf et al., 2019)*

Benefits	**Limitations**
Application	
It can be employed in situ, i.e., on-site removal of contaminants, whether within the soil, water, or groundwater	It is mainly applicable to the top layer of the soil and mine tailings
It is very effective at sites where low amount/toxic contaminants are present	It offers limited applicability to diverse kinds of wastes, especially with high-level toxicity wastes
Cost factor time factor	
It offers lower labor expenditures and reduced cost in operations	Plant deaths may occur in highly toxic sites which could increase the cost of the process
It comes with low investment cost and minimal equipment requirement (constitutes substantial savings)	Mostly there is incomplete removal of contaminants with long-term low performance
Contaminants can be recovered from the plant tissues and offer an opportunity for commercialization	Good cultivation practices and maintenance is required to avoid accidents
Performance	
It can be used for remediating soils that are nonproductive for agricultural purposes	The effectiveness of this remediation process is affected by seasonal factors
It has the potential to treat sites polluted with more than one type of pollutant	A good considerate of the performance and physiological changes of plants in response to different varieties of wastes is needed
Impact on the environment and population	
It is aesthetically pleasing and widely accepted by the public community	There is the possibility of bioaccumulation of pollutants in the food chain
It can reduce erosion of soils, especially thinner inorganic soils	There is the possibility of introduction and spreading of undesirable invasive species of plants
It is nondestructive, nonintrusive, highly biologically active, therefore have a very low environmental impact on soil and water	Proper discarding of plant matter is required with proper risk assessment
It reduces leaching of particulate substance and spreading of toxicants	

Interaction of phytotransformation, phytoextraction, and phytovolatilization technologies

Phytotransformation, otherwise known as phytodegradation, as aforementioned is the decomposition of organic contaminants released by plants: the action of compounds (like enzymes) is produced by plants (Saleem, 2016). There is the degradation of organic pollutants into simple compounds that integrate within plant tissues to encourage plant growth. Restoration of sites by phytotransformation relies on the direct uptake of contaminants via a medium and buildup in the plant (Abdullah et al., 2020). Plants absorb hydrocarbons and extra complex organic molecules and then metabolize or mineralize them through sunlight-driven chemical reactions (Schwitzguébel, 2017). For instance, some enzymes can break down waste from ammunition (explosives), chlorinated solvents, or herbicides. This technology can similarly be used to get rid of noxious waste from petrochemical and storage sites, fuel leakages, leachate stacking, and agrochemicals (Kumar et al., 2018). To successfully implement this technique, the transformed compounds accumulated in the plant must be non-toxic or less harmful than the parent compound. Hybrid *Poplars* are proven in research to convert TCE into trichloroethanol, dichloroacetic acid, and trichloroacetic acid which is partially mineralized into CO_2 (Leung et al., 2019; Feng et al., 2017). Here, organic pollutants and heavy metals are being investigated too. Soil conditioning, including chelating agents, may be needed to break the compounds that connect pollutants with soil particles to encourage their uptake by plants (Verma, 2017; Franchi and Petruzzelli, 2017). In some cases, plant transformation is used in cooperation with other restoration techniques or as an improving technique (Mustapha and Lens, 2018).

The discharge of volatile contaminants into the atmosphere via plant leaves refers to phytovolatilization as previously described and is a form of phytotransformation (Limmer and Burken, 2016). Even if the discharge of contaminants into the atmosphere might not attain the full clean-up goal, phytovolatilization treatment may be ideal merits to the long-term properties of the soil and the danger of groundwater contamination (Limmer and Burken, 2016). In literature, phytovolatilization is generally considered beneficial because it usually dilutes atmospheric pollutants and undergoes photochemical degradation. In this technology plants is not just a research area of traditional organic pollutants but also an important research area for other contaminants that occur naturally in the soil and roots of plants. Phytovolatilization of many inorganic and organic contaminations in the natural and agricultural environment is usually observed. Studies by Arya et al. (2017) on the phytovolatilization of pollutants have shed light on ways by which many pollutants are evaporated from plants. In phytovolatilization, certain organic contaminants become volatile in plants and then become evaporated. Compounds having a low octanol-air partition coefficient (log Koa b 5) are reported as been more volatile in plants (Limmer and Burken, 2016). Research conducted by Nwaichi et al. (2015) showed that plant can promote the migration and/or degradation of carbon monoxide in the soil; just like *Fibrristylis littoralis* which is employed for the biological regeneration of agricultural soil polluted by crude oil (up to 92% PAH, shelf life 90 days). Moreover, compounds that cannot be transferred to plants owing to being hydrophobic can still be absolved in plant tissues during particle deposition or air distribution over the soil (Limmer and Burken, 2016). But, the relative prominence of various remediation techniques remains unclear, especially for less studied connections (Limmer and Burken, 2016).

Phytoextraction interactions with phytovolatilization are two methods of removing organic contaminants and detoxification in agricultural soils. It has been reviewed in this paper that phytoextraction removes soil contaminants by concentrating them on parts of the harvested plant. Previous research studies (Izinyon and Seghosime, 2013; Sun et al., 2018) have unraveled *Zucchini* (*Cucurbita pepo*) as a good organic compound storage medium for agricultural land. The mechanistic interaction of phytoremediation involving phytotransformation, phytoextraction, and phytovolatilization technologies is illustrated in *Figure 2*.

Future perspectives in biotechnological enhancement for phytoremediation

Recent studies have offered the physiological and molecular technique of remediation to improve remediation and the cleanup of the agricultural and natural environment. Food waste being used has also helped to control the proper management of food/vegetables/fruit. This gives plants the natural ability to absorb, decompose, or concentrate pollutants from soil, water, and air. Contaminants and toxic metals are the core objectives in phytoremediation

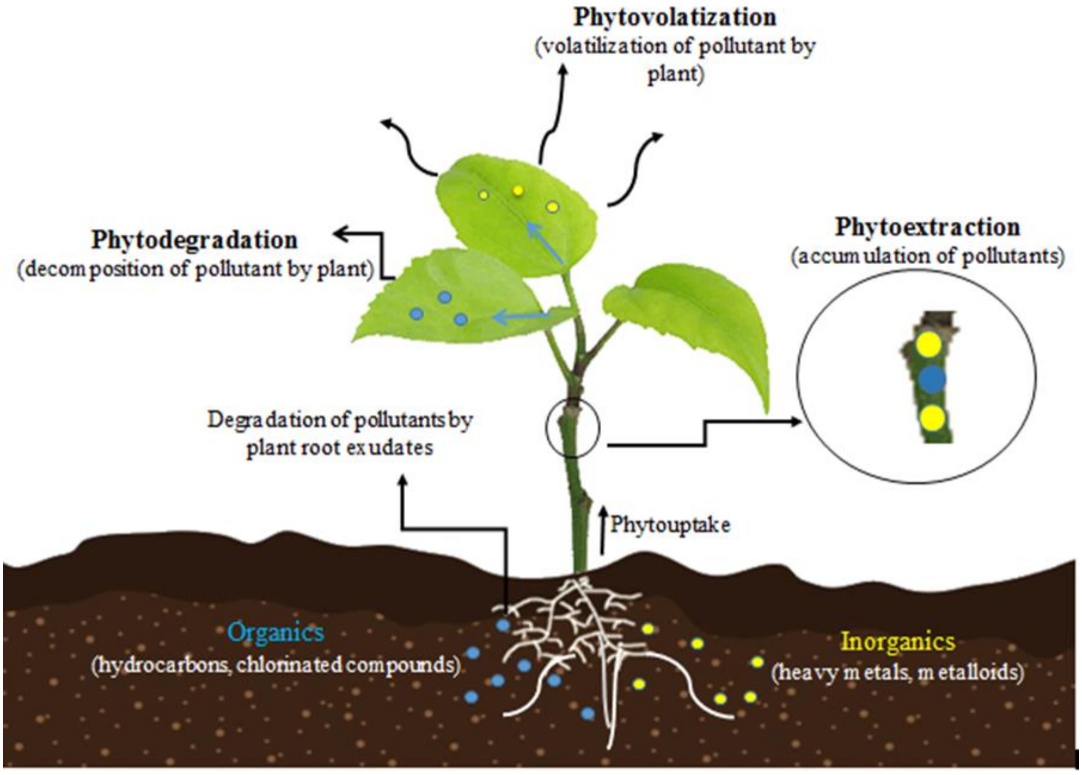

Figure 2. *Mechanistic overview of 3-phase phytoremediation process*

Plant-microbial assisted interaction

Plant and rhizosphere microorganisms are generally employed to remediate contaminated land. Under this mechanism, plants work together to promote soil regeneration through the action of roots and soil microorganisms. Microorganisms utilize root metabolites (secretions), which in turn allow plants to benefit from microbial processing/mineral dissolution (Asemoloye et al., 2019). Plants can absorb pollutants from the soil and transfer them to themselves, while microorganisms mainly decompose pollutants. With the introduction of transgenic techniques, microorganisms and plants can progress to better degrade pollutant. Nonetheless, the use of inherently improved organisms in many countries, different political and moral issues, and related legal power limits the effectiveness of the application. It is well known that microorganisms play key roles in the decomposition of toxic substances as they help in the elimination of undesirable molecules in the environment (Maier and Gentry, 2015). As microbiology evolves, biologists hire the smallest living things on earth to clean and remediate highly oil-contaminated ecosystems. Undoubtedly, microbes are a viable and unused resource for novel environmental biotechnologies (Gaur et al., 2018). Plant growth in a contaminated field often improves soil quality by increasing microbial populations and organism diversity, plus adding organic matter to the soil. Biological treatment (mainly microbial decomposition) is a natural way of eradicating contaminants by decomposing contaminated nutrients. Soil microorganisms can be tested aerobically (aerobic biodegradation) or anaerobically (aerobic biodegradation). Organic compounds through biological treatment have been effectively performed on agricultural land under natural conditions (Girma, 2015; Odukkathil and Vasudevan, 2016). Plant in combination with microbes efficiency can be enhanced by mixing, aerating, and adding nutrients, for example, heterotrophic bacteria are employed to clean agricultural soils contaminated with crude oil (Odukkathil and Vasudevan, 2016). An important condition is the presence of microbes with sufficient metabolic potential. Microbes can be native to the infected area (biostimulation) or insulated from the subsequent area (bio-augmentation) (Varjani and Upasani, 2019; Salimizadeh et al., 2018). If these microorganisms are present (Nishiwaki et al., 2018), the biodegradation of contaminants can be sustained by providing sufficient nutrients, moisture, and oxygen. Other variables, for example, salinity are usually out of control. The destructive potential of microorganisms for various pollutants has been previously reported (Mishra et al., 2020; Chen et al., 2019), namely; hydrocarbons, pesticides, and furans for many compounds, including PCBs, PAHs, DDT, and others. The application of the pesticide in the soil can cause problems because according to Abatenh et al. (2017), biological methods are appropriate for conditions where the pesticide is not harmful to microorganisms and plants employed for remediation. Compared to other biological methods, microbiological re-purification is considered to be the most effective method, but high molecular weight hydrocarbons, with low adsorption and solubility, limit their availability to microorganisms (Koshlaf and Ball, 2017). Microbe-assisted phytoremediation can be also carried out by stimulation via inoculation with pesticides degrading microorganisms (Mitton et al., 2012). It is reported that microorganisms can secrete enormous amounts of surfactants and enzymes, hence it is possible for pesticides to undergo extracellular degradation due to these secreted enzymes (Sharma et al., 2018; el Zahar Haichar et al., 2014).

A study by Balcom et al. (2016) reported the potency of microorganisms to metabolize micropollutants such as xenobiotics during the process of wastewater treatment.

These include the concentration of contaminants and chemical nature, the physicochemical properties of the surroundings, and their availability to microorganisms (Koshlaf and Ball, 2017; Bharathi et al., 2017). Due to various factors, monitoring and improving the biological treatment procedure is a challenging system. These factors consist of the microbial populace that can decompose the contaminant and environmental factors (temperature, soil type, pH, nutrient uptake, and oxygen or other electrons) present (Abatenh et al., 2017; Kothe, 2015). The non-existence of information concerning the effects of several environmental factors on the proportion and the extent of biodegradation creates uncertainty.

Nano-phytoremediation enhancement

Nano-phytoremediation involves a combined application of nanotechnology and phytoremediation to decontaminate the environment. Nanotechnology improves the efficacy of phytoremediation. Nanotechnology can provide an environmentally friendly alternative to remediation and management without harming nature. Nanoparticles are used to remediate soil and water contaminated by heavy metals, organic and inorganic pollutants (Srivastav et al., 2018). A variety of plants, bacteria, and fungi in studies

(Mallikarjunaiah et al., 2020) also enhance their ability to accumulate very high concentrations of metals, which are also recognized as hyperaccumulators. Plant species used in nano-plant engineering cleaning (nano-phytoremediation) technology to decontaminate contaminated soil include the application of phytoremediation techniques (for instance, phytodegradation, phytoextraction, phytostabilization) and nanoparticle.

Due to the high efficiency of pollutants remediated by plants using this technology, numerous reports (Srivastav et al., 2018) have shown that various nanoparticles/nanomaterials significantly detoxify or restore contaminated soil from organic, inorganic, and heavy metal pollutants. Nano zerovalent iron (nZVI), bimetallic nanoparticles (Pd/Fe) and magnetite nanoparticles (nFe3O4), according to the literature (Alonso et al., 2018) may rapidly decompose organic pollutants such as atrazine, chlorpyrifos, trichloroethylene (TCE), pentachlorophenol, pyrene, polychlorinated biphenyls, lindane, 2,4-Dinitrotoluene and ibuprofen from the contaminated soil environment.

Studies by Pillai and Kottekottil (2016) reveals that plant species (*Cymbopogon citratus*) and nanoparticle (nZVIs) can be used to remediate Endosulfan pollutant at an efficiency rate of 86.16 ± 0.09 (%). Souri and coworkers (Souri et al., 2017) also reported that Arsenic (As) pollutant was removed using plant (*Isatis cappadocica*) and nanoparticle (SANPs) at 705 ppm and 1188 ppm accumulate in roots and shoots, respectively. A recent study by Ma and Wang (Ma and Wang, 2018) proves that 82% of Trichloroethylene pollutants can be remediated by a combination of Fullerene (nC60) and *Populus deltoids* from the environment. The success of phytoremediation, or more precisely the phytoextraction, depends on the hyperaccumulator specific to the particular pollutant. Preferably, researchers (Srivastav et al., 2018) suggest that the nano-phytoremediation must be able to accumulate excess contaminants (organic, inorganic, and heavy metals), specifically in the aboveground part (sinking potential). It ought to be a fast-growing plant with high biomass (growth and productivity). The use of selected nanoparticles significantly increased plant growth and treatment with nano augmentations improves the efficiency of phytoremediation and significantly removed pollutants from the soil (Pillai and Kottekottil, 2016).

Despite the many benefits, we obtain from this combination of technology; research on phytoremediation using nanomaterials is very scanty. So far, only microcosm studies (Simonin and Richaume, 2015) have been carried out, so future studies need to use more realistic studies and a better understanding of field practicals is needed.

Genetic engineering enhancement

Genetically improved technology creates effective means of plants and microbes combined with systems of bacterial-plant remediation. Combined cultivation of contaminant sources and individual microbes, whole cells, living plants and plant wastes, food, agriculture, and forestry wastes plays key roles in reducing the content of heavy metals in mining locations to bring a good return to agriculture or the natural environment. Similarly, genetic manipulations of plant hosts in microbial communities can improve phytoremediation capabilities (Tripathi et al., 2020). This includes isolation of bacteria and gene integration that direct the production of specific enzymes thus resulting in degradation of pollutants using the transport of modified organisms and an increase in the number of responsible microbial species in the host system. Biotechnology (genetic engineering) from a previous research study (Dhanwal et al.,

2017) can be engaged to attach one or more active accumulator genes from higher plants into smaller plants, thereby increasing the final biomass. Novel catalytic enzymes can be used in present biotechnology for soil remediation; new microorganisms can be a replica with precise degrading genes for active hydrocarbon degradation (Asemoloye et al., 2019).

Currently, genetically improved plant species are produced using genetic engineering techniques and are used for a plant in remediating soils contaminated with methyl mercury, a neurotoxic agent (Dhanwal et al., 2017). Conversely, modern biotechnological advances, for instance, the new omic revolution, the emergence of nanotechnology, and the innovation of new catabolic genes, may improve the competence of bioremediation and its applicability in removing soil pollution. To identify plant traits that depend on a particular combination of several genes; for instance, a quantitative map of the trait loci between zinc-tolerant (*Arabidopsis helleri)* and non-zinc-tolerant (*Arabidopsis lyrate)* hybrids identified several genomic regions, and combining them explains why more than 42% of the plant was tolerance to zinc (Nahar et al., 2017). Arabidopsis and Transgenic tobacco are some examples of the genes of transgenic bacteria merB and merA (Dhanwal et al., 2017) that have the potential to eliminate mercury from the soil. Studies have shown that transgenic plants combined with bacterial genes can transform the herbicide Simazine into different non-toxic forms (Azab et al., 2016). Nahar et al. (2017) also reported the *Arabidopsis thaliana* AtACR2 gene (encoding arsenic reductase 2) which was cloned and transformed into the tobacco genome (*Nicotiana tabacum*). The results obtained showed that transgenic tobacco has a higher tolerance to arsenic than wild tobacco.

For genetic manipulation, the use of bacteria is employed to assist plant remediation. Therefore, several strains of bacteria and fungi are known to degrade these compounds (Gilani et al., 2016). In another study, Gilani et al. (2016) identified 14 species of *Pseudomonas* and isolated them from the soil as the organisms that could degrade chlorpyrifos. Many of these soils have been contaminated with a mixture of pollutants let us say pesticides (Barchanska et al., 2019). Therefore, preserving the steadiness of genes transferred to a host is a very difficult task (Tripathi et al., 2020), and there are signs that recombinant organisms with certain characters often lose their efficacy to degrade some contaminants.

Improvements in omics technology provide opportunities for isolating and cultivating such useful microorganisms and studying non-cultivable organisms. The next-generation of sequencing technology can provide an ideal method for analyzing microbial communities (Van Dorst et al., 2016). Although the higher nutrient content in the artificial medium usually restricts oligotrophic bacteria (i.e microorganisms that require only a small amount of nutrients) and prefers copiotrophs bacteria (i.e. microorganisms that grow under nutrient-rich conditions), therefore, it is similar to the new cultivation technology of the natural environment is closing the gap between culturally dependent methods and culturally independent techniques (Van Dorst et al., 2016; Ferrari et al., 2011).

Conclusion

Biotechnological integration may provide a crucial step towards the development viability of the remediation of the ecosystem. However, there is a need for more research into understanding the mechanisms underlying plant-microbial interactions of the rhizosphere. Further exploration is also required to develop the kinetics and simulations for synergistic degradation procedures and their field applications. Additionally, developments in bioremediation are expected to focus on ways to provide conditions that promote plant growth and microbial activity in the soil to enable bioavailability and degradation of organic and inorganic compounds.

Since phytoremediation research is actually interdisciplinary, we recommend the following:

a) Plant breeders, biotechnologists, physiologists, agronomists, soil scientists, biochemists, and environmentalists must work together to produce robust methods to develop genetically modified plants and enhance the potential of existing plants for better contaminant control.
b) In transgenic research on phytoremediation, future research should be feasible to solve the problem of mixed pollution that occurs in many contaminated locations to remove mixed or complex pollutants.
c) Future research should also focus on making better use of metabolic diversity, not only for plants, but also for a better understanding of the complex interactions between pollutants in the rhizosphere, plant roots, soil, and microorganisms (bacteria and mycorrhizae).

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