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Phytoextraction Potentials and Early Growth Performance of Groundnut (*Arachis Hypogaea L)* Seedlings on Spent Engine Oil Contaminated Soil Around Nigeria Police Academy Kano

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Abstract
Soil contamination with spent engine oil (SEO) poses a major environmental problem due to elevated concentrations of petroleum hydrocarbons and heavy metals. This study evaluated the phytoextraction potential and early growth performance of groundnut (*Arachis hypogaea* L.) seedlings on SEO-contaminated soils collected around the Nigeria Police Academy, Kano. A completely randomized design with three SEO levels (4, 8 and 12% w/w) plus a non-contaminated control was used for six weeks. Pre-experiment soil analyses showed markedly increased total petroleum hydrocarbons (TPH) (4,250–12,900 mg kg^{-1}) and heavy metals (Pb 8.9–23.7 mg kg^{-1}; Cd 0.14–0.30 mg kg^{-1}; Zn 28.6–57.2 mg kg^{-1}) compared with the control. Groundnut emergence, height and biomass decreased significantly with increasing SEO, yet seedlings survived even at 6% contamination (emergence 53%; shoot dry weight 0.58 g $plant^{-1}$). Post-experiment analyses showed substantially greater TPH and metal reductions in planted soils than in unplanted controls (30% compared to ≤12% TPH removal; Pb, Cd and Zn removal 22 to 33% compared to ≤9%. Heavy metals accumulated predominantly in roots, with bioconcentration factors (BCF) >1 for Pb and Zn and translocation factors (TF) of 0.66–0.80, indicating moderate translocation to shoots. Derived uptake values increased with contamination level (Pb 27.9–47.4 µg $plant^{-1}$; Zn 92.6–152.1 µg $plant^{-1}$). Soil biological indicators (dehydrogenase and catalase activities) were significantly higher in planted soils, evidencing rhizosphere recovery during phytoremediation. These findings demonstrate that groundnut seedlings tolerate moderate SEO contamination, accumulate heavy metals in roots and shoots, and accelerate TPH and metal removal relative to natural attenuation. Groundnut therefore showed promise, as a cost-effective species for initial remediation or stabilization of SEO-polluted soils.

Keywords: Contamination, Engine Oil, Groundnut, Metals, Phytoextraction, Soil

Introduction

The relentless expansion of human industrial and automotive activities has precipitated a global environmental crisis, with soil contamination representing a particularly pernicious challenge. Among the various pollutants, spent engine oil (SEO) is a ubiquitous and hazardous waste product, generated in massive quantities from vehicle maintenance workshops, auto garages, and industrial machinery across the globe, and Nigeria is no exception (Ossai *et al.*, 2020) [14]. Improper disposal practices, such as direct dumping onto soil, drainage into water bodies, or open burning, have led to the widespread contamination of terrestrial and aquatic ecosystems, posing significant risks to ecological integrity and public health (Adeel *et al*., 2023) [1].

Spent engine oil is a complex mixture of hydrocarbons, heavy metals, and toxic additives that have undergone thermal and mechanical degradation during use. Its composition includes aliphatic and polycyclic aromatic hydrocarbons (PAHs), which are known carcinogens and mutagens, as well as heavy metals like lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), nickel (Ni), and chromium (Cr) that are leached from engine parts (Ossai *et al.*, 2020) [14]. When released into the soil, SEO alters its physical structure, reduces aeration and water infiltration, and creates an anoxic environment that is detrimental to soil biota the microorganisms essential for nutrient cycling and ecosystem functioning (Adeel *et al*., 2023) [1].

The soil environment in and around automotive mechanic workshops and institutional motor pools in Nigeria, including the vicinity of the Nigeria Police Academy in Kano, is under severe threat from chronic pollution caused by spent engine oil. This contamination is not a hypothetical risk but a present and escalating environmental emergency with multifaceted consequences (Ossai *et al.*, 2020) [14]. The problem is fundamentally driven by a lack of adequate waste management infrastructure, limited enforcement of environmental regulations, and a low level of awareness among operators regarding the long-term toxicological impacts of SEO (Adeel *et al.*, 2023) [1].

The choice of groundnut as the test crop is particularly strategic and justified for the Nigerian, and specifically the Kano, context. Kano State is a major agricultural hub in Nigeria, and groundnut was historically it's most valuable cash crop ("the groundnut pyramid" era). Promoting a remediation technology centered on a familiar and economically valuable crop significantly enhances its potential for adoption by local farmers and community-based remediation projects (Udechukwu *et al*., 2023) [17]. From a scientific standpoint, while there is a growing body of literature on phytoremediation of hydrocarbon-contaminated soils, studies often focus solely on the degradation of the organic fraction or on the metal accumulation in known hyperaccumulators. There is a relative paucity of research, particularly in Nigeria, on the dual application of a major leguminous crop like groundnut for the phytoextraction of metals from SEO-contaminated soil a matrix that contains both organic and inorganic toxins (Adenipekun & Kassim, 2020; Ogoko, 2021) [2, 12]. Therefore, this research seeks to evaluate the phytoextraction potential and early growth performance of groundnut seedlings on these SEO-contaminated soils. By investigating its tolerance, biomass production, and metal accumulation capabilities.

Materials and Methods

Study Area and Soil Collection

Bulk surface soil was collected 0-20 cm depth from a pristine, uncontaminated agricultural land within the vicinity of the Nigeria Police Academy, Wudil, Kano State. The site was selected for its lack of history of petroleum hydrocarbon pollution to serve as the control soil. The soil was air-dried at room temperature for two weeks, crushed manually using a wooden roller, and sieved through a 2 mm mesh to remove stones, plant debris, and other coarse materials to obtain a homogenous sample for the experiment (Okonokhua *et al*., 2007) [13].

Soil Spiking and Experimental Design

The sieved soil was artificially contaminated with spent engine oil (SEO) obtained from a mechanic workshop in Wudil to achieve the desired concentrations. The SEO was thoroughly mixed into the soil to achieve final concentrations of 4% (Low), 8% (Moderate), and 12% (High) w/w (weight of SEO per weight of dry soil). An uncontaminated portion was reserved as the control (0% SEO). The spiked soils were placed in perforated black polythene bags and allowed to equilibrate for four weeks under a shed with periodic turning twice a week to ensure proper weathering and homogenization of the hydrocarbons (Agbogidi *et al*., 2013) [3].

The experimental design was a 4 x 2 factorial in a Completely Randomized Design (CRD) with three replications. The factors were four levels of contamination (0%, 4%, 8%, 12% SEO) and two planting conditions (Planted with groundnut and Unplanted). The unplanted pots served as natural attenuation controls for each contamination level.

Pre-Experiment Soil Characterization

Prior to planting, a composite sample from each treatment was analyzed for key physicochemical and heavy metal properties. Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil: water suspension using a glass electrode pH meter and conductivity meter, respectively (Page *et al.*, 1982). Organic Matter (OM) content was estimated by the Walkley-Black wet oxidation method (Nelson and Sommers, 1982) [11]. Total Petroleum Hydrocarbon (TPH) content was extracted with dichloromethane and quantified using Gas Chromatography-Flame Ionization Detection (GC-FID) as described by USEPA Method 8015 (USEPA, 1996) [18]. For heavy metals (Pb, Cd, Zn, Cu, Fe, Ni), soil samples were digested with a tri-acid mixture (HNO_3:H_2SO_4:$HClO_4$ in a 5:1:1 ratio) (Allen *et al*., 1974) [5]. The concentrations of the metals in the digestate were quantified using Atomic Absorption Spectrophotometry (AAS, Model: Buck Scientific 210VGP).

Plant Establishment and Growth Conditions

Certified seeds of groundnut (*Arachis hypogaea* L.) var. Spanish were obtained from the Institute for Agricultural Research (IAR), Ahmadu Bello University, Zaria. Three seeds were sown per pot containing 5 kg of the equilibrated soil. After emergence, the seedlings were thinned to one uniform plant per pot. The plants were watered twice daily (morning and evening) with tap water to maintain field capacity and were grown for 6 weeks, from the early growth to maturity phase under natural sunlight. No fertilizer was added to isolate the effect of the contaminant.

Emergence and Growth Parameters

The number of days to seed emergence was recorded, emergence percentage was calculated at 10 Days after planting (DAP) as `(Number of seeds emerged / Total seeds sown) × 100`. Survival percentage was also calculated at the end of the experiment (38 DAP) as; `(Number of plants alive / Number of seeds emerged) × 100`. Plant height (from soil base to the apex) and number of leaves were measured at 2, 4, and 6weeks after emergence. At harvest (38 DAP), the plants were carefully uprooted, washed, and separated into shoots and roots. The biomass was oven-dried at 70°C for 48 hours to a constant weight to determine the shoot and root dry weights (Agbogidi, 2010).

Post-Experiment Soil and Plant Analysis

After plant harvest, soil from each pot was collected, air-dried, and analyzed for residual TPH and heavy metal concentrations using the same methods described in section 3.3. The percentage removal of each pollutant was calculated as:

`Removal Efficiency (%) = [(Ci - Cf) / Ci] × 100`, where Ci is the initial concentration and Cf is the final concentration.

The oven-dried plant samples (shoots and roots) were ground separately. A 0.5 g sample from each part was digested using the tri-acid mixture (HNO_3:H_2SO_4:$HClO_4$). The concentrations of heavy metals in the digestate were determined using AAS (Chapman and Pratt, 1961) [7].

Soil Enzyme Activity Assay

Dehydrogenase enzyme activity was assayed by the method of Casida *et al*. (1964) [6] based on the reduction of 2, 3, 5-triphenyltetrazolium chloride (TTC) to triphenylformazan (TPF) and expressed as μg TPF g^{-1} soil h^{-1}. Catalase activity was determined by measuring the volume of O_2 gas released from H_2O_2 after 5 minutes using the method of Johnson and Temple (1964) [8], and expressed as mL O_2 g^{-1} soil min^{-1}.

Calculation of Phytoremediation Indices

The following indices were calculated to evaluate the phytoextraction potential of groundnut:

Bioconcentration Factor (BCF) = [Metal] in root / [Metal] in soil` (Zhuang *et al.*, 2007) [22].

Translocation Factor (TF) = [Metal] in shoot / [Metal] in root` (Yoon *et al.*, 2006) [21].

Metal Uptake: `Total Uptake (µg/plant) = ([Metal]_shoot × Shoot DW) + ([Metal]_root × Root DW)` (McGrath and Zhao, 2003).

Statistical Analysis

All data collected were subjected to a two-way Analysis of Variance (ANOVA) using SPSS software version 28.0. Treatment means were compared using Tukey's Honest Significant Difference (HSD) test at a 5% probability level ($p < 0.05$). All values are presented as mean ± standard error (SE) of three replicates.

Results

Pre-experiment of soil characterization before planting

The result in Table 1 characterized the environment before the experiment began. It confirmed a successful experimental setup where increased in SEO concentration (0% to 12%) led to a significant, dose-dependent increase in soil pollution. The soil pH became progressively more acidic with higher SEO (from 6.8 to 6.0). This acidification is a common effect of hydrocarbon degradation, which can release organic acids. Electrical conductivity (EC) increased significantly from 0.21 to 0.62 dS/m, indicating a higher concentration of soluble salts and ions, likely from the inorganic additives and metal residues in the SEO. Organic matter (%) (OM) content rose dramatically from 1.9% to 6.5%, because SEO itself is an organic carbon source. However, this is not beneficial OM like humus; it is a toxic, polluting carbon. The total petroleum hydrocarbons (TPH) concentration also increased directly with the amount of SEO added, creating a strong contamination gradient (35 mg/kg to 12,900 mg/kg). All measured heavy metals showed a highly significant ($p<0.05$) and dose-dependent increase in concentration. For instance, Lead (Pb) rose from 2.4 mg/kg in the control to 23.7 mg/kg in the 6% SEO treatment, nearing or exceeding typical regulatory guidelines for soil safety. This confirms that SEO is a significant vector for heavy metal contamination.

Table 1: Pre-experiment of soil characterization before planting

Treatment SEO	pH	EC (dS/m)	OM (%)	TPH (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Ni (mg/kg)
Control (0%)	6.8 ± 0.1^{a}	0.21±0.02^{c}	1.9±0.1^{d}	35 ± 6^{c}	2.4±0.1^{d}	0.05±0.01^{c}	12.8±0.5^{c}	3.1± 0.2^{c}	118 ± 4^{c}	1.3± 0.1^{c}
Low (4%)	6.5±0.1^{ab}	0.36±0.03^{b}	3.6±0.2^{c}	4,250±120^{b}	8.9± 0.3^{c}	0.14±0.01^{b}	28.6±0.6^{b}	5.8± 0.3^{b}	163 ± 5^{b}	2.9± 0.2^{b}
Moderate (8%)	6.2 ± 0.1^{b}	0.48±0.04^{b}	5.2±0.2^{b}	8,650±210^{a}	15.9±0.4^{b}	0.23±0.02^{a}	45.1±0.8^{a}	9.1± 0.4^{a}	206 ± 6^{a}	4.8± 0.2^{a}
High (12%)	6.0 ± 0.1^{b}	0.62±0.05^{a}	6.5±0.3^{a}	12,900±260^{a}	23.7±0.5^{a}	0.30±0.02^{a}	57.2±0.9^{a}	11.4±0.5^{a}	244 ± 7^{a}	6.4± 0.3^{a}

Mean ± SE, n=3; different superscripts within a column indicate $p < 0.05$ (ANOVA + Tukey). TPH = total petroleum hydrocarbons.

Early Growth Performance of Groundnut Seedlings

The result in Table 2 clearly demonstrated that, the contamination characterization of soil was highly toxic to the groundnut seedlings, severely impacting on their early growth performance in a dose-dependent manner. Both germination success (Emergence %) and the ability of seedlings to survive for 6 weeks (Survival %) declined significantly from 96 to 68% as SEO concentration increased. At the highest dose (12% SEO), only about half of the seeds emerged, and over 30% of those subsequently died. The result of the growth metrics showed that, all measures of plant health and vigor were negatively impacted, days to Emergence increased from 3 to 5 days, meaning seeds took longer to germinate under stress. The plant height (6.4cm) and number of leaves (4) were significantly stunted. Biomass accumulation (shoot and root dry weight) which is the most telling metric, drastically reduced from1.9 to 0.58 and 0.98 to 0.31 in the shoot and root respectively. Plants in the 12% SEO treatment had only about 30% of the shoot biomass and 32% of the root biomass of the control plants. This indicates severe physiological stress, likely due to impaired nutrient and water uptake, reduced photosynthesis, and direct cellular toxicity.

Table 2: Early growth performance of groundnut seedlings

Treatment (Planted)	Emergence (%)	Daysto Emergence	Survival (%)	Height (cm)	Leaves (no.)	ShootDW (g/plant)	RootDW (g/plant)
Control (0%)	95 ± 2^{a}	3.5 ± 0.3^{a}	96 ± 2^{a}	15.6±0.9^{a}	10 ± 1^{a}	1.90 ± 0.10^{a}	0.98± 0.05^{a}
Low (4%)	84 ± 3^{b}	4.0 ± 0.3^{ab}	90 ± 3^{a}	12.6 ± 0.8^{b}	8 ± 1^{b}	1.38 ± 0.08^{b}	0.72± 0.04^{b}
Moderate (8%)	69 ± 4^{c}	4.7 ± 0.4^{b}	80 ± 3^{b}	9.2 ± 0.7^{c}	6 ± 1^{c}	0.95 ± 0.07^{c}	0.49 ± 0.03^{c}
High (12%)	53 ± 5^{d}	5.3 ± 0.5^{c}	68 ± 4^{c}	6.4 ± 0.6^{d}	4 ± 1^{d}	0.58 ± 0.05^{d}	0.31± 0.02^{d}

Mean ± SE; different superscripts indicate $p < 0.05$.

The Phytoextraction Process: Metal Uptake and Translocation

Despite the observed toxicity, the result in Table 3 revealed that, the groundnut plants were actively absorbing metals from the soil. The concentrations of all the four heavy metals (Pb, Cd, Zn, Cu) in both the roots and shoots increased significantly and consistently with the increasing initial soil contamination (from Table 1). For instance, Pb in shoots rose from 2.2 mg/kg (control) to 20.5 mg/kg (12% SEO treatment). For all metals and across all treatments, the concentration was higher in the roots than in the shoots most especially Pb in roots at 12% SEO was 31.1 mg/kg compared to. 20.5 mg/kg in shoots. This suggests that, the roots act as the primary site for metal accumulation and that translocation to the shoots was partial. This result had provided the first direct evidence of phytoextraction that, the plants are taking up and storing contaminants.

Table 3: Heavy Metal Concentrations in Plant Tissues (6 Weeks)

Treatment	Pb (mg/kg) Shoot	Pb (mg/kg) Root	Cd (mg/kg) Shoot	Cd (mg/kg) Root	Zn (mg/kg) Shoot	Zn (mg/kg) Root	Cu (mg/kg) Shoot	Cu (mg/kg) Root
Control (0%)	2.2 ± 0.2^{c}	3.7 ± 0.3^{c}	0.02±0.01^{c}	0.04±0.01^{c}	10.6 ± 0.3^{c}	15.5± 0.5^{c}	2.8 ± 0.2^{c}	4.2 ± 0.3^{c}
Low (4%)	8.1 ± 0.3^{b}	12.3± 0.5^{b}	0.08± 0.01^{b}	0.14± 0.02^{b}	23.1± 0.6^{b}	29.6± 0.7^{b}	5.5 ± 0.3^{b}	7.4 ± 0.4^{b}
Moderate (8%)	15.2 ± 0.5^{a}	21.5± 0.7^{a}	0.16 ± 0.02^{a}	0.23± 0.02^{a}	35.3 ± 0.7^{a}	48.9± 0.9^{a}	8.9 ± 0.4^{a}	11.2± 0.5^{a}
High (12%)	20.5 ± 0.6^{a}	31.1± 0.9^{a}	0.24 ± 0.03^{a}	0.30± 0.03^{a}	46.5 ± 0.8^{a}	64.7± 1.1^{a}	11.5 ± 0.5^{a}	14.8± 0.6^{a}

Means ± SE, n=3.

Derived Phytoremediation Indices and Metal Uptake

The results presented in Tables 1 and 3 were used to calculate standardized indices that quantify the efficiency of the phytoextraction process (Table 4). Bioconcentration factor (BCF) which is the ratio of metal in the root to metal in the soil. A BCF > 1 indicates the plant is effectively concentrating the metal in its roots from the soil. All the BCF values for Zn (1.03 to 1.13), and Pb were consistently (1.31 to 1.38) >1, showing a strong ability to concentrate zinc and lead in its roots hence, identifying groundnut as a good zinc and lead accumulator. The BCF for Cd was (0.67-0.71) <1, indicating poorer root concentration for this metal. Translocation factor (TF) which is the ratio of metal in the shoot to metal in the root. The TF values for all metals ranged from 0.57 to 0.80 were <1. This implies that, while metals were absorbed, they were primarily retained in the roots. This defines groundnut's strategy as being a 'phytostabilizer' (immobilizing metals in roots) rather than classic phytoextraction for these metals. The TF values were highest for Cd and Zn at higher concentrations, suggesting some potential for their extraction. Despite the lower biomass in higher SEO treatments (Table 2), the much higher metal concentration in the tissues (Table 3) resulted in a net increase in total metal uptake per plant for both Pb and Zn as pollution levels rose.

Table 4: Derived Phytoremediation Indices and Metal Uptake

Treatment	Pb BCF	Pb TF	Cd BCF	Cd TF	Zn BCF	Zn TF	PbUptake (µg/plant)	ZnUptake (µg/plant)	Total Metal Removal from Soil (%)†
Low (4%)	1.38	0.66	0.71	0.57	1.03	0.78	27.9 ± 2.4	92.6 ± 6.1	18.9 ± 1.2
Moderate (8%)	1.35	0.71	0.70	0.70	1.08	0.72	40.9 ± 3.2	128.4 ± 7.3	26.5 ± 1.5
High (12%)	1.31	0.66	0.67	0.80	1.13	0.72	47.4 ± 3.6	152.1 ± 8.4	27.9 ± 1.7

BCF = Root conc./Soil conc.; TF = Shoot conc./Root conc. Metal uptake (µg/plant) = Shoot conc. (mg/kg) × Shoot DW (g) + Root conc. (mg/kg) × Root DW (g). †Total removal includes plant uptake plus observed soil reduction relative to unplanted.

Post-Experiment of Soil (6 weeks) at Residual Levels and Removal Efficiency

Table 2 provided the most critical evidence for the effectiveness of the phytoremediation process, which compared the final soil contamination in planted pots with unplanted pots (natural attenuation). The unplanted pots (Natural attenuation) showed only minor reductions in total petroleum hydrocarbon (TPH) and metals (4.9% to 12.0% removal). This represents losses due to volatilization, leaching, and minimal microbial activity. Meanwhile, the planted pots (Phytoremediation) showed a dramatically higher removal efficiency for all pollutants consistently around 30% for TPH and 22-33% for metals. Statistically, the residual levels of TPH and metals in all planted treatments were significantly (p<0.05) lower than in their unplanted counterparts.

Table 5: Post-experiment of Soil (6 Weeks) at residual levels and removal Efficiency

Treatment	Planting	TPH (mg/kg)	TPH Removal (%)	Pb (mg/kg)	Pb Removal (%)	Cd (mg/kg)	Cd Removal (%)	Zn (mg/kg)	Zn Removal (%)
Low (4%)	Unplanted	3,760±110^{c}	12.0	8.1±0.3^{b}	9.0	0.13±0.0^{b}	7.1	26.9±0.7^{b}	5.9
Low (4%)	**Planted**	**2,950 ± 95^{b}**	**30.6**	**6.7±0.2^{c}**	**24.7**	**0.10±0.01^{c}**	**28.6**	**22.4±0.6^{c}**	**21.7**
Moderate (8%)	Unplanted	7,730±190^{c}	10.7	14.7±0.4^{b}	7.5	0.21±0.02^{b}	8.7	42.4±0.9^{b}	6.0
Moderate (8%)	**Planted**	**5,980±170^{b}**	**30.9**	**12.0±0.3^{c}**	**24.5**	**0.16±0.01^{c}**	**30.4**	**35.1±0.8^{c}**	**22.2**
High (6%)	Unplanted	11,650±240^{c}	9.7	22.1±0.5^{b}	6.8	0.28±0.02^{b}	6.7	54.4±1.1^{b}	4.9
High(12%)	**Planted**	**8,950 ± 220^{b}**	**30.6**	**17.8±0.4^{c}**	**24.9**	**0.20±0.02^{c}**	**33.3**	**44.1±0.9^{c}**	**22.8**

Planted = groundnut; Unplanted = natural attenuation control at same SEO level.

Removal (%) = (Initial−Residual)/Initial(Initial − Residual)/Initial × 100. Means ± SE, n=3. Bold rows show phytoremediation benefit vs unplanted.

Soil Biological Indicators (Enzyme Activities) Post-Experiment

The result presented in Table 6 explained why and how the removal of metals was higher in planted pots, especially for organic TPH, since it measured soil enzyme activities, which were indicators of microbial health and metabolic activity. Dehydrogenase and catalase; An enzyme indicative of overall microbial metabolic activity and enzyme that breaks down toxic H_2O_2, often produced during stress and hydrocarbon degradation respectively. This Results showed that, enzyme activities were severely suppressed in the unplanted contaminated soils. However, in the planted contaminated soils, enzyme activities were significantly higher most especially at low (4%) planted (26.7µg TPF g^{-1} h^{-1}) dehydrogenase and (2.3 mL O_2 g^{-1} min^{-1}) catalase. This further explained that, groundnut roots released exudates (sugars, acids) that stimulated microbial populations in the rhizosphere. These microbes, in turned, were more active and capable of degrading the petroleum hydrocarbons (TPH).

Table 6: Soil biological indicators (enzyme activities) post-experiment

Treatment	Dehydrogenase (µg TPF g^{-1} h^{-1})	Catalase (mL O_2 g^{-1} min^{-1})
Control (0%)	35.2 ± 1.8^a	2.9 ± 0.2^a
Low (4%) Unplanted	18.6 ± 1.2^c	1.6 ± 0.1^c
Low (4%) Planted	**26.7 ± 1.5^b**	**2.3 ± 0.1^b**
Moderate (8%) Unplanted	14.1 ± 1.0^c	1.2 ± 0.1^c
Moderate (8%) Planted	**22.9 ± 1.3^b**	**2.0 ± 0.1^b**
High (12%) Unplanted	10.8 ± 0.9^c	0.9 ± 0.1^c
High (12%) Planted	**18.4 ± 1.1^b**	**1.6 ± 0.1^b**

Higher enzyme activity in planted soils evidences rhizosphere recovery during phytoremediation.

Discussion

The results of this study provide a comprehensive evaluation of the early growth response and phytoextraction potential of groundnut (*Arachis hypogaea* L.) in spent engine oil (SEO)-contaminated soil. The findings revealed a complex interplay between soil contamination, plant health, microbial activity, and metal removal efficiency, demonstrating both the promise and the limitations of using groundnut for phytoremediation.

Soil Contamination and its Phytotoxic Effects on the Seedlings

The pre-experiment soil characterization carried out during this study confirmed the successful creation of a contamination gradient. The significant increased in total petroleum hydrocarbons (TPH) and all heavy metals (Pb, Cd, Zn, Cu, Fe, Ni) with rising SEO concentration was consistent with the known composition of spent engine oil (Ossai *et al.*, 2020) [14]. The observed acidification decrease in soil pH from 6.8 to 6.0 was a common consequence of hydrocarbon contamination, often resulting from the release of organic acids during microbial degradation or the oxidation of sulfur compounds in the oil (Adeel *et al.*, 2023) [1]. The increase in electrical conductivity (EC) and organic matter (OM) content was directly attributableted to the ionic constituents and the high carbon content of the added engine oil, respectively (Agbogidi *et al.*, 2013) [3].

This contaminated environment exerted significant phytotoxic stress on the groundnut seedlings, as evidenced by the results obtained during the study. There was a dose-dependent inhibition of all growth parameters: emergence percentage decreased, days to emergence increased, and survival rate, plant height, leaf number, and biomass (shoot and root dry weight) all declined significantly with increasing SEO concentration. This suppression of growth aligned with numerous studies on hydrocarbon stress (Ogoko, 2021; Adenipekun & Kassim, 2020) [12, 2]. The mechanisms were multifaceted; the oil coating on seeds impedes water and oxygen uptake, hindering germination; the hydrophobic layer formed by hydrocarbons disrupts soil water relations and gas exchange, causing drought stress and hypoxia; and the direct toxicity of hydrocarbons and heavy metals impairs cellular functions, chlorophyll synthesis, and photosynthetic efficiency (Adeel *et al.*, 2023) [1]. Despite this stress, the survival of over 50% of seedlings even at the highest (12%) contamination level indicates a notable level of tolerance in groundnut, hence, a prerequisite for any phytoremediation candidate.

The core finding of this research is the demonstrably superior remediation performance in planted pots compared to unplanted controls (natural attenuation), as detailed in Table 2. For all contaminants (TPH, Pb, Cd, Zn), the removal efficiency in planted soils was consistently and significantly higher (approximately 30% for TPH and 22-33% for metals) than in unplanted soils (7-12%). This clearly indicates that the presence of groundnut actively facilitated the cleanup process.

This enhancement cannot be attributed to phytoextraction alone. The total metal uptake calculated for groundnut, while significant, accounts for only a fraction of the total mass of metals removed from the soil. This suggests that, the primary role of groundnut was not direct extraction but the stimulation of other remediation mechanisms in the rhizosphere. This was strongly supported by the enzyme activity, dehydrogenase activity, a robust indicator of overall microbial metabolic activity, and catalase activity, which indicates the breakdown of toxic peroxides generated during hydrocarbon stress, were significantly higher in planted soils than in their unplanted counterparts at the same contamination level. This phenomenon, known as rhizoremediation, was well-documented by Adenipekun & Kassim, (2020) [2]; Liu *et al.*, (2022) [9]. The groundnut root exudated sugars, amino acids,and organic acids serve to as a readily available carbon source for hydrocarbon-degrading microbes, boosting their population and catalytic activity. This enhanced microbial community is responsible for the majority of TPH degradation and also influences metal bioavailability through acidification and chelation, potentially facilitating their removal through various pathways (Yan *et al.*, 2020) [20].

Metal Accumulation and Phytoextraction Potential

Despite rhizoremediation being the dominant process, the findings confirmed that, groundnut also functions as a moderate accumulator of heavy metals. The concentrations of all metals in root and shoot tissues increased significantly with rising soil contamination, confirming active uptake. The key phytoremediation indices provide a nuanced understanding of this potential. A plant suitable for phytoextraction should ideally have a bioconcentration factor (BCF > 1) and a translocation tactor (TF > 1), indicating efficient uptake and transfer to easily harvestable shoots (Yoon *et al*., 2006) [21]. In this study, groundnut exhibited BCF values greater than 1 for Pb and Zn across all treatments, indicating a strong ability to concentrate these metals in its roots. However, the TF values for these metals were consistently below 1 for Pb and Zn, signifying that the metals were largely retained in the root system. This defines groundnut as a phytostabilizer for Pb and Zn, effectively immobilizing them in the roots and preventing their leaching into groundwater or entry into the food chain via grazing animals (Yan *et al*., 2020) [20]. For Cadmium, the BCF was less than 1, but the TF increased with contamination level, reaching the highest dose. This suggests a relatively lower root uptake but a high proportional translocation to shoots, indicating a potential for phytoextraction of Cd, especially over multiple cropping cycles. The increasing total metal uptake per plant with contamination level was a crucial finding. It demonstrated that, despite reduced biomass at higher contamination, the increased metal concentration in the tissues resulted in a greater total metal offtake from the soil. This highlights that even non-hyperaccumulator, high-biomass crops can contribute significantly to metal removal (Raza *et al*., 2020) [16].

Implications for Practical Application and Future Research

The results obtained during the study suggested that, groundnut was a highly suitable candidate for the phytomanagement of SEO-contaminated sites. Its dual strategy of rhizoremediation (for THP degradation) and phytostabilization for metals like Pb and Zn makes it an effective and sustainable solution (Ali *et al*., 2020) [4]. The fact that it is a legume added further agronomic value, as it may improve soil nitrogen content through symbiotic fixation, aiding the recovery of soil fertility post-remediation. For practical application, this study suggests that groundnut could be deployed on moderately contaminated lands. However, the significant growth reduction at 4% and 6% SEO indicates that highly contaminated sites might require a pre-treatment step or the use of groundnut in a later stage of a remediation sequence. Future research should focus on longer-term field trials to validate these pot findings, investigate the role of soil amendments (e.g., biochar, fertilizers) in alleviating phytotoxicity and enhancing efficiency, and identify the specific microbial consortia enriched in the groundnut rhizosphere to optimize the process (WHO, 2021) [19].

Conclusion

In conclusion, while spent engine oil contamination imposed significant phytotoxicity on groundnut, the plant demonstrated remarkable tolerance. The research conclusively shows that groundnut enhances remediation far beyond natural attenuation, primarily through the stimulation of microbial activity in the rhizosphere (rhizoremediation) leading to TPH degradation and metal mobilization. Furthermore, groundnut acts as an effective phytostabilizer for lead and zinc, accumulating them in the root system and reducing their environmental mobility. Although not a classic hyperaccumulator, its ability to remove a quantifiable amount of metals, combined with its agronomic value, positions *Arachis hypogaea* L. as a viable and sustainable crop for the phytomanagement of spent engine oil-contaminated soils.

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