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Utility of Jatropha for Phytoremediation of Heavy Metals and Emerging Contaminants of Water Resources: A Review

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Contamination of water resources by organic and inorganic pollutants emitted from industrial and non-industrial activities is a global concern. The availability of toxic pollutants in high concentrations may be lethal to humans and the natural ecosystem. Established technologies that range from biological to chemical methods are available to ameliorate polluted environments. Traditional remediation technologies including physical, chemical, and thermal processes have several drawbacks. The key point is that the fate of most of their products is not known. Recently, phytoremediation has gathered momentum and has attracted the interest of many scientists. It has more advantages than traditional methods. Phytoremediation uses plant mechanisms to remodel contaminated environments. The technologies include phytoextraction, rhizofiltration, phytostabilization, phytodegradation, and phytovolatization. These approaches differ in purposes and goals, which can be remediation, detoxification, management of water movement, and leaching of contaminants, containment, and stabilization. Jatropha has now emerged as a plant that can be exploited for phytoremediation. The plant is able to survive on degraded land, often poor and fragile soils. Jatropha has the ability to facilitate sequestration, uptake, translocation, and detoxification of pollutants. The objective of this paper is to provide a review of the utility of Jatropha for phytoremediation of heavy metals and emerging contaminants. Phytoremediation is a new area undergoing extensive scientific research and development. Thus, amalgamation of trends in research and development is essential in order to shape and guide future work.

1. Introduction

Deterioration of the environment due to contamination of soils, sediments, and water has always attracted the interests of the public, scientists, regulators, and public administrators on a global scale.[1] A wide range of contaminants of the environment are documented in literature. These now include chemical and microbial constituents that have not been previously considered as contaminants and are known as “emerging contaminants.” Emerging contaminants are still largely unregulated or in the process of being regulated. They include a wide range of pollutants such as synthetically and naturally occurring hormones, nanomaterials, industrial and household chemicals, disinfectants and their transformation products, and pharmaceuticals and personal care products.[2] The emerging contaminants are mainly of industrial, municipal, or agricultural origin.[3] Persistence of these contaminants in nature may generate severe hazards to the environment and human health due to their toxicity.[4,5] Several technologies have been discovered that provide long-term solutions regarding remediation of besmirched environments. Past experiences have shown the inadequacy of physical, thermal, and chemical treatment methods as control measures. Use of these technologies may even result in new phases of pollution, for example, air pollution.[6] Phytoremediation has recently emerged as an innovative, simple, efficient, environmentally beneficial, and cost-effective alternative strategy to most established remediation technologies.[7–9] It presents one of the largest economic opportunities for remediation, based on plants’ aptitude to work as phytopumps, extracting, and concentrating particular solutes.[10]

Phytoremediation is a technique that uses non-edible green plants to remove environmental pollutants or to render them harmless.[8] The process is a set of novel techniques that exploit vegetation and allied microflora, soil amendments, and agro-techniques to decontaminate the environment.[9] The techniques include rhizofiltration, phytostabilization, phytoextraction, phytodegradation, and phytovolatilization.[8] Generally, these methods are based mainly on physiological pathways such as transpiration, translocation, photosynthesis, respiration, and evaporation that occur in higher plants and their associated microflora. Phytoremediation uses a variety of plant species ranging from small aquatic plants to higher order deep rooted trees. Examples of such potential plants comprise *Pterocarpus indicus*, *Jatropha curcas*,[10] transgenic plants,[11] *Amaranthus* spp.[12] duckweed, and water hyacinth (*Eichhornia crassipes*). These are applicable to remediate contaminants such as several metals, radionuclides, and various organics.[13]

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Jatropha has been known to be a multipurpose plant. It is perennial, nonedible, oil bearing small tree/shrub that belongs to the family Euphorbiaceae. The plant is native to Mexico and Central America.[14] Its uses include serving as feedstock for biofuels, production of medicines and pesticides, and reclamation of degraded lands. The plant has highly efficient and specialized mechanisms against abiotic stresses. Jatropha is able to endure harsh climatic conditions such as drought, nonfertile, and heavily polluted soils.[15] This is due to its well-developed root system that is capable of penetrating a wide range of unfertile and rocky soils.[16] Studies have shown that Jatropha can accumulate a variety of inorganic and organic constituents. Examples include works by Kumar et al.[17] where *J. curcas* removed up to 87% of octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) in contaminated soil and Ahmadpour et al.[18] who used *J. curcas* to accumulate and reduce concentrations of zinc (Zn), lead (Pb), chromium (Cr), cadmium (Cd), and copper (Cu) in sewage sludge by 67.7, 78.3, 77.2, 78.5, and 75.0%, respectively. Elsewhere, the rhizodegradation of lindane (a pesticide) by *J. curcas* L. was demonstrated in greenhouse experiments.[19] The conclusion from these works is that Jatropha is a potential phytoremediator that can compete with food crops as a hyperaccumulator.

Most research work done on Jatropha is on small-scale demonstrations, hence there is need to adopt full-scale applications. Potential applications of several technologies utilized by Jatropha for phytoremediation can still be explored. Phytoremediation can be of economic importance in cases of rhizofiltration, phytoconcentration, and phytodegradation where the metal-enriched plants can be harvested and processed by drying, ashing, or composting. Consequently, a few metals can be derived from the ash. Furthermore, a multipurpose bio-oil can be obtained after harvesting Jatropha seeds. This paper provides a review of the potential utility of Jatropha for phytoremediation of heavy metals and emerging contaminants. The strength of phytoremediation as a clean-up technology is reliant upon merits and demerits of the attendant technologies. These will be outlined in this article.

2. Traditional and Emerging Contaminants of Water Resources

A water contaminant is defined as any physical, chemical, biological, or radiological matter that may alter the quality of water. Inorganic pollutants, and in particular, heavy metals have been extensively studied and their numerous undesirable health effects have been known for many generations. It is Pb, Cd, mercury (Hg), and arsenic (As) that are well known to pose high risk impacts in relation to human health.[20] There are chemical compounds that were not monitored strictly by regulatory agencies in the past, but have now been determined to be hazardous to people. **Table 1** shows the broad categories of contaminants of water resources.[21,22]

Technological advances in industrial, municipal, and agricultural sectors are introducing new contaminants into water resources. These are mainly chemical constituents that have not been previously considered as contaminants. The contaminants are referred to as "emerging contaminants." Emerging contaminants can be broadly defined as any synthetic or naturally occurring chemical compounds or any microorganism that is still unregulated or in the process of regularization and can be a potential threat to the natural ecosystem and human health.[23] The term emerging contaminants embraces a wide range of pollutants, including medicines, disinfectants, contrast media, laundry detergents, surfactants, pesticides, dyes, paints, preservatives, food additives, nanomaterials, and personal care products.[2] The major sources of these contaminants are chemical and pharmaceutical industries, agricultural and household activities. **Figure 1** is an illustration of the pathways through which the contaminants arise.[2] The fate of these compounds is not quantified and may present unknown risks to the global community. Therefore, the removal of emerging contaminants with respect to provision of safe drinking water and release of eco-friendly wastewater has become very important.

3. Principles of Phytoremediation

It is prudent to outline from the onset the principles underpinning phytoremediation. Phytoremediation is the use of non-edible vegetation to remove or render harmless pollutants from contaminated soil or water.[1,8] The process, also known as green remediation, botano-remediation, agro-remediation or vegetative remediation,[9] is applicable in low level contamination either singly or in conjunction with other techniques. Recently, the traditional word of phytoremediation has been supplanted by the word "phytotechnologies." The term implies to all the mechanisms in which plants are used to deal with pollutants.[24] Phytoremediation is now preferred to other remedial options despite the presence of few limitations including extended periods of time required and the possibility of the contaminants to enter the food chain if the plant is consumed by animals.[13]

Deep rooted trees/shrubs, grasses, legumes, and aquatic plants all have proven to be valuable phytoremediators. These plants are either hyperaccumulators or normal plants in combination with soil amendments to either increase bioavailability or stabilize metals.[8] The advent of the technology has brought transgenic plants as new dimension of significance. Phytoremediation is effective against a wide array of substances including metals, radionuclides and organic pollutants (such as nutrients, explosives, surfactants, chlorinated solvents, polychlorinated biphenyls, PCBs, polyaromatic hydrocarbons, PAHs, pesticides/insecticides), and benzene, toluene, ethylene, and xylene (BTEX).[25]

Certain physiological processes occur along specific pathways in plants to eliminate, accumulate, metabolize, and volatilize pollutants (**Figure 2**).[25] Plant root systems play a key role to support a variety of microorganisms that degrade contaminants in the subsurface. In addition, roots supply organic carbon sources to promote cometabolism in the rhizosphere region.[25]

3.1. Merits and Demerits of Phytoremediation

Several merits can be derived from phytoremediation despite the fact that it has not been widely applied. These vary

Table 1. Categories of water contaminants.

Contaminant category	Descriptor	Example
Biological	These are organisms present in water. Alternatively, they are also referred to as microbes or microbiological contaminants	Bacteria, viruses, protozoa, and other parasites
Physical	They principally affect the physical appearance or other physical properties of water (e.g., color, odor, and pH)	Sediment or organic matter suspended in surface water sources such as lakes, rivers, and streams from soil erosion
Chemical	These are elements or compounds that are naturally occurring or man-made	Metals, salts, nitrogen, bleach, pesticides, animal or human drugs, and toxins produced by plants, bacteria, fungi, and algae
Radiological	The group represents chemical elements with unbalanced number of protons and neutrons resulting in unstable atoms that can release ionizing radiation (e.g., alpha, gamma, and beta)	Cesium, uranium, plutonium, and americium

from cost-driven to technical merits. Phytoremediation is now preferred over conventional remediation. Contrary to many encouraging aspects, the process does have some weaknesses. This novel technology is not yet fully developed; therefore, it is likely to face some barriers toward its implementation. The modest regulatory experience and fundamental features of phytoremediation will reduce the size of the role that it plays in the site remediation market. The merits and demerits of phytoremediation as compared to conventional technologies are shown in **Table 2**.[26–28]

3.2. Phytoremediation Mechanisms

There are numerous classification schemes related to the diversity of phytoremediation. Five basic phytotechniques will be elaborated in this section. These are rhizofiltration, phytostabilization, phytoextraction, phytodegradation, and phytovolatilization.[8]

Rhizofiltration is a cost-competitive technique that utilizes plant roots to absorb, precipitate, and concentrate pollutants from surface water or aqueous streams.[8,29]

Phytostabilization refers to the in-place activation technique that utilizes tolerant plants to inhibit mobility or stabilize contaminants. This reduces the bioavailability of contaminants in the environment and minimizes the risk of further environmental degradation by leaching or by airborne means.[8]

The most commonly utilized technique applied for the uptake of inorganic contaminants, primarily metals by plant roots and their translocation within the plant tissues is phytoextraction. In this technique, the metal-saturated above-ground biomass is subsequently harvested via phytomining techniques prior to disposal of the contaminants.[30–32]

Phytodegradation involves the use of plants and enzymes released from associated-microorganisms to take-up, metabolize and degrade contaminants in soil, sediments, sludge, ground water, or surface water.[9,33]

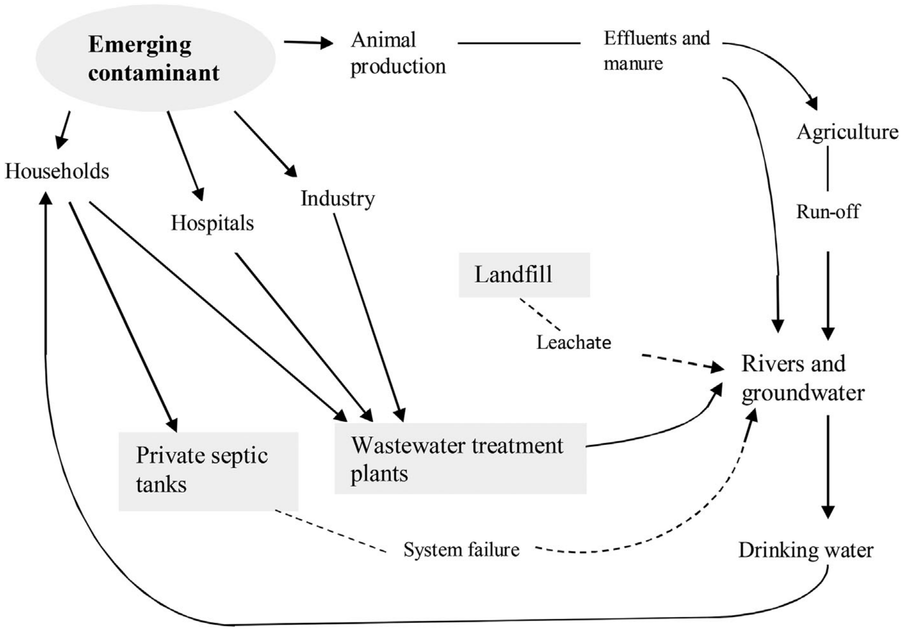

Figure 1. Potential sources and routes of emerging contaminants into water resources.

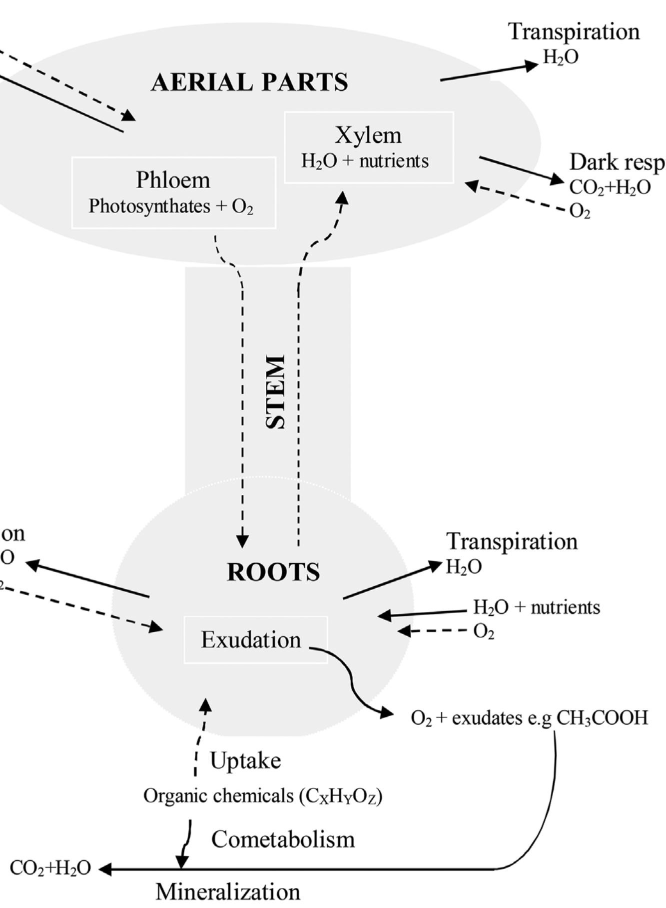

Figure 2. A model of phytoremediation pathways.

Phytovolatilization is the most controversial of all the phytotechnologies. The technology makes use of natural or genetically engineered plants to take up elemental forms of contaminants from the media, biologically converting them into volatile forms, and releasing them into the atmosphere.[33,34]

4. Removal of Heavy Metals and Emerging Contaminants by Different Plants

Experiences in phytoremediation with different plants are valuable in assessing the utility of Jatropha for this purpose. Plant systems operate as solar-driven pumps, and filters as they take up contaminants through their roots and convey them up through various plant tissues where they can be metabolized, sequestered, or volatilized.[9] Research on phytoremediation of contaminated sites has been carried out with a variety of plants. Applications were attempted to remove emerging contaminants (such as pesticides, hormones, and antibiotics) and several heavy metals. Some of the studies have produced valuable information. A summary of selected experiences for phytoremediation and the major findings is shown in **Table 3**. Most of these experiences were small-scale demonstrations.

5. Potential Applications of Jatropha for Phytoremediation

5.1. Rhizofiltration

Rhizofiltration is a cost-competitive technology.[31] Pragmatic data on Jatropha-rhizofiltration related applications is inadequate. There are few examples in the literature mainly on removal of heavy metals. An example is revealed by the work of Luhach and Chaudry[7] on *J. curcas*. They demonstrated the potential of *J. curcas* for phytoremediation of heavy metals from refinery sludge. The study reported higher heavy metal accumulation in the roots than the rest of plant parts, indicative that rhizofiltration was the responsible process. A similar investigation was carried out using sunflower (*Helianthus annuus* L.) and bean (*Phaseolus vulgaris* L. var. vulgaris) to treat uranium polluted water. The uranium removal efficiencies for the bean and sunflower were about 60–80% and more than 80%, respectively.[40] The information on application of rhizofiltration in remediation of organic pollutants by Jatropha is scarce and is not well documented in the literature. Noteworthy is further elucidating the impact of uptake of organic pollutants on root morphology, and metabolic processes of Jatropha for demystification and utilization of this symbiotic relationship in the area of phytoremediation.

Table 2. Merits and demerits of phytoremediation.

Merits	Demerits
• Cost effective	• Prolonged remediation time
• Can be easily implemented and maintained	• Climate dependent
• Several mechanisms for removal	• Effects to food web might be unknown
• Environmentally beneficial	• Ultimate contaminant fate might be unknown
• Aesthetically pleasing	• Results are variable
• Costs 10–20% mechanical treatments	• Slower than mechanical treatments
• Faster than natural attenuation	• Only effective for moderately hydrophobic compounds
• High public acceptance	• Unknown toxicity and bioavailability of biodegradation products
• Fewer air and water emissions	• Contaminants may be mobilized into the ground water
• Conserves natural resources	• Influenced by soil and climate conditions of the site
• Jatropha is an energy plant: A multipurpose bio-oil can be extracted from its harvested seeds	

5.2. Phytostabilization

Information on Jatropha's potential to immobilize contaminants in soil and aqueous solution is lacking. The ability of Jatropha to bioaccumulate and translocate Cu from contaminated soils in Malaysia was evaluated.[18] A high root concentration factor (RCF > 1) and a low translocation factor (TF < 1) were obtained. This species showed a credible future use for phytostabilization of slightly Cu contaminated areas. Another study by Wu et al.[15] determined the phytostabilization potential of *J. curcas* L. in polymetallic acid mining tailings. The accumulation of metals was higher in roots than in stems which were in turn higher than in leaves. In addition, a high tolerance index of more than 90% without phytotoxic symptoms and stunted growth in moderately contaminated soil indicated the plant's suitability for phytostabilization.

A research was also carried out by Moursy et al.[41] to elucidate the potential of *J. curcas* to clean toxic heavy metals derived from sewage sludge. The fact that highest levels of Zn (169 mg kg^{-1}), Cu (173.7 mg kg^{-1}), Pb (3.8 mg kg^{-1}), and Cd (169 mg kg^{-1}) accumulation were found in roots showed the potential of the plant species for phytostabilization. Nonetheless, phytostabilization plays a negligibly significant role in remediation of organic compounds,[42] including emerging compounds, therefore very little is known about the plants species involved. The technique does not require the disposal of hazardous plant material and it is very efficient when rapid immobilization is desirable to maintain the quality of surface and ground water.[9]

5.3. Phytoextraction

There is no substantial information to provide empirical evidence on Jatropha's ability for phytoextraction. In Nigeria, the potential of *J. gossypifolia* for ethylenediaminetetra acetic acid, EDTA, enhanced phytoextraction of heavy metals (Pb, Cu, and Cd) in soil recovered from dumpsites was evaluated.[43] The concentrations of these metals were found to be higher than the threshold value of 100 mg kg^{-1} indicating the plant suitability for Pb, Cu, and Cd phytoextraction. In addition, the values of bioaccumulation factor, TF, and remediation ratio, RR, of *J. gossypifolia* also revealed the usefulness of the plant to translocate Pb, Cu, and Cd to respective plant tissues and phytoextraction efficacy under chelant-assisted phytoremediation.

Similar studies were undertaken by Ghavri and Singh[44] to expound the endurance of *J. curcas* L. to Fe and its phytotranslocation by the plant from a Fe-rich marginal soil. A higher TF in wasteland soil than normal field soil as well as bio-concentration factor and concentration index, CI, of 0.12–0.3 and 1.0–6.2, respectively, indicated the potential of *J. curcas* L. to remediate Fe-contaminated soils. As stated earlier, the translocation of approximately 87% HMX in parent form to shoot and leaves of *J. curcas* provided empirical evidence on the plant's potential to successfully remove emerging contaminants in explosive contaminated sites by phytoextraction.[17] Other tolerant, nonedible, and succulent plants such as ornamental shrub crown of thorns (*Euphorbia milli*) have also demonstrated the capability for Cr phytoextraction with a translocation efficiency of 80%.[45]

The advantage of phytoextraction is that it can be a useful resource mobilization strategy with particular reference to the plant biomass containing the extracted contaminant. For example selenium (Se) in plant biomass is an essential element for Se-deficient areas and can also be a useful stock feed.[31]

5.4. Phytovolatilization

Phytovolatilization is a useful technique for removal of high volatile pollutants that are treated by conventional air-stripping such as BTEX, trichloroethylene (TCE), venyl chloride, and carbon tetrachloride.[46] There is insufficient literature on research concerning the potential of Jatropha for phytovolatilization. This new area is subject to exploration. One such potential was the work of Agamuthu et al.[35] who revealed phytovolatilization as one of the processes that was responsible for loss of lubricating oil via abiotic factors like evaporation. However, other plant species have demonstrated the potential to transform emerging contaminants and some other inorganic pollutants into harmless or less harmful products. For example, Gunther et al.[47] as cited by Qixing et al.[42] observed the potential of rye grass to eliminate some hydrocarbons by evaporation.

5.5. Phytodegradation

There are few published articles on the potential of Jatropha for phytodegradation. This is shown by a limited number of studies conducted on Jatropha's ability to degrade recalcitrant and xenobiotic compounds. The phytoremediation of soil contaminated with waste lubricating oil when the growth of *J. curcas* was enhanced with organic wastes, brewery spent grain, and spent mushroom compost was studied.[35] A large number of

Table 3. Selected examples of experiences of phytoremediation of various contaminants.

Plant type used	Mechanism	Media and contaminants	Growth condition	Main finding	Reference
Amaranthus spp.	Phytoextraction	Pb, Cd, Cu, Zn, and nickel (Ni) in soil contaminated with industrial sewage	Greenhouse demonstration	Young plants have more potential to uptake and accumulate metals than older ones More Pb and Cd were transmitted at pH 6.3–6.5 after 35–45 days of growth	[12]
Jatropha curcas	Phytostabilization	Aluminum (Al), Cu, Zn, Pb, and Cd in polymetallic acid mine tailings	Greenhouse pot experiments	Highest accumulation of metals in roots A high tolerance index (>90%), no phytotoxic symptoms and stunted growth in moderately contaminated soil	[15]
	Rhizodegradation	Hydrocarbons in soil contaminated with lubricating oil	Room experiments	A large number of hydrocarbon-utilizing bacteria in the rhizosphere region	[35]
	Phytoaccumulation	Cd, Cr, Pb, Zn, Ni, and Cu in contaminated field soils	Field scale	Best absorption capability for Cd, Cr, Zn, and Ni	[36]
	Uptake and translocation	Heavy metals in sawdust sludge contaminated soils		Potential to accumulate high amounts of Cu, iron (Fe), aluminum (Al), Pd and Zn in roots, leaves, and stems	[37]
	Rhizoremediation	Lindane in garden soils	Greenhouse experiments	Accumulation of up to $20.85\,\mu g\,g^{-1}$ lindane and reduction of up to 89% applied lindane	[19]
Hybrid poplars	Phytovolatization	Tetrachloroethylene (TCE) in water	Cell cultures and greenhouse experiments	Formation of TCE metabolites in tree tissues and cell cultures Evapotranspiration and incorporation of TCE into an insoluble residue within the trees	[38]
Mauritius hemp (*Furcraea gigantea* Vent.)	Phytostabilization	Cr-contaminated soils	Pot culture experiment	Cr mainly accumulated in the roots with a tolerance of up to $50\,mg\,Cr\,kg^{-1}$ soil	[39]

hydrocarbon-utilizing bacteria were recorded in the rhizosphere region, suggestive of rhizodegradation as the main mechanism of the oil degradation. This was also further supported by the fact that hydrocarbons did not accumulate in the roots of Jatropha. Phytodegradation has been demonstrated several times by other plant species.[42] For instance, hairy root cultures of sunflower (*H. annuus*) secreted reactive oxygen species into the nutrient medium that degraded oxytetracycline.[48] In yet another study, water hyacinth (*E. crassipes*) proved to be an efficient phytoremediator by removing color and degrading textile dyes.[49] In addition, the expression of a bacteria organophosphorous hydrolase (OPH), in tobacco plants and the subsequent degradation of more than 99% organophosphorous (OP) pesticide showed the ability of transgenic plants to provide a new strategy for eliminating OP contaminants.[50]

6. Possible Research and Development Agenda for Enhancing Use of Jatropha in Phytoremediation

It is evident from the review of available data that the use of Jatropha in phytoremediation is still in its infancy. Data available are encouraging but inadequate. Thus, a research and development agenda is desirable in order to provide more convincing data. The limited experience with Jatropha for phytoremediation provides an authentic basis for setting a schedule for enhancing the status of Jatropha as a valuable plant for phytoremediation. The obvious observation from existing literature is the "demonstration scale" at which most research has been conducted. The need for up-scaling becomes a necessity.

The main issue is to collect as much information as possible on the performance of Jatropha in phytoremediation. The areas of focus may include the following:

- Up-scaling of experiments to go beyond small-scale demonstrations;
- Experimentation on the mechanisms of phytoremediation most beneficial with Jatropha;
- Elucidation of Jatropha's efficacy as a phytoremediator; and
- Possible plant improvement interventions that can enhance Jatropha's utility as phytoremediator.

7. Conclusion

Phytoremediation is a promising innovative technology for managing pollutants such as emerging contaminants and heavy metals in land and water bodies. The use of Jatropha for phytoremediation is relatively a new approach in its early stages of research and development. It is still undergoing laboratory research with few field trials being conducted to determine the process and improve methods. Results have already revealed that Jatropha is effective and could be used in remediation. Much work still needs to be done in order to elucidate the phytoremediation footprint of Jatropha. While there is consensus in the literature that Jatropha is a potential phytoremediator, the success of this practice rests on the constant chronological flow of information from research into practice. The need to increase knowledge and understanding of Jatropha as a phytoremediator will add to the stock of options for phytoremediation. Applications of Jatropha for phytoremediation are likely to become a commercially feasible technology in the near future.

8. Recommendations

Phytoremediation is interdisciplinary in nature. Technical expertize from various backgrounds is a prerequisite to undertake more research on the potential of Jatropha for phytoremediation. A "best fit" option or a combination of techniques that offer the maximum possible phytoremediation efficiency is very much recommended if the use of Jatropha is to be transformed into a commercially viable enterprise. Innovative development programs should be initiated in order to come up with successful technical knowledge for emboldening the utility of Jatropha in phytoremediation. Eco-toxicological risk assessment and validation should be done before Jatropha undergoes field trials for phytoremediation.

Abbreviations

BTEX, benzene, toluene, ethylene and xylene; HMX, octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine; OP, organophosphorous; TCE, trichloroethylene; TF, translocation factor.

Conflict of Interest

The authors have declared no conflict of interest.

Keywords

environment, heavy metals, phytoremediation, pollution, toxicity

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