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Review Article

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Phytoremediation of Pharmaceutical Wastes: A Safer Approach for Sustainable Environment

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ABSTRACT
The persistence release of pharmaceutical wastes in soil and water bodies is now a growing concern and this leads to reduction in soil fertility, food chain contamination, reduction in crop production, antibiotic resistance and aquatic biodiversity loss. Encapsulation, incineration and acid leaching are few of the conventional methods pharma-industries utilize in treatment of pharmaceuticals wastes. These methods are inefficient and releases harmful emission to the environment which affect the ecosytem. Therefore, there is need for exploration of sustainable approaches such as phytoremediation, whereby green plants are employed to clean up pollutants. These green plants can accumulate and degrade pollutants through Cytochrome-450 mediated metabolism to less toxic compounds. Also, there is a low level of awareness available to discuss the potential of this approach in cleaning up of pharmaceutical wastes. Several studies have focused on removal of pharmaceutical wastes using varieties of plant species; thus, this review covers a summary of these plants and their phytoremediation capabilities on commonly found pharmaceuticals in the environment. In this review, literature findings indicated that green plant species can absorb and metabolise pharmaceutical residues from soil and waterbodies, with uptake depending on both plant species and pharmaceutical wastes type. This supports their potential application in environmentally sustainable waste treatment strategies. In conlusion, such green plants can be cultivated in lands suspected to have been contaminated with pharmaceuticals and pharma- industries can as well scale up this approach in treatment of wastes inorder to promote a sustainable ecosystem.

Keywords: Pharmaceutical wastes, Phytoremediation, Green plants, Ecosystem, Sustainability

Introduction

High levels of pharmaceuticals detected in water bodies and soil is becoming a global threat and a growing concern and most conventional remediation approaches do not provide appropriate solutions [1,2,3]. Pharmaceutical wastes products getting accumulated in soil and water are causing harmful effects on plants and developing health issues in humans and animals [4,5]. Most commonly found pharmaceutical wastes like antibiotics, hormones, non-steroidal anti-infammatory drugs (NSAIDS), steroidal medicines, analgesics, and therapeutic agents are an outcome of the improper disposal of pharmaceuticals that are being used in the treatment of humans and animals, industrial production, hospitals and agriculture (Lavrukhina et al., 2024;) [5,6]. These pharamaceuticals usually come through irrigation, sewage wastes and throwing of expired and unused medicine into domestic drains which eventually enter into soil and waterbodies, and become a part of the food chain (Iori et al., 2012) [7,8].

Over the years, some conventional strategies like excavation of soil, its decontamination and refilling, chemical and thermal remedy of soil, acid leaching, electro reclamation, pyrolysis etc had been evolved to remediate pharmaceutical wastes (Zhou et

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al., 2024) [9-11]. These strategies had been located to have a large downside of being costly, releases harmful emission and gases into the atmosphere, ex-situ, not too efficient and may simplest be operated at a small scale (Schwarzenbach et al., 2010) [12,13].

However, phytoremediation technique is emerging as a bio-based, cost effective and ecofriendly approach for treatment of pollutants (Priya et al.,2023) [14,15]. This technique involves the use of green plants in cleaning up of pollutants through Cytochrome-450(CYP450) mediated metabolisms and mechanisms such as phytoextraction, phytostabilization, phytodegradation and rhizofiltration [16,17]. While phytoremediation has been extensively studied for heavy metal remediation (Anyasi&Atagana 2020; Akomolafe&Nkemdy 2020; Ikhajiagbe et al., 2020), its application to pharmaceutical waste management within our environment remains underexplored. Recent studies have reported the potentials of green plants for pharmaceutical wastes removal [18-20]. This paper aim to review the roles, metabolism and mechanism of green plants in pharmaceuticals uptake from wastewaters and soil.

Structure of the Study

The introductory section of this review article discussed the background of the study, and aim of the study. Section two discussed the roles, metabolism and mechanism of green plants in pharmaceutical uptake from wastewaters and soil. While section three centered on summary of findings and finally, section four is the conclusion of the study.

Methodology of the Study

Pharmaceuticals, wastewater, green plants, soil and phytoremediation were used as keywords to search relevant articles in Google scholar site. Only recent studies (2016 till date) invloving green plants in phytoremediation of pharmaceutical wastes were selected for review. The main target of this review paper is to put togther varieties of green plants that can be expolred in treatment of pharmaceutical wastes. So far, more than twenty-five green plants were mentioned in this article. This paper provides adequate information that will guide pharma- industries and environmental protection agencies on selection of appropriate plants for pharmaceutical wastes treatment.

The Roles of Green Plants in Phytoremediation of Pharmaceuticals

Green plants are essential in treatment of pharmaceutical wastes in waterbodies and soil due to their removal mechanisms and enzymes (such as oxidases, reductases, dehalogenases, esterases, and transferases) taking part during phytoremediation [21]. The uptake of pharmaceuticals by green plants greatly depends on the concentration of pharmaceuticals present in wastewaters and soil, time of exposure, environmental media, the biological characteristics of the plant species such as degree of root growth, transpiration rates, size and shape of leafy materials etc (Pandey et al., 2021), physicochemical characteristics of the pharmaceuticals including dissociation constant, lipophilicity, molecular weights, water solubility and octanol-water partition coefficient [22-25].

However, it is worthy to note that different species of green plants have been utilized in phytoremediation of pharmaceutical wastes with notable success. In this context, existing records of green plant species that has been utilized in phytoremediation of pharmaceuticals are outlined in Table1. These plants have become more suitable for phytoremediation due to their high tolerance to environmental stress, high biomass production, availability and harvesting.

Table 1: Green plants utilized in phytoremediation of pharamaceuticals

Green plants	Type of pharmaceticals	Concentration	Removal efficiency	Reference
Hydrilla verticillate	Metronidazole	10mg/L	86% at day 14 of treatment	[26]
Lemna gibba	Ibuprofen	High level: 0.20 and 1 mg/L Environmental level: 0.02mg/L	89- 92.5%	[27]
Juncus effusus Typha latifolia Berula erecta Phragmites australis Iris pseudacorus	Ibuprofen	10 and 100 μg/L	29-99%	[28]
Phragmites australis	Ibuprofen	60μg/L	100%	He et al., 2017
Canna hybrid	Carbamazepine	9.51μg/L	Root to shoots 1.9-44.7%	[29]
Alternanthera spp.	Paracetamol	20 mg/L 60mg/L 100mg/L	88.6%	[30]
Lemna minor	Cefadroxil Metronidazole Trimethroprim Sulfamethoxazole	10-2000μg/L	100% 96% 59% 73%	[31]

Scripus lacustris	Metronidazole	0.5,5,10, 15 and 20 mg/L	93+- 2%	[32]
Juncus acutus	Ciprofloxacin Sulfamethoxazole	50mg/L	92% ciprofloxacin 61% Sulfamethoxazole	[33]
Eichhornia crassipes	Naproxen Ibuprofen diclofenac	Environmental concentration detected	Naproxen was most abundant in the plant with maximium concentration of 12ng/g found in leaves	[34]
Raphanus sativus Beta vulgaris	Clonazepam, Diazepam, Flurazepam, Chlordiazepoxide, Oxazepam, Temazepam, Triazolam		>65% of all pharmacuticals	Carter et al., 2018
Cicer arietinum	Ciprofloxacin Progesterone Estrogen	5-25 ppm, 50-500 ppm, 50-500 respectively	60% Ciprofloxacin , 64.66%Progesterone 63.3% estrogen	[1]
Brassica juncea	Aspirin Tetracycline		90% Aspirin 71% Tetracycline	[35]
Helianthus annuus	Metformin	20mg/L 50mg/L	69.53% and 65.7 removal	[36]
Phragmatis australis	Praziquantel	20 mg /L	90%	[37]
Zantedeschia rehmannii Spathiphyllum wallisii	Enrofloxacin	5, 10, 100, and 1000 $\mu g\ L^{-1}$	> 80% removal by both plant	[38]
Lemna minor	Amoxicillin	2.0 mg/L	92%	[39]
Canadian pondweed, rigid hornwort, eurasin watermilfoil	Ciprofloxacin		Highest removal rate of ciprofloxacin found in rigid hornwort	[40]
Cyperus papyrus	Fluoroquinolone		69%	[41]
Iris pseudacorus Typha domingensis	Furosemide	2 mg/ L	42.0-66.9% for Thypa 40.5-57.8% for Iris	[42]
Ocimum basilicum	Ciprofloxacin	$100mg.kg^{-1}$ $200mg.kg^{-1}$	93.81% 92%	[43]
Typha angustifolia Ipomoea aquatica	Doxylamine	0.5, 1, 2.5 and 5 mg/L	48-80.5%	[44]
Salvinia molesta	Ciprofloxacin	1 and 10 µg/L	90%	[45]

Metabolism of Pharmaceuticals by Greenplants

The metabolic pathway for the transformation of pharmaceuticals by green plants have been identified [46,47]. The exposure of these plant species to pharmaceuticals results in rapid uptake followed by transformation or degradation by enzymatic actions [48,49].

Phase I Metabolic Transformation: Pharamaceutical compounds undergoes hydroxylation, dehydrogenation, demethylation, reduction, hydrolysis and oxidation reactions [50]. These reactions result in the formation of more polar, chemically active and water-soluble compounds. In plants, oxidative metabolism is mediated primarily by CYP450 mono-oxygenase [51]. These enzymes are very crucial during the oxidative process of bioactivation to breakdown highly hydrophobic pharmaceuticals and make them chemically reactive electrophilic compounds which form conjugates [52]. Notably, studies have shown the detection of phase I metabolic transformation in plant tissue. He et al., 2017 reported three transformation products (TPs) of ibuprofen (hydroxyl-ibuprofen, carboxyl-ibuprofen, 1,2-dihydroxyl ibuprofen) were detected in Phragmites australis plant tissue. Wang et al., 2024 reported that 68% of ciprofloxacin was transformed via phase I transformation (reduction and methylation) in Phragmites australis. Cui et al., 2017 reported eight TPs of iopromide formed by oxidation, decarboxylation, deiodination and hydroxylation in Thypha latifolia. Three TPs formed by hydroxylation and two TPs formed by mono-and di-oxidation of trimethoprim were identified in Limnobium laevigatum [53,54]. Monohydroxylated TPs of sulfamethoxazole have been identified in Arabidopsis thaliana [55].

Phase II Metabolic Transformation: Activated pharmaceutical compounds get conjugated with small polar endogenous molecules such as glucuronic acid, sulphate, amino acids and glutathione [56]. Conjugation results in the formation of high molecular weights, more polar and less toxic compounds as compared to the parent compound [57]. Only few recent studies reported phase two metabolic transformation of pharmaceuticals in plant species via glycosylation (Wang et al., 2024) [55,58].

Phase III compartmentalization: During compartmentalization, pharmaceutical compounds are bounded to the cell wall material. Wang et al., 2024 reported a Phase III compartmentalization of ciprofloxacin in Phragmites australis.

Key Summary from Literature

From literature, it showed that concentration of pharmaceuticals heavily depends on plant uptake. Recent studies discussed the use of these plant species in a controlled laboratory condition. However, the use of these plant species are yet to be fully explored in a real environmental condition. Studies also showed the presence of pharmaceuticals uptake in food crops such as paracetamol detoxificaion in cucumber plants via induction of gluthathione-S-transferases, detection of ibuprofen and its metabolites in cabbage and barley, carbamazepine detection in hydroponically grown tomato plants, and the absorption, accumulation, and translocation of paracetamol in different organs of leafy vegetable spinach [59-62]. This is evidence that pharmaceuticals also have higher tendency of uptake in food crop plants and this serves as a threat to food security [63].

Conclusion

Phytoremediation looks promising for a sustainable waste management of pharmaceuticals, pharma- industries and environmental protection agencies should collaborate with researchers to fully utilize these plant species in pharmaceutical waste treatment.

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