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Soil Remediation Using Soybean-Coated NPK Fertilizer and Poultry Manure: Effects on Photosynthetic Pigments of Edible Amaranthus viridis and Implications for Sustainable Development Goals (SDGs)

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ABSTRACT

Spent engine oil contamination threatens soil quality and vegetable production. This study investigated soybean-coated NPK fertilizer and poultry manure for restoring contaminated soil and improving photosynthetic pigments in edible Amaranthus viridis. Soil containing 6 kg per container was exposed to 0, 2.5, 5.0, or 7.5 mL of spent oil, followed by fertilizer amendments. Over eight weeks, petroleum hydrocarbons, soil pH, microbial populations, and enzyme activities were evaluated, while chlorophyll and carotenoids were measured at harvest. Oil contamination impaired soil conditions and reduced plant pigments. Fertilizer amendments promoted microbial recovery, modified enzymatic activities, reduced petroleum contamination, and improved pigmentation. These findings highlight potential applications in sustainable soil management and vegetable cultivation, supporting Sustainable Development Goals (SDGs).

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1. INTRODUCTION

Soil contamination by petroleum hydrocarbons is a major environmental challenge that can reduce agricultural productivity and affect the quality of crops cultivated on polluted land. Spent engine oil contains petroleum-derived compounds and potentially toxic substances that can alter soil physicochemical properties, microbial activity, and nutrient availability [1, 2]. Petroleum contamination can disrupt soil biological processes, while organic amendments may enhance hydrocarbon biodegradation and facilitate soil recovery [3, 4]. These effects are particularly important in agricultural systems where contaminated land may be used for vegetable cultivation, potentially increasing concerns regarding crop quality and food safety [5].

Amaranthus viridis is an edible leafy vegetable cultivated in tropical regions and valued for its nutritional properties. However, vegetables grown in contaminated environments may accumulate potentially harmful substances, raising concerns about agricultural sustainability and food safety. Previous investigations have examined heavy metals, organic micropollutants, and associated human health risks involving edible Amaranthus leaves [5-8]. Therefore, improving contaminated soil conditions is important for sustainable vegetable cultivation, although soil remediation alone does not establish that harvested vegetables are safe for consumption.

Biological remediation using organic and inorganic amendments provides a potential approach for restoring petroleum-contaminated soils. Nutrient supplementation may stimulate microbial growth, enzymatic activity, and hydrocarbon degradation, while changes in soil biochemical indicators can provide information about remediation processes [3, 4, 9]. Soybean-coated Nitrogen-Phosphate-Kalium (NPK) fertilizer represents an approach combining mineral nutrient supplementation with a soybean-protein-based coating, whereas poultry manure provides an organic amendment that may contribute nutrients and support microbial activity. Nevertheless, the combined relationships among petroleum degradation, soil enzymatic responses, and photosynthetic pigments of edible A. viridis under these amendment conditions remain insufficiently established.

Sustainable soil management is closely associated with agricultural productivity, food security, and environmental protection. Integrated nutrient management and regenerative agricultural practices have been discussed as approaches supporting sustainable agriculture and food production [10]. Furthermore, soil conservation and food safety are relevant to the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land) [11, 12]. However, achieving these goals requires consideration of both agricultural productivity and environmental safety, particularly when edible crops are cultivated in previously contaminated soil.

The relationship between soil remediation and crop physiological responses remains an important consideration for sustainable vegetable production. Soil microbial populations and enzymatic activities can provide information regarding biological recovery, whereas chlorophyll and carotenoid contents reflect aspects of plant photosynthetic physiology. Evaluating these indicators together may help explain how fertilizer amendments influence soil conditions and plant pigmentation under petroleum contamination. Nevertheless, improvements in photosynthetic pigments should not be interpreted as direct evidence of

improved nutritional quality or food safety because contaminant accumulation in edible plant tissues must be assessed separately [6-8].

This study aims to evaluate the effects of soybean-coated NPK fertilizer and poultry manure on the remediation of spent engine oil-contaminated soil and the photosynthetic pigments of edible Amaranthus viridis. Specifically, the study examines total petroleum hydrocarbons (TPH), soil pH, microbial populations, catalase, acid phosphatase, alkaline phosphatase, dehydrogenase activities, chlorophylls, and carotenoids. The findings are discussed in relation to soil recovery, vegetable cultivation, and their potential implications for sustainable food production and SDGs 2, 12, and 15.

2. MATERIALS AND METHODS

2.1. Materials and Experimental Design

Spent engine oil was obtained from an automobile mechanic workshop in Owerri, Imo State, Nigeria, while soil samples were collected from the Botanical Garden of the Federal University of Technology Owerri. Poultry droppings (PD) were obtained from a local poultry farm, whereas NPK fertilizer and soybeans were purchased from local suppliers. Seeds of Amaranthus viridis were collected locally and identified by a plant science specialist at the Federal University of Technology Owerri. The experiment was conducted for eight weeks using plastic containers containing 6 kg of soil each. Four contamination levels were investigated, consisting of 0 (control), 2.5, 5.0, and 7.5 mL of spent engine oil per container. Following seed germination, the soil was contaminated with spent oil and amended separately with soybean-coated NPK fertilizer or poultry droppings. Unamended contaminated soil was maintained for comparison. Treatments were conducted in triplicate. Soil physicochemical properties, microbial populations, and enzymatic activities were evaluated at two-week intervals, while plant photosynthetic pigments were measured at the end of the eighth week.

2.2. Preparation of Soybean-Coated NPK Fertilizer

Soybean-coated NPK fertilizer was prepared using soybean protein isolate (SPI) as the coating material and glutaraldehyde as a cross-linking agent. The SPI mixture was sprayed onto NPK granules placed in a rotating drum maintained at approximately 70 °C. The coating was allowed to solidify, producing a film surrounding the fertilizer granules. This formulation was designed to regulate nutrient release and support microbial interactions in petroleum-contaminated soil. Poultry droppings were applied separately as an organic amendment for comparison.

2.3. Soil Physicochemical Characterization

Soil texture was determined using the hydrometer method to quantify the proportions of sand, silt, and clay [13]. Soil samples were dispersed using sodium hexametaphosphate and sodium carbonate, mechanically shaken, and subjected to hydrometer measurements. The percentages of clay and silt were calculated from the corrected hydrometer readings, while sand content was determined by difference. TPH was determined using cold toluene extraction, following the analytical procedure described in the original study and associated literature [3]. A 10 g soil sample was mixed with 20 mL of toluene and shaken for 30 minutes. The extracted liquid phase was subsequently analysed at 420 nm using a spectrophotometer. TPH concentrations were estimated using a calibration curve prepared from crankcase oil

diluted with toluene. Soil pH was measured using a calibrated pH meter after preparation of a soil suspension. Calibration was performed using standard buffer solutions at pH 4.0 and 7.0.

2.4. Determination of Soil Microbial Populations

Soil microbial populations were determined using serial dilution and plate-counting techniques. Diluted soil suspensions were inoculated onto mineral salt agar containing 1% spent engine oil as a carbon source. The medium contained K_2HPO_4, NH_4Cl, $MgSO_4{\cdot}7H_2O$, KH_2PO_4, $FeSO_4{\cdot}7H_2O$, NaCl, and agar. The inoculated plates were incubated at 30 °C for five days, after which microbial colonies were counted and expressed as colony-forming units per gram of soil (CFU/g). Selected microbial isolates were purified through subculturing and characterised using conventional microbiological and biochemical identification procedures. API 20 NE was used for Gram-negative bacteria, whereas the BBL Crystal rapid identification system was used for Gram-positive bacteria. Microbial populations were monitored at two-week intervals to evaluate biological responses to petroleum contamination and fertilizer amendments.

2.5. Determination of Soil Enzymatic Activities

Soil enzymatic activities were evaluated through catalase, acid phosphatase, alkaline phosphatase, and dehydrogenase assays. Catalase activity was determined based on the decomposition of hydrogen peroxide, followed by spectrophotometric measurement at 480 nm, according to the referenced analytical approach [14]. Acid and alkaline phosphatase activities were determined using a colorimetric assay based on the hydrolysis of p-nitrophenyl phosphate [15]. The released p-nitrophenol was measured spectrophotometrically at 410 and 405 nm for acid and alkaline phosphatase, respectively. The reactions were conducted in buffered solutions at pH 6.5 and 11.0. Dehydrogenase activity was determined using the reduction of 2,3,5-triphenyltetrazolium chloride (TTC) to formazan [16]. Samples were incubated with TTC, followed by ethanol extraction and spectrophotometric measurement at 485 nm. The enzyme assays were performed at two-week intervals to evaluate changes in soil biochemical activities associated with petroleum contamination and fertilizer amendments.

2.6. Extraction and Quantification of Photosynthetic Pigments

Photosynthetic pigments were extracted from A. viridis leaves collected at the end of the eighth week. Leaf samples were homogenised using 80% aqueous acetone and centrifuged at 5,000 rpm for 10 minutes. The extraction was repeated, and the collected supernatant was adjusted to a final volume of 25 mL. Absorbance was measured at 645, 663, 480, and 510 nm using a UV-visible spectrophotometer. Chlorophyll a, chlorophyll b, and total chlorophyll were determined using the spectrophotometric approach described in previous literature [17].

The concentrations of photosynthetic pigments were calculated using the following equations (1), (2), (3), and (4):

$$\text{Chlorophyll } a = (12.7A_{663} - 2.69A_{645})\frac{V}{1000W} \quad (1)$$

$$\text{Chlorophyll } b = (22.9A_{645} - 4.68A_{663})\frac{V}{1000W} \quad (2)$$

$$\text{Total chlorophyll} = (20.2A_{645} + 8.02A_{663})\frac{V}{1000W} \quad (3)$$

$$\text{Total carotenoids} = (7.6A_{480} - 1.49A_{510})\frac{V}{1000W} \quad (4)$$

where *A* represents absorbance at the corresponding wavelength, *V* is the final extract volume (mL), and *W* is the fresh leaf mass (g). The pigment contents were expressed in mg/g fresh weight.

2.7. Statistical Analysis

Experimental data were analysed using the Statistical Package for the Social Sciences (SPSS), version 20. One-way analysis of variance (ANOVA) was used to evaluate differences among treatments. Measurements were performed in triplicate, and differences were considered statistically significant at $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1. Soil Characteristics and Petroleum Hydrocarbon Contamination

The initial soil characteristics indicated a composition of 42% sand, 38% clay, and 20% silt, as presented in **Table 1**. These fractions describe the soil medium used for evaluating petroleum contamination and fertilizer-assisted remediation. Soil texture is relevant because it can influence water movement, nutrient availability, and the distribution of contaminants within the root environment.

Table 1. Soil textural characteristics.

SOIL COMPONENT	COMPOSITION (%)
Sand	42
Clay	38
Silt	20
Total	100

Spent engine oil contamination significantly increased TPH compared with the uncontaminated control ($p < 0.05$), as illustrated in **Figure 1(a)**. Higher contamination levels were associated with greater petroleum hydrocarbon loading. The addition of soybean-coated NPK fertilizer and poultry droppings reduced TPH under the investigated contamination conditions, as presented in **Figures 1(b), (c), and (d)**. Nutrient amendments may contribute to biological recovery processes in petroleum-contaminated soil. Previous studies have similarly demonstrated the potential of organic amendments to support hydrocarbon biodegradation and improve contaminated soil conditions [3, 4].

Petroleum contamination reduced soil pH compared with the uncontaminated control, indicating changes in soil chemical conditions associated with increasing oil exposure. The temporal responses are presented in **Figure 2(a)**. Application of soybean-coated NPK fertilizer and poultry droppings increased soil pH relative to the corresponding contaminated treatments, as illustrated in **Figures 2(b), (c), and (d)**. Nutrient amendments modified the chemical environment of contaminated soil.

Soil pH is important for microbial activity, nutrient availability, and biochemical processes associated with plant growth. Changes in soil physicochemical conditions following petroleum contamination have also been discussed in previous studies [1, 2]. Nevertheless, increased pH alone does not establish complete remediation, and its interpretation should be considered alongside TPH, microbial populations, and soil enzymatic activities.

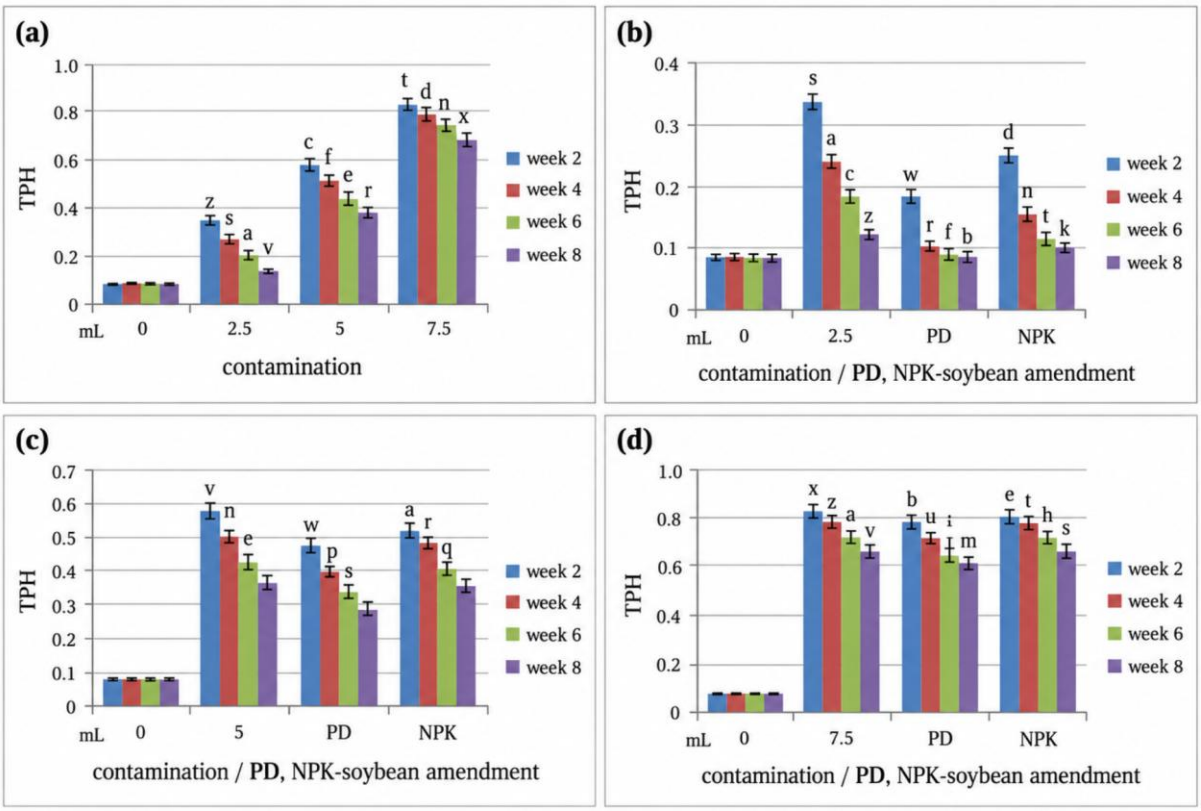

Figure 1. Changes in TPH in spent engine oil-contaminated soil during the eight-week experiment: (a) effects of different oil contamination levels (0, 2.5, 5.0, and 7.5 mL); effects of PD and soybean-coated NPK fertilizer on TPH at (b) 2.5, (c) 5.0, and (d) 7.5 mL of oil contamination. Different letters indicate statistically significant differences ($p < 0.05$; $n = 3$).

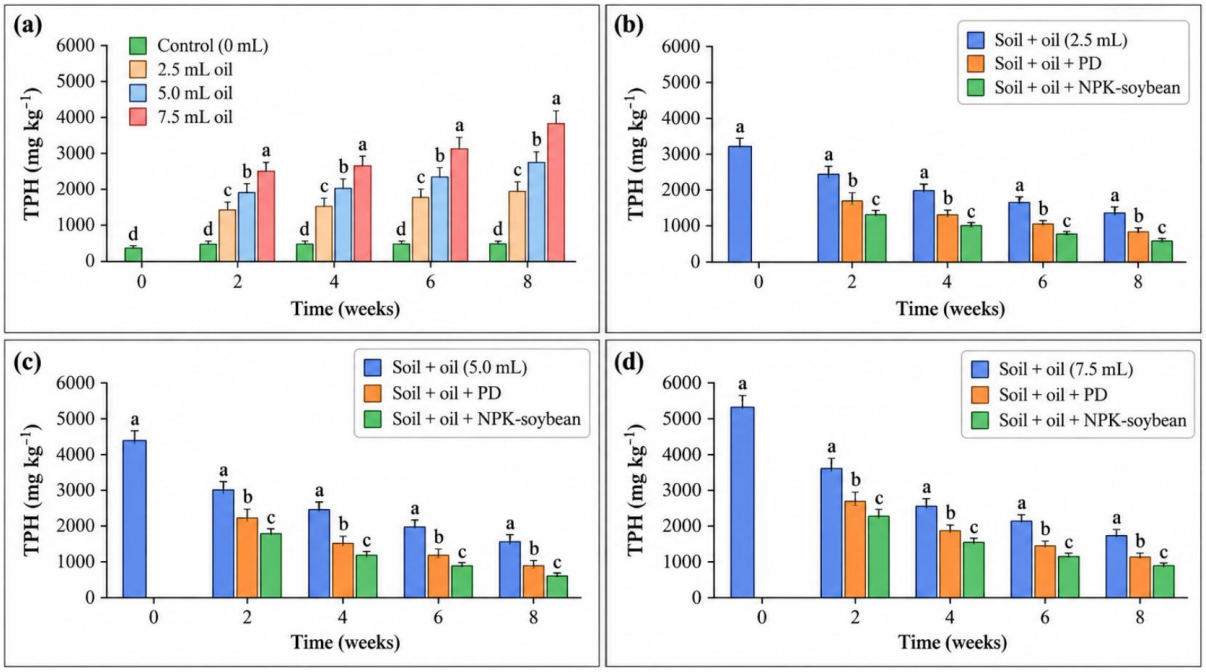

Figure 2. Changes in soil pH during the eight-week experiment: (a) effects of different spent engine oil contamination levels (0, 2.5, 5.0, and 7.5 mL); (b-d) effects of PD and soybean-coated NPK fertilizer on soil pH ((b) 2.5, (c) 5.0, and (d) 7.5 mL of oil contamination). Different letters indicate statistically significant differences ($p < 0.05$; $n = 3$).

3.3. Microbial Population Responses to Soil Contamination and Amendments

Spent engine oil contamination reduced soil microbial populations, with greater reductions generally observed at higher contamination levels. Fertilizer amendments increased culturable microbial populations compared with the corresponding oil-contaminated treatments. The responses varied with contamination level, treatment type, and incubation time, as presented in **Tables 2-4**. At 2.5 mL of oil contamination, microbial populations increased from 6.26×10^8 CFU/g in untreated contaminated soil to 8.58×10^8 and 8.42×10^8 CFU/g following poultry droppings and soybean-coated NPK amendments, respectively, at week eight. Similar treatment-related increases occurred at 5.0 and 7.5 mL of contamination, although microbial populations remained lower under greater oil exposure. Amendments supported the growth of culturable microorganisms under petroleum stress. Organic amendments have previously been investigated for their contribution to microbial activity and petroleum hydrocarbon biodegradation [3, 9].

Table 2. Microbial populations in soil contaminated with 2.5 mL of spent engine oil. Values reproduced from the original manuscript; microbial populations expressed as CFU/g.

TREATMENT	WEEK 2	WEEK 4	WEEK 6	WEEK 8
Soil + oil	$6.08 \times 10^8 \pm 0.03^b$	$6.81 \times 10^8 \pm 0.10^a$	$6.54 \times 10^8 \pm 0.01^c$	$6.26 \times 10^8 \pm 0.20^r$
Soil + oil + PD	$6.42 \times 10^8 \pm 0.00^e$	$7.90 \times 10^8 \pm 0.10^a$	$8.19 \times 10^8 \pm 0.00^s$	$8.58 \times 10^8 \pm 0.05^v$
Soil + oil + NPK-soybean	$6.49 \times 10^8 \pm 0.01^a$	$7.86 \times 10^8 \pm 0.00^f$	$8.24 \times 10^8 \pm 0.20^v$	$8.42 \times 10^8 \pm 1.01^t$

Note: Control soil: $10.32 \times 10^8 \pm 0.05$ CFU/g. $p < 0.05$; $n = 3$.

Table 3. Microbial populations in soil contaminated with 5.0 mL of spent engine oil.

TREATMENT	WEEK 2	WEEK 4	WEEK 6	WEEK 8
Soil + oil	$5.26 \times 10^8 \pm 0.10^a$	$5.78 \times 10^8 \pm 0.05^b$	$5.70 \times 10^8 \pm 1.01^c$	$5.62 \times 10^8 \pm 1.02^v$
Soil + oil + PD	$5.45 \times 10^8 \pm 0.20^a$	$6.41 \times 10^8 \pm 0.02^b$	$6.84 \times 10^8 \pm 2.01^c$	$7.40 \times 10^8 \pm 1.05^r$
Soil + oil + NPK-soybean	$5.47 \times 10^8 \pm 0.05^f$	$6.30 \times 10^8 \pm 0.10^d$	$6.90 \times 10^8 \pm 2.02^a$	$7.10 \times 10^8 \pm 0.01^c$

Note: $p < 0.05$; $n = 3$.

Table 4. Microbial populations in soil contaminated with 7.5 mL of spent engine oil.

TREATMENT	WEEK 2	WEEK 4	WEEK 6	WEEK 8
Soil + oil	$4.50 \times 10^8 \pm 1.10^a$	$4.61 \times 10^8 \pm 0.12^b$	$4.57 \times 10^8 \pm 0.02^c$	$4.29 \times 10^8 \pm 0.01^z$
Soil + oil + PD	$4.68 \times 10^8 \pm 0.02^a$	$4.72 \times 10^8 \pm 0.05^b$	$5.36 \times 10^8 \pm 0.00^c$	$5.75 \times 10^8 \pm 1.00^f$
Soil + oil + NPK-soybean	$4.59 \times 10^8 \pm 1.10^a$	$4.70 \times 10^8 \pm 1.00^d$	$5.40 \times 10^8 \pm 0.02^t$	$5.60 \times 10^8 \pm 1.01^x$

Note: $p < 0.05$; $n = 3$.

3.4. Effects of Soil Contamination on Enzymatic Activities

Soil enzymatic activities responded differently to petroleum contamination and fertilizer amendments. Catalase and acid phosphatase activities were inhibited by spent engine oil, whereas alkaline phosphatase and dehydrogenase activities increased under contamination. Petroleum exposure altered soil biochemical processes rather than producing a uniform response across all enzymes. Soil enzyme activity has been recognised as an important indicator of biological disturbance in contaminated environments [2, 15, 16].

Catalase activity decreased under petroleum exposure but increased following the addition of soybean-coated NPK fertilizer and poultry droppings, as shown in **Figures 3(a), (b), and (c)**. Similarly, acid phosphatase activity was inhibited by petroleum contamination, with partial recovery following fertilizer amendments (**Figures 4(a), (b), and (c)**). Soil amendments modified conditions associated with oxidative stress and phosphorus-related biochemical processes.

Alkaline phosphatase and dehydrogenase activities were stimulated by petroleum contamination and subsequently decreased following fertilizer amendments, as presented in **Figures 15-20**. These changes may reflect shifts in substrate availability, microbial activity, or biochemical conditions during remediation. However, enzyme activities alone cannot establish specific microbial degradation mechanisms. Their interpretation should therefore be considered together with TPH reduction and microbial population changes.

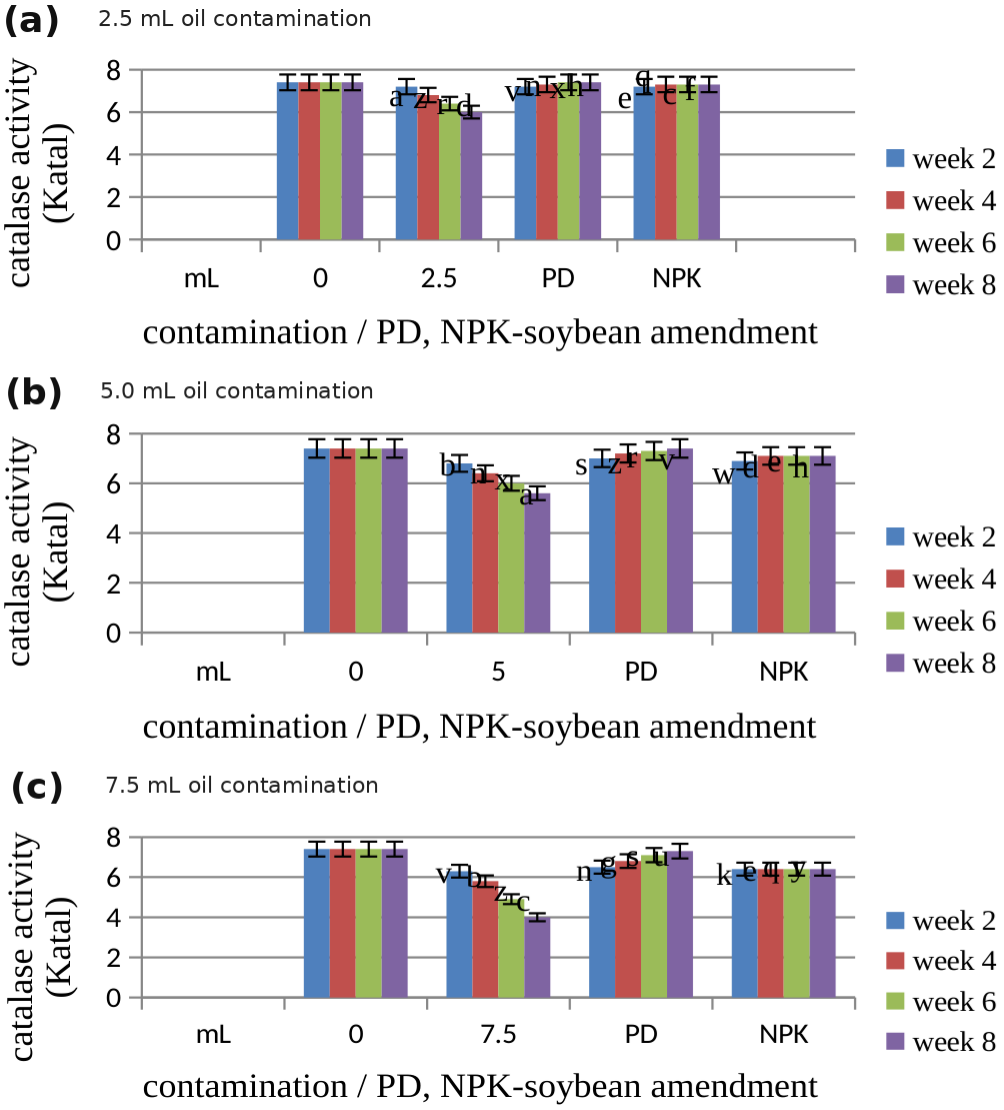

Figure 3. Changes in soil catalase activity during the eight-week experiment under different spent engine oil contamination levels: (a) 2.5, (b) 5.0, and (c) 7.5 mL. The effects of PD and soybean-coated NPK fertilizer are compared with untreated contaminated soil. Different letters indicate statistically significant differences as reported in the original study ($p < 0.05$; $n = 3$).

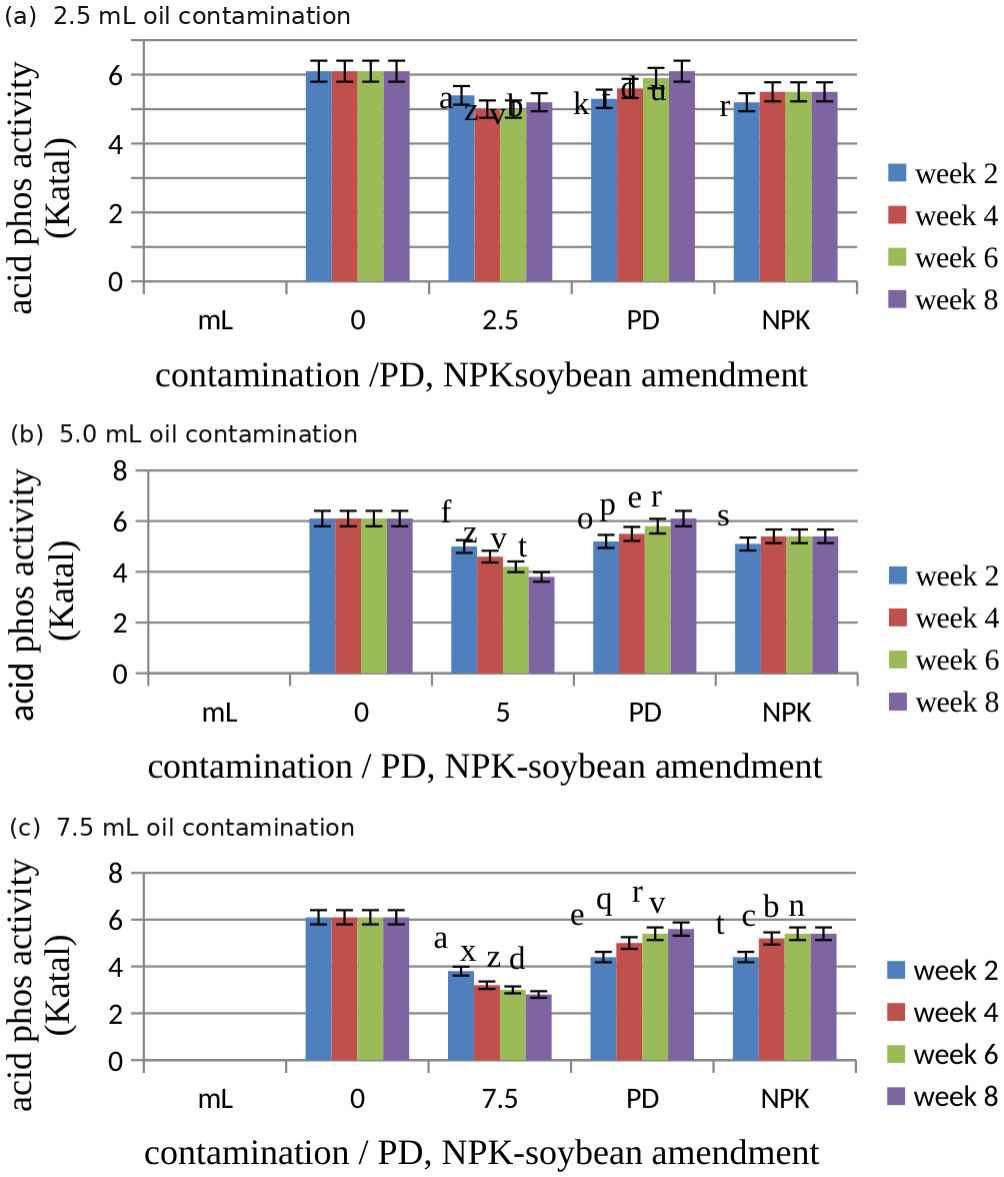

Figure 4. Changes in soil acid phosphatase activity during the eight-week experiment under different spent engine oil contamination levels: (a) 2.5, (b) 5.0, and (c) 7.5 mL. The effects of PD and soybean-coated NPK fertilizer are compared with untreated contaminated soil. Different letters indicate statistically significant differences as reported in the original study ($p < 0.05$; $n = 3$).

3.5. Effects of Soil Remediation on Photosynthetic Pigments of Amaranthus viridis

Spent engine oil contamination negatively affected the photosynthetic pigments of A. viridis, including chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids. Increasing oil contamination generally reduced pigment concentrations, whereas fertilizer amendments partially restored these parameters. The findings are presented in **Tables 5-7**.

At 2.5 mL of contamination, total chlorophyll decreased from 2.10 in the control to 1.76 in oil-contaminated plants. Application of poultry droppings and soybean-coated NPK fertilizer increased total chlorophyll to 2.00 and 2.24, respectively. At 5.0 mL of contamination, both

amendments improved chlorophyll concentrations relative to untreated contaminated soil. Similar responses occurred at 7.5 mL of contamination, although pigment concentrations generally remained below the control. Fertilizer-assisted soil remediation supported photosynthetic pigment accumulation under petroleum stress.

The decreasing chlorophyll and carotenoid concentrations under greater petroleum contamination indicate stress-related changes in plant pigmentation. Photosynthetic pigments play important roles in light harvesting and photoprotection, making them useful indicators of plant physiological responses. However, these measurements do not directly quantify photosynthetic rate, vegetable yield, nutritional composition, or food safety.

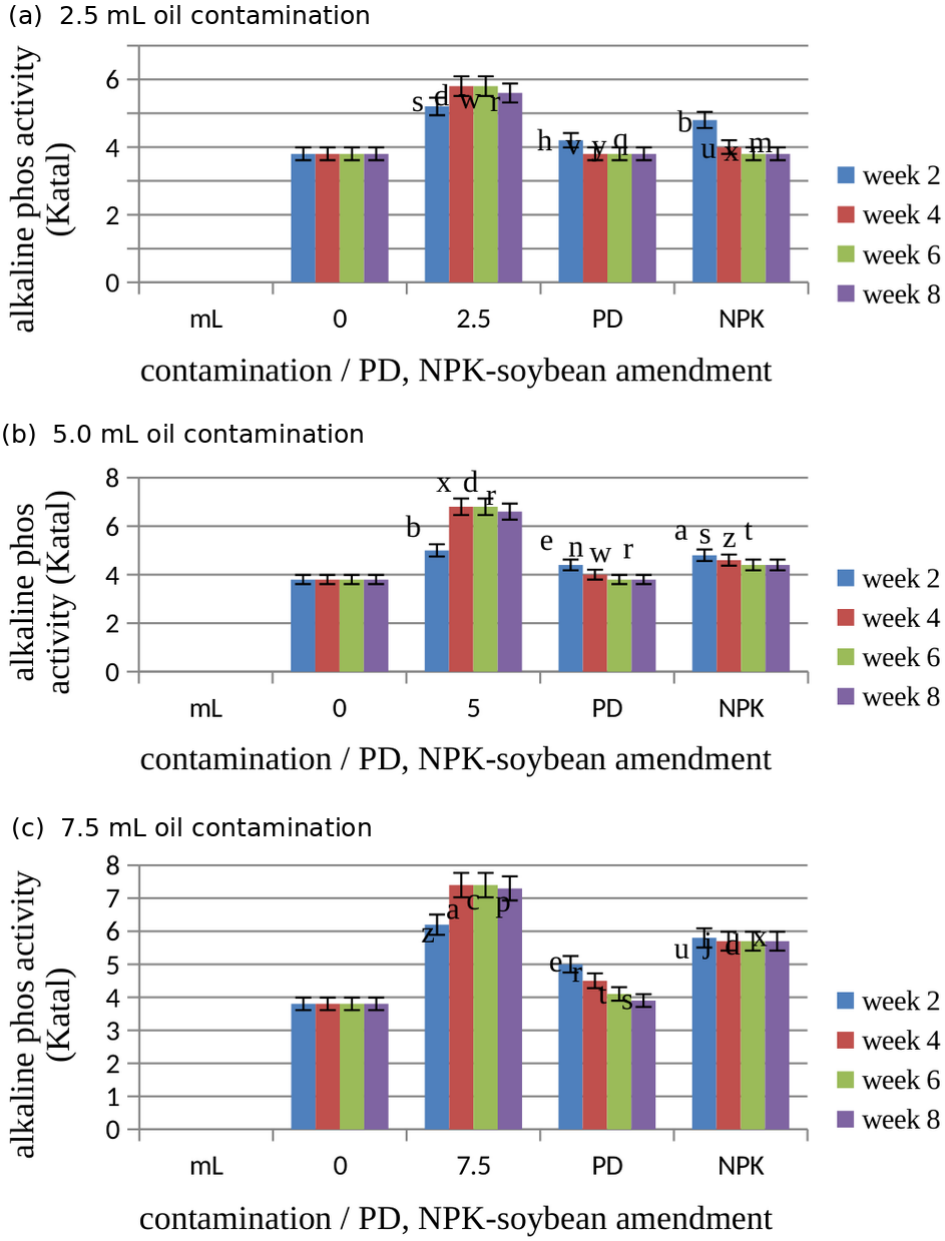

Figure 5. Changes in soil alkaline phosphatase activity during the eight-week experiment under different spent engine oil contamination levels: (a) 2.5, (b) 5.0, and (c) 7.5 mL. The effects of PD and soybean-coated NPK fertilizer are compared with untreated contaminated soil. Different letters indicate statistically significant differences as reported in the original study ($p < 0.05$; $n = 3$).

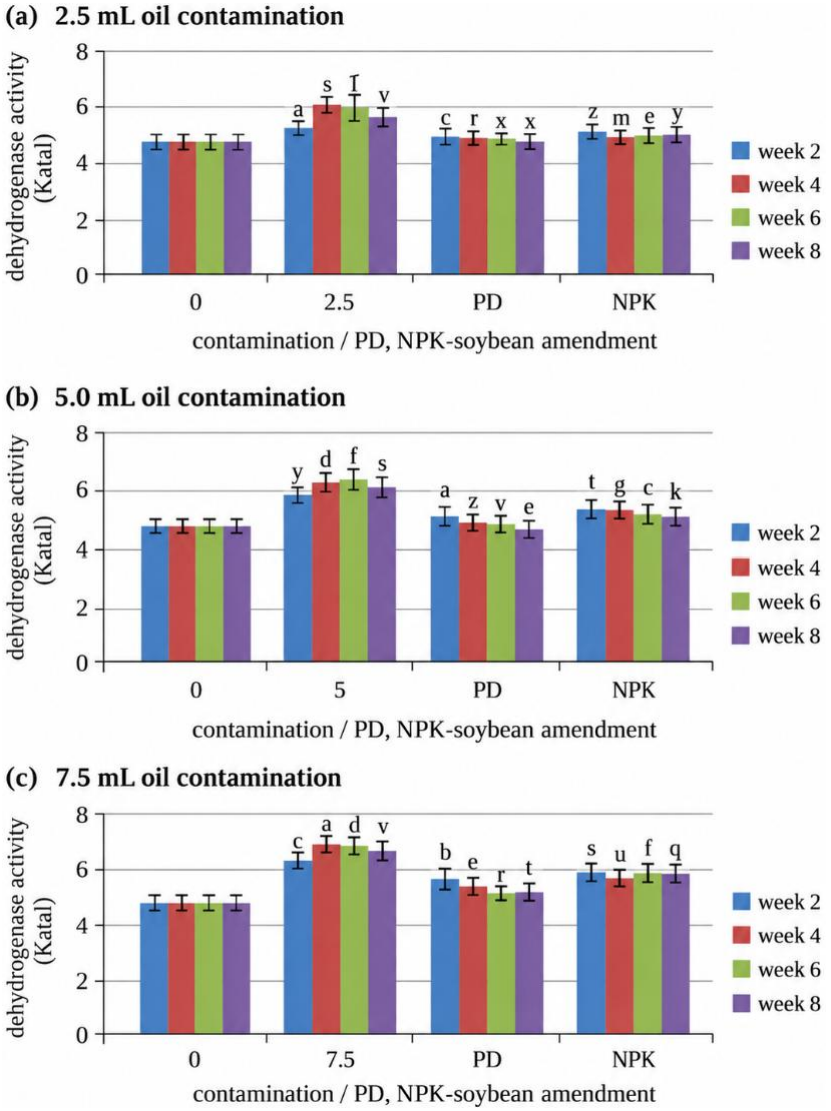

Figure 6. Changes in soil dehydrogenase activity during the eight-week experiment under different spent engine oil contamination levels: (a) 2.5, (b) 5.0, and (c) 7.5 mL. The effects of PD and soybean-coated NPK fertilizer are compared with untreated contaminated soil. Different letters indicate statistically significant differences as reported in the original study ($p < 0.05$; $n = 3$).

Table 5. Photosynthetic pigment contents of *A. viridis* at week eight under 2.5 mL of oil contamination.

PARAMETER	CONTROL	OIL IMPACT	OIL + PD	OIL + NPK-SOYBEAN
Total chlorophyll	2.10 ± 0.05^{w}	1.76 ± 0.01^{s}	2.00 ± 0.00^{t}	2.24 ± 1.01^{f}
Chlorophyll a	0.61 ± 0.00^{d}	0.58 ± 0.11^{b}	0.74 ± 1.01^{f}	0.80 ± 1.00^{s}
Chlorophyll b	1.49 ± 1.01^{x}	1.18 ± 1.00^{a}	1.26 ± 0.02^{n}	1.44 ± 0.05^{r}
Carotenoids	0.19 ± 0.01^{v}	0.16 ± 0.05^{e}	0.18 ± 0.01^{r}	0.19 ± 0.00^{e}

Table 6. Photosynthetic pigment contents of *A. viridis* at week eight under 5.0 mL of oil contamination.

PARAMETER	CONTROL	OIL IMPACT	OIL + PD	OIL + NPK-SOYBEAN
Total chlorophyll	2.10 ± 0.02^{w}	1.49 ± 0.02^{a}	1.98 ± 1.01^{t}	1.94 ± 0.01^{f}
Chlorophyll a	0.61 ± 0.00^{c}	0.49 ± 0.10^{v}	0.84 ± 2.00^{z}	0.75 ± 1.02^{e}
Chlorophyll b	1.49 ± 1.00^{z}	1.00 ± 1.05^{r}	1.14 ± 0.01^{u}	1.19 ± 0.05^{a}
Carotenoids	0.19 ± 0.01^{v}	0.12 ± 0.02^{e}	0.15 ± 0.02^{b}	0.16 ± 0.01^{n}

Table 7. Photosynthetic pigment contents of *A. viridis* at week eight under 7.5 mL of oil contamination.

Parameter	Control	Oil impact	Oil + PD	Oil + NPK-soybean
Total chlorophyll	2.10 ± 0.01^{e}	1.24 ± 1.02^{a}	1.68 ± 1.00^{t}	1.66 ± 0.05^{f}
Chlorophyll a	0.61 ± 0.20^{c}	0.22 ± 0.20^{v}	0.43 ± 0.00^{z}	0.39 ± 1.01^{e}
Chlorophyll b	1.49 ± 1.00^{x}	1.02 ± 1.01^{r}	1.25 ± 0.01^{u}	1.27 ± 0.20^{a}
Carotenoids	0.19 ± 0.01^{v}	0.08 ± 0.05^{e}	0.13 ± 1.02^{b}	0.15 ± 0.01^{n}

From an agricultural perspective, the partial recovery of pigments following fertilizer amendments suggests potential benefits for supporting edible leafy vegetable cultivation under contaminated soil conditions. Nevertheless, previous studies have identified risks associated with the accumulation of potentially toxic metals and organic contaminants in Amaranthus species [5-8]. Therefore, improved pigmentation should not be interpreted as evidence that plants grown in treated soil are safe for human consumption.

3.6. Implications for Sustainable Food Production and SDGs

The findings provide insights into the potential role of soil remediation in supporting sustainable vegetable production. Soybean-coated NPK fertilizer and poultry droppings were associated with reductions in petroleum contamination and improvements in several soil biological and plant pigmentation indicators. These results highlight the importance of managing soil conditions when cultivating edible vegetables in environments affected by petroleum pollution. The study is conceptually relevant to SDG 2 (Zero Hunger) through its focus on soil conditions for vegetable cultivation, SDG 12 (Responsible Consumption and Production) through the investigation of nutrient amendments, and SDG 15 (Life on Land) through soil remediation and biological recovery. Sustainable nutrient management and soil conservation have also been discussed in relation to agricultural resilience and food security [10-12]. These contributions remain potential implications rather than demonstrated SDG achievements. The study did not measure vegetable yield, nutritional quality, contaminant residues in edible tissues, or consumer exposure. Consequently, additional analyses of petroleum-derived contaminants, toxic metals, and any relevant coating-agent residues are necessary before recommending cultivation for human consumption in remediated soil.

3.7. Limitations and Future Research

The study demonstrated relationships among petroleum contamination, soil physicochemical changes, microbial populations, enzymatic activities, and photosynthetic pigments. However, several limitations should be considered. The experiment was conducted over eight weeks under container cultivation conditions, limiting direct extrapolation to field-scale agricultural systems. Furthermore, the specific mechanisms underlying the effects of soybean-coated NPK fertilizer were not independently verified through nutrient-release

measurements, microbial community profiling, or direct analyses of coating–contaminant interactions. Future investigations should examine the long-term stability of soil remediation, nutrient-release characteristics, crop growth, vegetable yield, and contaminant accumulation in edible plant tissues. Field-scale experiments would also help determine whether the observed improvements in soil biological indicators and plant pigmentation can be reproduced under practical agricultural conditions.

4. CONCLUSION

Spent engine oil contamination altered soil conditions, microbial populations, enzyme activities, and photosynthetic pigments in Amaranthus viridis. Soybean-coated NPK fertilizer and poultry droppings reduced petroleum contamination and supported recovery of several biochemical and pigmentation indicators. Responses varied with contamination level and amendment type, demonstrating the importance of evaluating multiple indicators of soil recovery. These findings suggest potential applications for managing polluted agricultural soils and supporting vegetable cultivation, consistent with SDGs 2, 12, and 15. However, pigment recovery does not establish food safety. Future studies should assess crop yields, contaminant residues, amendment safety, and field-scale performance before agricultural adoption.

5. ACKNOWLEDGMENTS

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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