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Research Article

Phytoremediation of Heavy Metals in Spent Engine Oil-polluted Soil by *Senna alata* L.

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Abstract

Background and Objective: Indiscriminate disposal of spent engine oil (SEO) pose adverse effects on the ecosystem, due to build-up of heavy metals and hydrocarbons in the environment. Therefore, the objective of this study is to determine the impact of different concentrations of SEO on the uptake and accumulation of heavy metals by *Senna alata* L. **Materials and Methods:** Polythene bags (120) filled with 20 kg of soil each were separated into part A and B. Part A contained *S. alata* seedlings while part B had no plant. To simulate spillage, 0.15, 0.75 and 3.75% v/w concentrations of SEO were used to pollute the soil-bags, 57 days after planting. Control had no pollution. Heavy metal content of the SEO, soil and vegetative parts of *S. alata* were analyzed 106 days after pollution. Vegetative and reproductive parameters were also determined. **Results:** Cu, Pb, Zn, Fe and Al were detected in SEO. Concentrations of heavy metals in vegetated soil were significantly ($p<0.05$) less than those in non-vegetated soil. Cu accumulated most in the stem while Zn and Al were highest in the root. Fe and Pb accumulated most in the leaf. Aerial roots were formed and plant height, leaf area, stem circumference and number of pinnules and roots increased after pollution but the number of inflorescence and dry weight of seeds decreased. **Conclusion:** Hence, *S. alata* is suitable for phytoremediation and particularly, phytoaccumulation of heavy metals in SEO contaminated soil.

Key words: Phytoremediation, *Senna alata*, spent engine oil, heavy metals

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

An increasing number of machines and automobile importation and usage, especially in developing countries have resulted in excessive use of various refined crude oil products such as engine oil, diesel and gasoline. Spent engine oil (SEO) is usually obtained after servicing and subsequent draining from automobile and generator engines by motor mechanics and much of this oil is poured into the soil, gutters, water drains, open plots and farms[1]. This indiscriminate disposal of SEO adversely affects plants, microbes and aquatic lives[2]. The SEO contain large quantities of heavy metals such as iron, lead, aluminum, nickel and copper. Friedlova[3] reported that the ratio of microbial biomass carbon to oxidizable carbon content and basal respiration dropped down significantly on heavy metal contaminated sites. Heavy metals may be retained in the polluted soil from season to season[4] and may lead to building up of essential and non-essential elements in the soil which eventually translocate into plant tissues[5]. Although heavy metals in low concentrations are essential micronutrients for plants[6], at high concentrations, they may cause metabolic disorder and growth inhibition for most plant species[7]. One of the most deleterious effects induced by heavy metal exposure in plants is lipid peroxidation, which can directly cause biomembrane deterioration[7]. Chaves *et al.*[8] reported a significant negative reduction in growth, development and yield of sunflower grown in soil contaminated with heavy metals. Chetan and Ami[9] also reported a significant decrease in root and shoot length, leaf number, dry and fresh weight of root, shoot and leaf of *Spinacia oleracea* and *Amaranthus caudatus* in heavy metal polluted soil. Also, Sen *et al.*[10] reported a significant decrease in root and shoot length of Indian mustard at higher concentrations of heavy metals in contaminated soil.

However, certain plants and associated microbes have been found to be effective in remediation of heavy metal polluted sites[11]. Some plants have developed mechanisms to combat such adverse environmental heavy metal toxicity problems[7]. These plants might have produced low molecular weight thiols that show high affinity for toxic metals. The most important/critical low molecular weight biological thiols are glutathione (GSH) and cysteine[7]. The GSH usually elevates serine acetyltransferase activity, which is crucial for detoxification of heavy metals[12]. The ability to accumulate heavy metals varies significantly between plant species and among cultivars since different mechanisms of ion uptake and metal accumulation are operative in various plants[13]. Cosio *et al.*[14] reported the existence of differential regulation mechanisms on the plasma membrane of Thlaspi caerulescens that resulted in storing of heavy metals in the root vacuoles. Hence, in phytoremediation, heavy metals are removed in a cost-effective and environment-friendly manner with reduced exposure to human, terrestrial and aquatic lives.

Senna alata (L.) Roxb. (Syn. *Cassia alata* L.), commonly known as candlestick senna, wild senna, ringworm cassia and the king of the forest is a medium-sized, ornamental flowering shrub belonging to the Family Fabaceae[15]. It is native to Amazon rain forest but spread widely in warm areas of the world especially in the tropical and subtropical regions. Silva *et al.*[16] reported that *S. alata* can remove heavy metals in the contaminated environment. However, heavy metal removal from SEO by *S. alata* has not been properly investigated; hence, this study. Therefore, the aim of this work was to evaluate the impact of different concentrations of SEO on the uptake and accumulation of heavy metals present in SEO by *S. alata*.

The objectives of the study were to ascertain the type and quantity of heavy metals that could be removed or accumulated by *S. alata* in soil contaminated with SEO and to determine the vegetative and reproductive parameters of *S. alata* growing on different concentrations of SEO.

MATERIALS AND METHODS

This study was conducted in the South-Eastern part of Nigeria from 22 March, 2014, through 3rd January, 2015.

Planting and pollution of *Senna alata* with spent engine oil: Topsoil collected at a depth of 10 cm from Botanic Garden, University of Nigeria, Nsukka was mixed with poultry manure at a ratio of 6:2. One hundred and twenty black, perforated polythene bags were each, filled with 20 kg of the mixed topsoil and poultry manure. These bags containing mixed soil and manure were separated into 2 parts: A and B (each with 60 bags). Sixty soil bags were planted with a seed of *Senna alata* each (part A: Vegetated soil), while the other 60 bags were non-vegetated (part B). To simulate spillage, 15 soil bags of vegetated soil were polluted with 30 mL (0.15% v/w) of SEO, 57 days after planting (DAPL). This was repeated using 150 mL (0.75% v/w) and 750 mL (3.75% v/w) of SEO each on 15 separate soil bags of the vegetated part instead of 30 mL. The remaining 15 soil bags were not polluted (control). Non-vegetated soil bags were also polluted in the same manner on the same day. The experiment was carried out in 3 replicates in a completely randomized design. The bags were displayed in an open place hence, watered by rainfall.

Heavy metal analysis: A sample of SEO, soil from control and polluted soil (vegetated and non-vegetated), leaves, stems and roots of *S. alata* were analyzed for the accumulation of heavy metals using flame atomic absorption spectroscopy (FAAS), 106 days after pollution (DAP). Soil and vegetative samples were dried at 45°C using Memmert 854 Schwabach oven and crushed into fine powder. One gram of each fine-powdered sample was heated for 8 h in a furnace and cooled in a desiccator. Five milliliter of trioxonitrate (v) acid (HNO_3) solution was added to the ash, evaporate to dryness on a hot plate, returned to the furnace and heated at 400°C for 15-20 min until perfect greyish-white ash formed and later cooled in a desiccator. Fifteen milliliter of hydrochloric acid (HCl) was added to the ash to dissolve it. The solution was filtered into 100 cm^3 volumetric flask and made up to 100 cm^3 with distilled water[17]. The SEO sample was prepared by the digestion method. This was done by putting 2 g into a digestion flask, followed by addition of 20 mL of an acid mixture (650 mL concentrated HNO_3, 80 mL perchloric acid and 20 mL sulfuric acid) and heating until a clear solution was obtained. Hexane was added to the flask up to the mark of 25 mL[18]. The FAAS analysis was carried out according to the method adopted by the American Public Health Association[17]. Series of standard metal solutions in the optimum concentration range were prepared by diluting the single stock element solution with water containing 1.5 mL concentrated HNO_3 L^{-1}. A calibration blank was also prepared using all the reagents except for the metal stock solution. The sample was aspirated into the flame using Varian AA240 Atomic Absorption Spectrophotometer (AAS) and atomized when the AAS's light beam is directed through the flame into the monochromator. The atomized sample was directed onto a detector that measured the amount of light absorbed by the atomized element in the flame. Calibration curve for each metal was prepared by plotting the absorbance of standard versus their concentration using Spectra AA scan (PC/Window 7) software[17].

Determination of vegetative and reproductive parameters of *Senna alata*: The vegetative parameters of the plant namely: Plant height, number of leaves/plant, number of pinnules/leaf, leaf area and stem circumference were determined before pollution, that is, at 56 DAPL following the procedures of Akingunsola *et al.*[19] and Aliu *et al.*[20]. After pollution, the same vegetative parameters, in addition to the number of roots, root length and root circumference were measured at 163 DAPL. As regards the reproductive parameters, the number of inflorescences/plant, flowers, pods, seeds and dry weight of seeds were determined at maturity (at 294 DAPL).

Statistical analysis: Data collected from FAAS, vegetative and reproductive parameters were analyzed using Genstat according to Payne *et al.*[21] to generate the means and variance at $p \leq 0.05$. Means of accumulated heavy metals in the experimental soil, root circumference, number of roots, aerial roots, inflorescences and dry weight of seeds, were compared using Fisher's Least Significance Difference. A t-test was used to compare vegetative parameters before and after pollution.

RESULTS

Heavy metals

Heavy metals accumulated in the soil: Heavy metals namely, copper (Cu), lead (Pb), iron (Fe), zinc (Zn) and aluminum (Al) were detected in SEO and in all polluted vegetated and non-vegetated soil samples (Table 1) and they generally increased with increase in concentrations of SEO applied. Also, heavy metal concentrations in polluted non-vegetated soil were higher than those in polluted vegetated soil for all treatments.

Heavy metals accumulated in the vegetative parts: Appreciable quantities of heavy metals were detected in vegetative parts of *Senna alata* (Table 2). Copper accumulated more in the stem when compared with those stored in leaves and roots of the plant especially for 0.75 and 3.75% v/w concentrations. The quantities of Cu that accumulated in root and leaf in 0.15% v/w treatment did not vary with control. Zinc and Al accumulation in root were higher than those in the leaf and the stem for all concentrations. Also, the concentration of Fe and Pb in leaf were higher than those that accumulated in stem and root for all concentrations. Generally, heavy metals detected in some vegetative parts of *S. alata* were higher than the concentrations retained in polluted vegetated soil for all concentrations.

Table 1: Composition and quantity (ppm) of heavy metals in vegetated and non-vegetated soils of *Senna alata* polluted with spent engine oil

Treatments (% v/w)	Sample type	Cu (ppm)	Pb (ppm)	Zn (ppm)	Fe (ppm)	Al (ppm)
SEO	SEO	1.63 ± 0.012^{a}	3.50 ± 0.008^{a}	10.12 ± 0.004^{a}	18.80 ± 0.005^{a}	12.19 ± 0.005^{a}
0 (control)	Vegetated soil	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}
	Non-vegetated soil	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}
0.15	Vegetated soil	0.09 ± 0.005^{c}	0.01 ± 0.002^{b}	0.17 ± 0.014^{c}	0.95 ± 0.002^{c}	0.16 ± 0.003^{c}
	Non-vegetated soil	0.95 ± 0.006^{d}	1.90 ± 0.023^{c}	3.50 ± 0.001^{d}	6.00 ± 0.006^{d}	3.71 ± 0.001^{d}
0.75	Vegetated soil	$0.10\pm0.001^{e,c}$	0.74 ± 0.007^{d}	1.26 ± 0.012^{e}	2.34 ± 0.018^{e}	1.50 ± 0.058^{e}
	Non-vegetated soil	1.00 ± 0.001^{f}	2.01 ± 0.001^{e}	5.47 ± 0.001^{f}	9.97 ± 0.001^{f}	6.49 ± 0.001^{f}
3.75	Vegetated soil	0.56 ± 0.023^{g}	0.55 ± 0.012^{f}	1.81 ± 0.002^{g}	2.58 ± 0.002^{g}	1.56 ± 0.001^{g}
	Non-vegetated soil	1.20 ± 0.002^{h}	2.15 ± 0.002^{g}	6.47 ± 0.002^{h}	10.46 ± 0.002^{h}	7.09 ± 0.001^{h}

SEO: Unused spent engine oil, values represent Mean±Standard error, means followed by different letters in the same column are significantly different at $p\leq0.05$

Table 2: Composition and quantity (ppm) of heavy metals that accumulated in root, stem and leaf samples of *Senna alata* polluted with spent engine oil

Treatments (% v/w)	Sample type	Cu (ppm)	Pb (ppm)	Zn (ppm)	Fe (ppm)	Al (ppm)
SEO	SEO	1.63 ± 0.012^{a}	3.50 ± 0.008^{a}	10.12 ± 0.004^{a}	18.80 ± 0.005^{a}	12.19 ± 0.005^{a}
0 (control)	Root	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.001^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}
	Stem	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}
	Leaf	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}	0.00 ± 0.000^{b}
0.15	Root	0.01 ± 0.000^{b}	0.10 ± 0.001^{c}	1.00 ± 0.002^{c}	0.60 ± 0.001^{c}	1.32 ± 0.012^{c}
	Stem	0.18 ± 0.002^{c}	0.01 ± 0.006^{d}	0.02 ± 0.002^{d}	0.64 ± 0.002^{c}	0.20 ± 0.002^{d}
	Leaf	$0.003\pm0.001^{c,b}$	0.15 ± 0.002^{e}	0.05 ± 0.001^{e}	3.67 ± 0.012^{d}	0.19 ± 0.017^{e}
0.75	Root	0.29 ± 0.012^{d}	0.48 ± 0.001^{f}	2.62 ± 0.002^{f}	$0.60\pm0.001^{e,c}$	2.02 ± 0.002^{f}
	Stem	0.56 ± 0.002^{e}	$0.11\pm0.006^{g,c}$	0.15 ± 0.001^{g}	1.70 ± 0.173^{f}	0.19 ± 0.003^{g}
	Leaf	0.03 ± 0.023^{f}	1.06 ± 0.002^{h}	0.43 ± 0.001^{h}	4.96 ± 0.003^{g}	0.14 ± 0.001^{h}
3.75	Root	0.37 ± 0.012^{g}	0.41 ± 0.002^{i}	3.41 ± 0.002^{i}	0.78 ± 0.001^{h}	3.55 ± 0.002^{i}
	Stem	0.68 ± 0.001^{h}	0.24 ± 0.023^{j}	0.28 ± 0.002^{j}	1.80 ± 0.005^{i}	0.25 ± 0.029^{j}
	Leaf	0.08 ± 0.003^{i}	1.66 ± 0.006^{k}	0.58 ± 0.012^{k}	6.74 ± 0.003^{j}	0.20 ± 0.001^{k}

SEO: Unused spent engine oil, values represent Mean±Standard error, means followed by different letters in the same column are significantly different at $p\leq0.05$

Table 3: Vegetative parameters of *Senna alata* before and after pollution (56 and 163 days after planting, respectively)

	Plant height (cm)		No. of leaves		No. of pinnules		Leaf area (cm^2)		Stem circumference (cm)	
Treatments (% v/w)	Before pollution	After pollution	Before pollution	After pollution	Before pollution	After pollution	Before pollution	After pollution	Before pollution	After pollution
0 (control)	36.4 ± 2.4^{a}	225.00 ± 8.3^{b}	13.5 ± 0.6^{c}	27.3 ± 2.5^{d}	9.6 ± 0.3^{e}	18.3 ± 0.3^{f}	240.5 ± 21.5^{g}	1012.6 ± 83.4^{h}	3.8 ± 0.1^{j}	9.7 ± 0.4^{k}
0.15	38.4 ± 1.6^{a}	215.30 ± 9.9^{b}	13.6 ± 0.7^{c}	26.0 ± 3.0^{d}	9.6 ± 0.4^{e}	17.3 ± 1.1^{f}	251.6 ± 23.3^{g}	992.0 ± 59.3^{h}	3.9 ± 0.08^{j}	9.5 ± 0.4^{k}
0.75	36.2 ± 2.7^{a}	214.20 ± 7.8^{b}	13.5 ± 0.6^{c}	21.7 ± 2.2^{d}	9.3 ± 0.4^{e}	18.2 ± 0.5^{f}	249.5 ± 25.7^{g}	910.9 ± 60.8^{h}	3.9 ± 0.1^{j}	9.0 ± 0.4^{k}
3.75	37.8 ± 2.7^{a}	203.40 ± 9.3^{b}	14.5 ± 0.7^{c}	$18.3\pm2.2^{d,c}$	9.5 ± 1.2^{e}	16.7 ± 1.3^{f}	240.6 ± 27.2^{g}	842.6 ± 92.1^{h}	3.9 ± 0.1^{j}	8.6 ± 0.4^{k}

Values represent Mean±Standard error, means followed by the same letters in the same column are not significantly different at $p\leq0.05$, means followed by different letters in the same row for each vegetative parameter are significantly different at $p\leq0.05$

Vegetative and reproductive parameters

Shoot parameters: Shoot parameters (Table 3) were not statistically different between the treatments before pollution and also, after pollution (separately). However, in comparison, these shoot parameters determined before pollution were significantly ($p<0.05$) lower than shoot parameters measured after pollution within the treatments. The only exception was the number of leaves produced in 3.75% v/w treated plants whose value did not significantly differ before and after pollution.

Root parameters: Some of the root parameters differ significantly among treatments. Plants treated with 3.75% v/w significantly ($p<0.05$) produced the highest number of roots (Table 4). For mean root circumference, control and 0.15% v/w were significantly ($p<0.05$) thicker than 3.75% v/w treatment. *Senna alata* also produced aerial roots. Aerial roots counted at 56 DAP (initial number) and 106 DAP (final number) increased significantly ($p<0.05$) with an increase in concentrations of SEO applied. For each treatment, the final number of aerial roots was significantly ($p<0.05$) higher than the initial number.

Reproductive parameters: There were no differences between control and polluted plants as regards the number of flowers, pods and seeds produced by *S. alata* (Table 5). However, mean number of inflorescences for the control was significantly ($p<0.05$) more than that of

Table 4: Root parameters of *Senna alata* 163 days after planting

Treatments (% v/w)	Root number	Root length (cm)	Root circumference (cm)	Initial No. of the aerial root (56 DAP)	Final No. of aerial root (106 DAP)
0 (Control)	61.2 ± 6.009^{a}	56.52 ± 2.107^{b}	1.300 ± 0.058^{c}	0.67 ± 0.159^{h}	0.00 ± 0.000^{a}
0.15	65.2 ± 2.056^{a}	58.23 ± 0.716^{b}	1.150 ± 0.087^{c}	3.13 ± 0.904^{h}	6.40 ± 1.027^{b}
0.75	60.5 ± 4.406^{a}	55.92 ± 2.673^{b}	$1.125\pm0.025^{c,d}$	7.53 ± 0.867^{e}	13.60 ± 1.287^{c}
3.75	77.5 ± 3.227^{b}	54.67 ± 2.175^{b}	$1.050\pm0.029^{d,e}$	27.87 ± 1.973^{f}	55.07 ± 2.306^{d}

DAP: Days after pollution, values represent Mean±Standard error, means followed by the same letters in the same column are not significantly different at $p\leq0.05$

Table 5: Reproductive parameters of *Senna alata* 294 days after planting

Treatments (% v/w)	No. of inflorescences	No. of flowers	No. of pods	No. of seeds	Dry weight of seeds (g)
0 (control)	7.8 ± 0.917^{a}	155.1 ± 14.02^{b}	51.4 ± 4.672^{c}	30.7 ± 1.075^{d}	49.0 ± 4.392^{e}
0.15	8.5 ± 0.898^{a}	144.3 ± 14.20^{b}	43.8 ± 5.337^{c}	24.7 ± 1.350^{d}	$34.6\pm5.418^{e,f}$
0.75	$5.1\pm0.900^{b,c}$	131.5 ± 23.76^{b}	39.7 ± 9.175^{c}	21.4 ± 4.951^{d}	$37.5\pm10.47^{e,f}$
3.75	$5.2\pm1.104^{b,c}$	97.4 ± 17.06^{b}	27.7 ± 6.112^{c}	24.0 ± 4.266^{d}	21.3 ± 4.764^{f}

Values represent Mean±Standard error, means followed by the same letters in the same column are not significantly different at $p\leq0.05$

0.75% v/w and 3.75% v/w but not significantly different with 0.15% v/w treatments. Dry weight of seeds polluted with 3.75% v/w was significantly ($p<0.05$) less than that of control but not significantly different with 0.15% v/w and 0.75% v/w treatments.

DISCUSSION

In this study, quantities of heavy metals that remained in the soil in each treatment increased with an increase in the concentrations of SEO applied; showing a decrease in removal efficiency at higher concentrations. Carvalho and Martin[22] reported that the higher the concentration of metals in solution, the lower the removal efficiency. However, heavy metals accumulated in the polluted vegetated soil were less when compared to those of the non-vegetated soil. This might be as a result of heavy metals taken up and accumulated by the vegetative parts of the plant. Heavy metals accumulated more in the vegetative parts of the polluted plant than the soil as the concentration of SEO applied increased. Agbogidi and Ohwo[23] reported that heavy metal accumulation in the plant is dose-dependent. Therefore, SEO did not inhibit the uptake of these heavy metals by *S. alata* and the plant could hyper-accumulate these heavy metals affecting other organisms along the food chain. Yadav[7] explained that heavy metals in plants lead to biomembrane deterioration due to lipid peroxidation; consequently, leading to poor vegetative growth, death of seeds and plants[1,9,10]. However, these heavy metals that accumulated in the vegetative parts of *S. alata* had little or no adverse effects on the vegetative growth and development of the plant, since the plants grew and developed well when compared with the control. Hence, *S. alata* may perhaps possess substances that might have formed complexes with toxic metals[7], which might have protected the plant from the deleterious effect of heavy metals. Nevertheless, the quantities of each of the heavy metals in *S. alata* in each treatment were below the standard allowable limits for daily dietary intake (Cu: 60 mg/day, Zn: 15 mg/day, Pb: 3.0 mg kg^{-1}, Fe: 15 mg/day and Al: 60 mg/day)[24,25]. *Senna alata* accumulated Cu, Pb, Zn, Fe and Al in the leaves, stems and roots, depicting its potentials as a hyperaccumulator for phytoremediation of heavy metals. Similarly, Gupta and Sinha[26] reported hyperaccumulation of Fe, Zn, Cu and Pb by *Cassia tora*. Moreover, Cu was higher in the stems; Pb and Fe accumulated most in the leaves while Al and Zn were found in large quantities in the roots. These suggest that different mechanisms of metal accumulation, exclusion and compartmentalization exist in various plant organs and species[13]. Furthermore, Yoon *et al.*[27] reported that Cu and Pb accumulated more in the roots compared to the shoots. Also, the mobility of Pb in plants as reported by Vwioko *et al.*[5] decreased on reaching the root due to the protective mechanism in avoiding injuries to the shoot. However, in this study, Cu and Pb mobility was not restricted at the root zone but stored most in the stems and leaves, respectively. Therefore, *S. alata* might have biochemical substance(s) that increased Pb and Cu mobility beyond the root zone. For the Zn and Al accumulation in the roots, Cosio *et al.*[14] found out that more Zn was stored in the root vacuole of Thlaspi caerulescens and thus became unavailable for loading into the xylem.

The vegetative parameters did not differ with the control after pollution. This showed that SEO or heavy metal pollution had little/no adverse effects on the growth and productivity of the plant. Hence, the plant could be used for phytoremediation, because for effective phytoremediation, the plant must survive in the contaminated medium[28]. In contrast, Chaves *et al.*[8] reported a significant negative reduction in growth, development and yield of sunflower grown in soil contaminated with heavy metals. Higher concentrations of Al and Zn according to Mossor-Pietraszewska[29] and Vijayarengan and Mahalakshmi[30], respectively, inhibit root development. Also, many authors have reported a significant reduction in root length, root number and root cross-section of plants grown in soil contaminated with heavy metals[9,10,30]. On the contrary in this study, these heavy metals had little negative effects on root development, forming aerial roots. *Senna alata* might have adopted the formation of aerial roots to compensate for the disruptions of normal physiological activities by Al and Zn in the root zones. In contrast, Gomes *et al.*[31] reported that the architecture of the root systems of *Brachiaria decumbens* changed in soil contaminated with heavy metals, which led to the loss of root hairs. Therefore, SEO with heavy metals might have induced physiological or genetic changes that initiated aerial root formation, which hitherto, was not common in this plant.

The number of flowers, pods and dry weight of seeds of *S. alata* in polluted soil decreased with increase in the concentration of SEO applied. Similarly, Singh *et al.*[32] reported early flowering but significant reduction in a number of flowers, pods and yield of *Cajanus cajan* in soil polluted with cadmium. Okonokhua *et al.*[1] also reported that the grain yield of maize in SEO contaminated soil was adversely affected.

CONCLUSION AND RECOMMENDATION

Senna alata is a suitable plant for the phytoremediation of soil polluted with SEO. The plant was used to absorb and accumulate heavy metals such as Cu, Pb, Zn, Fe and Al from SEO. SEO did not inhibit the uptake of these heavy metals by *S. alata*. After phytoremediation, this plant should be disposed of to avoid negative impacts on biodiversity. More work is needed to unravel the causes and consequences of aerial root development in the plant. There is also a need to devise means of recycling SEO instead of disposing of indiscriminately since unidentified effects of this pollutant might pose a serious risk to the present and future generations.

SIGNIFICANCE STATEMENT

This study discovered the phytoremediation of heavy metals in SEO that can be beneficial for the cleaning of the environments contaminated with heavy metals or SEO. This study will help the researchers to uncover the critical areas of physiological changes induced by combine interactions of hydrocarbons and heavy metals in plants, which led to the formation of aerial roots by *S. alata* that many researchers were not able to explore. Thus, a new theory on the fate of environmental contaminants involving SEO may be arrived at.

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