

## Phytoremediation: An eco-friendly technology to decontaminate pesticide polluted soil and water

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### Abstract

Agrochemicals like pesticides have been an essential part of agricultural system throughout the world due to their efficiency in providing protection from pest infestations in fields. Despite their usefulness, these agrochemicals have posed a constant threat to the environment. The irrational use of pesticides to increase the quality and quantity of the crops is a matter of concern as they can affect some non-target entities like plants, animals, or human beings. These negative impacts have urged a necessity of research-oriented studies of the kind of damage done by them. The research studies include the origin of the harmful chemicals, their fate in the environment, target areas, affected crops and the treatment of polluted environment. Some major corrective steps must be taken to reduce the ill effects caused by these chemicals. Phytoremediation is an efficient technology which in association with the soil microflora aims to treat the target and non-target areas affected by irrational use of pesticides. The present review discusses the role of different phytoremediation techniques in treating pesticide polluted soils and water bodies with some emphasis on role of Biotechnology in Phytoremediation process. The novel concept of nano-phytoremediation, an emerging remediation technology in removing pollutants from environment is also introduced.

**Keywords:** Pesticides, phytoremediation, soil microflora, water bodies, biotechnology, nano-phytoremediation

### Introduction

Country like India has a mixed economy in which agriculture and its allied sectors are the main sources of income. Agriculture therefore remains an area of focus of Indian policy and planning. The agriculture sector has undergone a major revolution after the independence period and there is a tremendous increase in agricultural products due to introduction of advanced techniques and use of synthetic pesticides and fertilizers. However, there is a major relationship between use of pesticides and increasing soil, water and air pollution and associated health hazards

(Abhilash and Singh 2009) <sup>[1]</sup>. One of the major permanent global dilemmas is pollution and our environment is highly polluted due to use of different pollutants like pesticides. A pesticide must be lethal to the target pests and non-target pests must be left unaffected (Syafudin *et al.* 2021) <sup>[2]</sup>. Unfortunately, this is mostly not the case and as a result, the use of pesticides and current pesticide application techniques are in question. Irrational usage of pesticides has led to pollution of environment and it needs to be controlled to prevent further irreparable losses (Aktar *et al.* 2009) <sup>[3]</sup>. The fate of pesticides in nature is depicted in Figure 1.

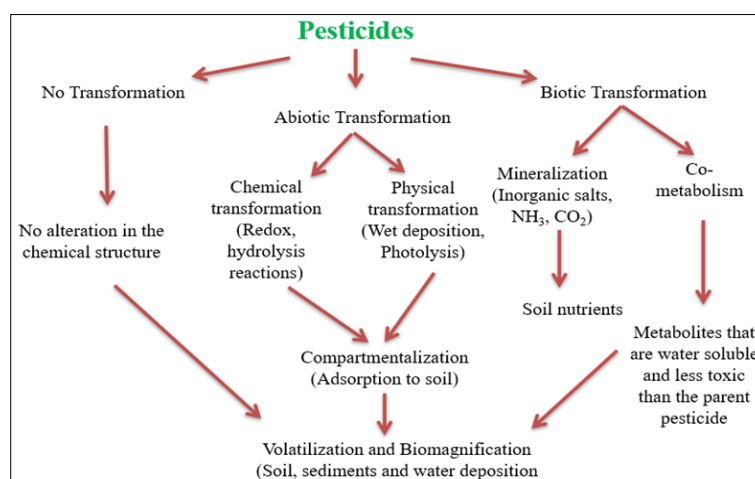


Fig 1: Fate of Pesticides in the environment (Syafudin *et al.* 2021) <sup>[2]</sup>

The currently used physical and chemical methods to treat polluted soil and water are inefficient to meet the remediation standards. The soil remediation techniques are broadly divided into two categories. In *in situ* method, the contaminated soil is directly treated on site or nearby the site.

*Ex situ* remediation requires the presence of a mobile decontamination unit off site, in which the soil is transported to a treatment facility. The most ideal method to remediate soil will be the one that is environment friendly, based on preexisting scientific knowledge and requiring appropriate time (Consea *et al.* 2012) <sup>[4]</sup>.

Phytoremediation is an autotrophic, eco-friendly, inexpensive and a better technology as it can be performed *in situ* and is driven by solar energy (Tripathi *et al.* 2016)<sup>[5]</sup>. It is simple to manage with a low installation cost and is applicable over a large area. As it releases organic matter in the soil, it also improves soil fertility (Jacob *et al.* 2018)<sup>[6]</sup>. Integration of nanotechnology with phytoremediation is considered as an emerging solution to remove excessive pesticides from soils (Gomes, 2025)<sup>[7]</sup>.

The current article focuses on the research and development activities related to the different aspects of phytoremediation and its application in removal of pesticides from soils and water. Utilization of plants that can metabolize and accumulate these pollutants from the environment is being explored to reduce the soil and water pollution (Jaswal *et al.* 2022)<sup>[8]</sup>. Role of Biotechnology in creating transgenic plants with improved potential to treat pesticides has been reviewed. It also discusses the possible merits of nano-phytoremediation, an emerging pollution cleanup method to wipe out excessive pesticides from natural resources.

### 1. Production and Usage of Pesticides

The pesticide production first began in India in 1952. Now, India is the world's fourth largest producer of pesticides. Pesticides are mainly used to protect the agricultural fields from insect manifestations which will help to enhance the agricultural production (Nayak and Solanki 2021)<sup>[9]</sup>. The usage of pesticides in India is different as compared to its usage in other parts of the world. In India, the insecticides are used in majority of places, followed by fungicides, bactericides and then herbicides. The pesticide usage pattern in the world comprises of heavy use of herbicides followed by fungicides and bactericides, then insecticides and rodenticides. About 40% of pesticides that are used belong to the organochlorine class of compounds. Due to their broad mode of action and less cost, chemicals like DDT, Aldrin, Dieldrin are most popularly used throughout the world (Lallas 2001)<sup>[10]</sup>.

Continuous use of organophosphates can lead to their accumulation in soil and nearby water bodies (Jayaraj *et al.* 2016)<sup>[11]</sup>. As these pesticides are highly water soluble, their accumulation in water run-off from agricultural fields is also high. Some pesticides like Carbamates are converted into different products via different paths like photolysis, hydrolysis, oxidation, biotransformation, biodegradation, and metabolic processes in living organisms. Carbamate metabolites are less toxic as compared with their parent compounds but in some cases, the metabolites can be more toxic than the parent compound (Cycon *et al.* 2017)<sup>[12]</sup>.

Neonicotinoids have become the most widely used class of pesticides in the world due to their toxic effects on insects, ease of choice of mode of application, long persistence and systemic nature which ensures its uniform application on the target plant (Jeschke *et al.* 2011)<sup>[13]</sup>.

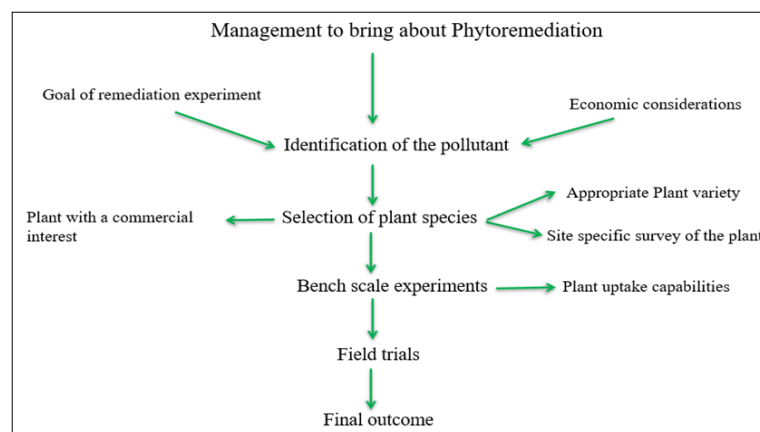
### 2. Exposure to Pesticides

The hazards caused by pesticide exposure can be short-term (nausea, skin and eye irritation, headaches) or long term (asthma, cancer, diabetes). Tragic incidences like extreme level infections, allergies, intoxications have been reported from rural areas. It is difficult to understand their risks as there are many factors that are involved like the type of pesticide, level and period of exposure and the environmental factors of the affected area. Not a single group in human population is unexposed to pesticides and the diseases caused by the exposure are multi casual. It is very important to develop eco-friendly alternatives of pesticide like Integrated Pest Management (IPM) as they help to reduce the negative impacts of pesticides (Arora *et al.* 2019)<sup>[14]</sup>.

### 3. Phytoremediation: A tool to remediate pesticide polluted soils and water:

Phytoremediation is defined as a set of technologies using plants to remediate or contain contaminants in soil, groundwater, surface water or sediments. This technology comprises of two parts: the rhizosphere microflora and the plants themselves which helps in conversion of harmful substances to harmless compounds. It is considered as a viable technique when some specific parameters like low economic value site, no time constraints, presence of infrastructure that offers safe treatment and disposal of the produced contaminated biomass are there (Vidal *et al.* 2019)<sup>[15]</sup>.

The selection of plants showing phytoremediation capabilities is based upon its fast growth, ease of handling and harvesting, rate of photosynthesis (Stefani *et al.* 2011)<sup>[16]</sup>. A variety of aquatic plants have been identified as efficient accumulators of organic and inorganic contaminants from water using hydroponics or field applications. These aquatic plants belong to the families like *Lemnaceae*, *Cyperaceae*, *Haloragaceae*, *Hydrocharitaceae*, *Potamogetonaceae* etc. However, now, there is a need to explore new plant candidates and the genes present in them that are involved in the remediation process. The current implementation strategies for phytoremediation techniques depend upon the criteria as shown in Figure 2.



**Fig 2:** Factors deciding the Phytoremediation techniques to be used (Consea *et al.* 2012)<sup>[4]</sup>

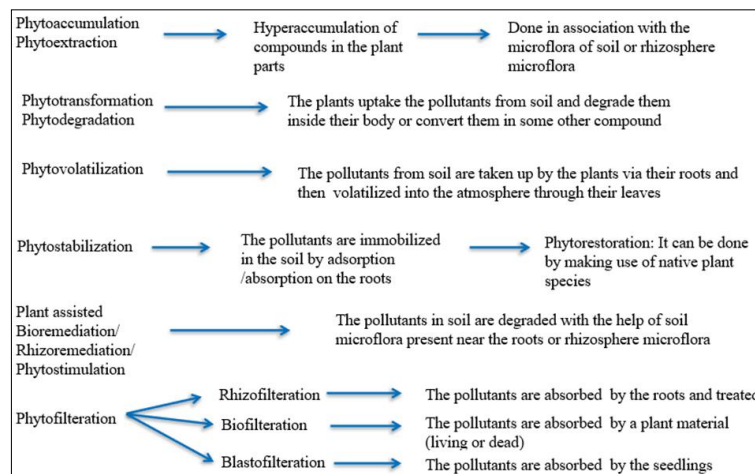
**4. Different methods of Phytoremediation**

- 4.1. Rhizodegradation is the use of rhizosphere components like microorganisms to remediate soils contaminated with organic pollutants. Plants release different organic compounds that attracts microbial population present in the soil which helps in the degradation of contaminants. The rhizosphere microflora is heterogenous due to availability of variety of nutrients and generally the species of *Pseudomonas* genus are present in this area (Khan *et al.* 2009)<sup>[17]</sup>.
- 4.2. Phytofiltration the plants absorb, precipitate, and concentrate the contaminants like pesticides, radioactive compounds from a liquid medium through their root system or other submerged parts. The plants can be kept in hydroponic system in which the effluents get filtered by the roots (Rhizofiltration) (Ruiz and Daniell 2009)<sup>[18]</sup>. Plants with high absorption surface, showing tolerance to the toxic compounds, good root biomass and more accumulation capacity (hyperaccumulators) are ideal candidates for this. The plants showing phytofiltration include *B. juncea*, *P. australis*, *H. annus*, *Salix*, *Populus* (Favas *et al.* 2013)<sup>[19]</sup>.
- 4.3. Phytostabilization inhibits mobilization of contaminants in the soil. Organic or inorganic contaminants can get incorporated into cell wall of plant root cells or in the humus. The action of root exudates allows metals to precipitate as insoluble forms and gets trapped in soil (Domínguez *et al.* 2009)<sup>[20]</sup>. Plants from *Haumaniastrum*, *Eragrostis*, *Gladiolus* genus are cultivated for this purpose. When phytostabilization is performed with the goal of

returning contaminated land to its former natural state using native plants, it is called as Phytorestoration (Manousaki *et al.* 2008)<sup>[21]</sup>.

- 4.4. In Phytodegradation, the organic contaminants are degraded inside plant the cells by enzymes like laccases, nitroreductases, dehalogenases (Rylott and Bruce 2008)<sup>[22]</sup>.
- 4.5. Phytovolatilization depends on the ability of some plants to absorb and volatilize pollutants. Plants like *Stanleya pinnata* and *Astragalus bisulcatus* for heavy metal volatilization or transgenic plants like *Arabidopsis thaliana*, *Nicotiana tabacum* and *Brassica napus* containing bacterial genes for Mercury volatilization have been studied (Ruiz and Daniell 2009)<sup>[18]</sup>.
- 4.6. Phytoextraction is the absorption of contaminants by roots which are translocated and accumulated in the aerial parts of the plant. This technique makes use of hyperaccumulator plants that has the ability to store high concentrations of specific contaminants in their aerial parts (Ansari *et al.* 2020)<sup>[23]</sup>.

Depending upon the nature of the contaminant, a single plant can utilize multiple phytoremediation mechanisms. For example, a plant can degrade organic pollutants, phytoextract heavy metals, and stabilize contaminants in the soil simultaneously. The plant’s ability to switch in between various phytoremediation mechanisms makes them a successful tool to remediate multi-contaminated environments (Gomes, 2025)<sup>[7]</sup>. The different Phytoremediation techniques which help remove organic and inorganic contaminants from soil and water bodies have been depicted in Figure 3.



**Fig 3:** Classification of Phyto-technologies used to treat organic and inorganic pollutants from soil and water bodies (Ansari *et al.* 2020)<sup>[23]</sup>.

Microorganisms are seen to play an important role in many biological processes associated with soil, like nitrogen transformations, enhancement of organic matter, nutrient release, and their availability. A complex combination of organic and inorganic constituents of soil creates a dynamic environment for the microorganisms which affects plants and other associated microorganisms (Arora *et al.* 2019)<sup>[24]</sup>. The microflora of soil is the first population that gets exposed to toxic substances introduced in soil. Such organisms are the ‘biomarkers’ that reflect the presence of toxic substances in the soil and usually considered in

ecotoxicological tests to evaluate the influence of chemicals on soil system (Sharma *et al.* 2019)<sup>[25]</sup>. The Microbial biomass in soils can be considered as a good measure of soil quality. Lo (2010)<sup>[26]</sup> reviewed the literature on the effects of about 20 pesticides on soil microorganisms, and concluded that it is the organism’s response is variable which depends upon the pesticide chemistry.

**New era of Phytoremediation- Nano-phytoremediation**  
Nano-phytoremediation comprises of integrated studies of nanotechnology and Phytoremediation. Traditional

phytoremediation technique although sustainable, have some challenges like slow rate of degradation or removal, excessive toxicity to plants in response to xenobiotic stress and limited contaminant bioavailability. Combining the use of carbon based, zinc oxides nanoparticles can help to improve the rate of phytoremediation, make contaminant easily available for its treatment and may impart stress resistance to the plants. This combined remediation technology can help to detect, degrade, remove, and neutralize a wide array of contaminants like organic material, heavy metals, and pharmaceuticals. Thus, nano-phytoremediation provides a multifaceted remediation approach which makes use of nanostructures, nanoparticles, and nanomaterials for effective treatment of excessively accumulated pollutants (Gomes 2025)<sup>[7]</sup>. The developed nano formulations are sustainable and economically adoptable technologies. They cause minimum toxicity in the environment and help to enhance microbial activity to degrade the targeted compounds (Gomes 2025)<sup>[7]</sup>. Azzam *et al.* (2023)<sup>[27]</sup> made use of heterogeneous porous biochar derived from banana peel to prepare a magnetic nanocomposite NiFe<sub>2</sub>O<sub>4</sub> for efficient bio absorption of Ciprofloxacin from pharmaceutical wastewater. The results showed that after multiple experiments, no major loss in absorption efficiency was observed, reflecting the stability and reusability of the prepared BC-NiFe<sub>2</sub>O<sub>4</sub> nanocomposite. Similarly, this technique is recently applied for remediation of soil polluted with organic pesticides, and herbicides (Gomez 2025)<sup>[7]</sup>.

### Pesticide Polluted soils

Soils system is the most complex and diverse ecosystems on earth, that contains nearly a quarter of the earth's diversity. In 2019, Food and Agriculture Organization (FAO) conducted a survey and reported that the excessive use of insect control methods are the most prominent practices that has caused the loss of soil biodiversity in the past 10 years (FAO, 2020)<sup>[28]</sup>. Pesticides enter the soil via drifting, wash-off to nearby areas after their foliar application, leaching in ground or during sowing of pesticide treated seeds. Some pesticides can be directly added to soil near the root area and can remain in soil for a longer time and cause pollution. The transport, persistence, and degradation of pesticides in soil depend upon the physical, chemical, and biological properties of the soil.

Based on the mode of application of pesticides, only a small fraction of the applied pesticides reaches their targets and the rest goes to the soil surface and gets distributed via different processes. The elimination of excessive residual pesticides from soils is gaining attention among researchers (Huang and Lu 2021)<sup>[29]</sup>.

Some recent studies report the occurrence of pesticide residues in those agricultural soil where they are not directly applied (Silva *et al.* 2019; Hvězdová *et al.* 2018; Chiaia-Hernandez *et al.* 2017)<sup>[30, 31, 32]</sup>. Silva *et al.* (2019)<sup>[30]</sup> has reported the presence of 76 pesticide residues in the top soil which have 6 cropping systems in eleven European countries. Most of the soils showed presence of at least one type of soil with a maximum concentration of 2.85 mg/kg. Different methods like LC-MS/MS, GC-HRMS were used to detect the pesticide concentration in soil.

Evaluation of the potential of three different plants, Plantain, Sunflower, and Soybean for the phytoremediation of Azoxystrobin-contaminated soil was done using a solubilizing agent like Tween 80 (Romeh 2015)<sup>[33]</sup>. The study concluded that *Soybean* and Plantain are the most suitable plant species for phytoremediation of Azoxystrobin contaminated soils.

A study was carried out to evaluate the possible role of Maize to remediate Atrazine contaminated soils. The metabolism of Atrazine by the plant is attributed to the chemical pathways leading to the formation of the inactive OH-2-atrazine inside the root and leaves during the first week (Ibrahim *et al.* 2013)<sup>[34]</sup>.

Work on degradation of Atrazine, Metolachlor and Trifluralin has been done in contaminated soils where plants of the *Kochia* sp. were planted (Coats and Anderson 1997)<sup>[35]</sup>. The increased degradation occurred in the rhizosphere of the plant suggesting that an interaction between the plant and microorganisms has led to the increased degradation of the pesticides in soil.

Role of Castor bean was evaluated for its phytoremediation capabilities to remove different organochlorine pesticides from polluted soils (Rissato *et al.* 2015)<sup>[36]</sup>. It was concluded that higher the hydrophobicity of the compound with more interaction with the soil or root, greater is the tendency to concentrate the pesticides in the roots of the plant.

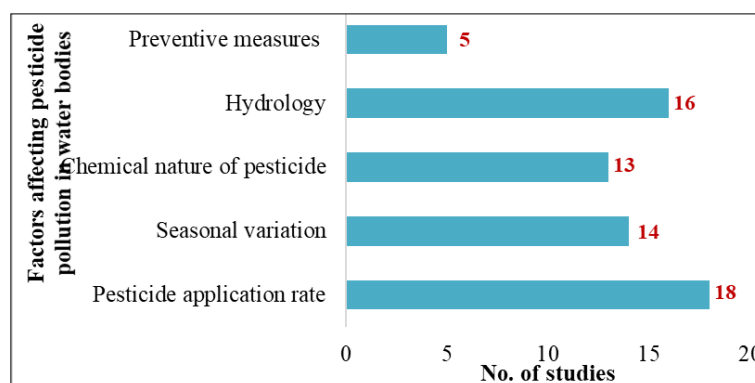
### Pesticide polluted water bodies

With the expansion of agricultural land, the trend of intensive use of pesticides to protect plants has been amplified in which irrigation plays a strategic role in improving productivity and transferring agricultural pollution to water bodies. If the pesticide selection and management is improper, it can lead to release of toxic substances like carcinogens present in them in water bodies (Schreinemachers and Tipraqsa 2012)<sup>[37]</sup>. They accumulate in water and demonstrates ill effects on humans and livestock drinking the water from contaminated water bodies.

Major agricultural contributors to water pollution are pesticides, organic carbon, and pathogens. Pesticides most commonly enter water bodies due to run off from adjacent fields, direct spray, airborne drift, and intentional dumping. Pesticide penetration into groundwater is a common phenomenon and is controlled by balancing of two factors, water applied (absorption) and interaction with organisms and solid particles (adsorption) (Huggenberger *et al.* 1973)<sup>[38]</sup>.

Environmental temperature plays an important role in dissociation of harmful chemicals in water as it determines the level of dissolved oxygen and affects the behavior of different chemicals in water by influencing volatility, solubility, and chemical activity of pesticides (Chovanec *et al.* 2003)<sup>[39]</sup>.

Chow *et al.* 2020<sup>[40]</sup> reviewed some papers and concluded that the two most common factors that influence aquatic pesticide pollution are temporal trends of pesticide use and hydrological conditions of the water bodies. Apart from these, the chemical nature of pesticides and seasonal variations also dictates the severity of water pollution (Figure 4). These studies are done for a period of more than 5 years.



**Fig 4:** Factors associated with pesticide pollution in water bodies and number of long-term (>5 years) monitoring studies supporting them (Chow *et al.* 2020)<sup>[40]</sup>.

An experimental work was carried out to demonstrate the role of *Plantago major* L. to remove Cyanophos residue from water and to assess the potential activity of the plant to bring pesticide phytoremediation. The study proved *Plantago major* L. to be an efficient pesticide remediator and three major degradation products were detected in roots and leaf samples (Romeh 2014)<sup>[41]</sup>.

Aquatic plants like *Eichhornia crassipes*, *Lemna minor* and *Elodea canadensis* were used to treat the pesticide polluted water body. The high photosynthetic activity and growth rate of plants makes it easy to harvest the pollutants along with a high absorption rate of pollutants (Waheed *et al.* 2014)<sup>[42]</sup>.

Dosnon-Olette *et al.* (2010)<sup>[43]</sup> used two types of duckweed species to test the efficiency of removal of Dimethomorph fungicide from agricultural waste water. It was shown that duckweed was able to remove the fungicide if the concentration is not too toxic and it inhibited the depuration mechanisms.

An experiment was performed on six species of trees to determine their feasibility to remediate ground water contaminated with an herbicide, Bentazon in Southern Louisiana. This study claimed that the herbicide was translocated to the leaves of the plant where it was degraded to less harmful compounds in a short time. It was concluded that the most efficient plant out of the six plants was Black Willow (*Salix nigra*) (Conger and Portier 1997)<sup>[44]</sup>.

### Role of Biotechnology in Phytoremediation

The potential of natural plants to remediate pesticide polluted resources is limited as the rate of degradation of these compounds is low, which requires more time to remove the toxic elements from the environment. The lack of proper disposal system of hyperaccumulator plant tissues with contaminants also possess a high risk of contamination of the food chain (Pandey and Bajpai 2019)<sup>[45]</sup>. The remedial capacity of plants can be improved by genetic manipulations and plant transformation methodologies. The introduction of novel traits in high biomass plants by using bacterial/mammalian genes involved in uptake, metabolism, translocation of different pollutants is proving a successful strategy for the development of modified phytoremediators (Jaiswal *et al.* 2019)<sup>[46]</sup>. Such transgenic plants may have genes encoding metal transporters/chelators, degradation pathway enzymes, metal homeostasis pathway enzymes, oxidative stress tolerance enzymes or xenobiotics detoxifying enzymes.

Azab *et al.* (2018)<sup>[47]</sup> reported that the heterologous expression of human P450 enzyme CYP1A2 had increased tolerance with better detoxification of the herbicide Linuron in transgenic *Arabidopsis*. This plant was able to grow at a high concentration of linuron supplemented in the culture medium or in the form of a foliar spray, and showed improved detoxification of the herbicide in their leaves when compared with untransformed control plants.

### Advantages of Disadvantages of Phytoremediation

Phytoremediation makes use of plants' natural ability to remove or degrade the pollutants from natural sources like soil or water. It is less expensive than other remediation methods like incineration or chemical degradation (Cycon *et al.* 2017)<sup>[12]</sup>. It can be successfully used in diverse locations where soil or water is contaminated. This technique is generally most effective near the root region as this region is harbored by rich diversity of rhizosphere microbes (Lasat 2000)<sup>[48]</sup>.

Few demerits of this technology include prolonged time required for the remediation process to complete as it is dependent on the plant's biological processes which are slow. Excessive pesticide concentrations can harm the existence of plants as many of the plants are not resistant to harsh conditions. But sometimes it is observed that the microorganisms in soil or near plant roots can use these xenobiotic compounds as their carbon or nitrogen source for growth and survive well. Many of the demerits discussed here can also be reduced by using genetically modified plants and coupling of nanomaterial or nanostructures with phytoremediation.

### Conclusion

Plants have beneficial effects in the management of pesticide-contaminated soil and water including direct metabolism of pesticides, stimulation of microbial activity in the root zone, extraction of contaminated water and reduction of infiltrating contaminated water. Researches from past indicates that there are a lot of differences in the tolerance of plants to pesticides present in soil and water, and that some plants are more effective than others in the remediation of pesticide-contaminated soil and water. Thus, it is important to identify the tolerant plants and favorable plant-based remediation technologies for management of pesticide contaminated sites (Karthikeyan *et al.* 2010)<sup>[49]</sup>. Plants can be used as 'Biotech Mops' to clean the contaminated environment due to over-use of pesticides. The use of Biotechnology to develop transgenic plants with

improved potential for efficient, cheap, clean, and sustainable bioremediation technologies is very promising, but several challenges persist. They generally remediate soil or sediment in the top three feet of the soil because of their root lengths. Plants which take up the contaminants from the soil and transport them to their stems or leaves without degrading them to non-toxic compounds can potentially harm herbivores that feed on the plants. A unique combination of nanotechnology and phytoremediation as a remediation tool can open new avenues to treat polluted natural resources like soil and water bodies.

Phytoremediation being a very important research area is carried out in almost all the continents especially in the United States of America, Africa, and Asia. More work is required as it remains in the developmental stage. Elaborate knowledge and relevant understanding in this field will help to make this technology a great success. Different ways of remediating pesticide polluted soils are being practiced in India on a large scale. Less work is done on remediation of pesticides using plants and more emphasis is given on exploring bioremediation capacity of microbial population present in soil. It is a known fact that this technology has not become a commercial practice in India even now (Sharma and Pandey 2014)<sup>[50]</sup>.

The commercial success of plant-based technologies largely depends on the generation of valuable biomass on contaminated land. Attempts should be made to produce some valuable biomass out of this technology which can have good commercial value (Consea *et al.* 2012)<sup>[4]</sup>.

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