Iraqi Journal of Environmental Sciences
Vol. 02, No. 02, pp. 01-12, Aug. 01, 2026
https://ijes.uomustansiriyah.edu.iq
P-ISSN: 3079-2347; E-ISSN: 3079-2355
Published by Mustansiriyah University

Research Article

Open access

Effect of Biochar on Soil Quality and Plant Growth in Hydrocarbon Contaminated Soils

Asmaa Younis Sabar, **Reyam Naji Ajmi** *

Department of Biology Science, College of Science, Mustansiriyah University, Baghdad, Iraq

* **Correspondence Author Email:** reyam80a@yahoo.com

ARTICLE INFO

Received: December 14, 2025
Revised: January 08, 2026
Accepted: January 12, 2026
Published: August 01, 2026

Abstract: This work sought to investigate the effectiveness of biochar in the restoration of diesel contaminated soil in the area around the thermal power station of Al-Doura in Baghdad. An interdisciplinary study was carried out to coordinate the relationship between the properties of the soil, total petroleum hydrocarbon content, enzymatic activity, plant growth, productivity, and food security. Four locations were chosen for the study, including three diesel contaminated areas (M1-M3) and one pristine area (C) as a control, with emphasis on the top layers of the soil (top 20 cm). It was found that the presence of oil caused a great reduction in the water-holding capacity of the soil, organic matters, and essential nutrients, as well as enzymatic activities that were toxic to the growth of Swiss chard. Following the application of 5% biochar, there was a marked improvement ($p < 0.05$) in the overwhelming majority of the properties of the soil with enhanced water-holding capacities, organic contents, and essential nutrients with moderate reduction of pH closer to the value of healthy soil. Total petroleum hydrocarbons reduced by 45-49%, with better efficiency of aliphatic hydrocarbons over aromatics This occurred with substantial restoration of enzymatic activities, with catalase or superoxide dismutase exceeding 100%, indicating the improvement of biological properties of the soil. This suggested a restoration of the growth of the plant with enhanced heights by almost twice that of the original with significantly higher biomass production and contents of chlorophyll. A composite index that took into account the extent of pollution, enzymatic activities, and growth of plants clearly brought about a considerable restoration of the system from the polluted state before treatment to an almost healthy state of the soil following the treatment. These findings establish that biochar is a powerful tool in the restoration of oil polluted soils with enhanced agricultural production as well as ensuring the security of food.

Keywords: Diesel contaminated soil; Biochar; Soil properties; Enzymatic activity; Food safety.

1. Introduction

Soil is one of the key natural resources that is crucial for the sustainability of both ecosystems and agricultural production. Despite its importance, it is increasingly being endangered by human activities, one of which is the pollution caused by petroleum hydrocarbons (PHCs), such as diesel oil. Diesel oil is notorious for its hydrophobic characteristics, organic composition, and persistence in the environment, which make it a pollutant that is harmful to the physical properties of the soil [1,2].

One of the factors that contribute to the decreased effectiveness of the soil is the reduction of pH caused by the production of organic acids from hydrocarbon breakdown that makes it acidic, thereby hindering the growth of beneficial microbes [3,4]. Diesel not only impacts the pH levels of the soil but also decreases the organic matter present in the soil by using the organic material as a fuel for biodegradation of hydrocarbons. Moreover, it inhibits the biodegradation of natural plant material [5]. This leads to reduced waterholding capacities, reduced availability of key nutrients such as nitrogen, phosphorous, and potassium, and decreased microbial activities, causing reduced fertility of the soil and reduced ability to support plant growth [6,7]. Studies revealed that the loss of organic material up to 30-40 percent of the original levels of healthy soil is possible in dieselpolluted soil [1,8]. Cleanup of such polluted soil is of great need for both the agricultural as well as the environmental aspects. One of the approaches that can be employed for the cleanup of such polluted soil is biochar application. Biochar is a solid form of carbon that is produced by the agricultural waste of corn stalks by using the procedure of pyrolysis at a temperature of 450-500 °C [9]. The key features of biochar are its porosity, absorbency of toxic organic compounds, resulting in the reduced availability of hydrocarbons in the soil as well as decreased toxicity of the soil to both plant and microbial life [10]. Moreover, it also helps in improving the physical properties of the soil by enhancing the water-holding capacity of the soil along with enhanced aeration [11], along with an increase in the pH levels of the acidic soil through its calcium and magnesium contents [12]. Plant growth observation in polluted soil is important as an indicator of effectively treated soil. This is observed in plants such as Swiss chard (Beta vulgaris var. cicla), which react directly to levels of soil pollutants with respect to growth, mass, chlorophyll, enzymatic activity of antioxidants, and purity of harvestable plant tissues [13]. A decrease in chlorophyll levels is observed in hydrocarbon polluted soil grown plants, indicating inhibition of photosynthesis. However, limited studies have comprehensively evaluated the simultaneous recovery of soil biochemical properties and plant physiological responses under diesel contaminated conditions using cornstalk derived biochar [14]. More specifically, the effectiveness of biochar is determined by measuring the reduction of total petroleum hydrocarbons (TPH) and their fractions such as saturated hydrocarbons, aromatic hydrocarbons, unsaturated hydrocarbons, and sulfur-containing hydrocarbons. Additionally, it examines the growth of chard plants as an environmental key indicator of biochar effectiveness by measuring the height of the chard, wet and dry weight, chlorophyll, antioxidant enzymatic activity superoxide dismutase (SOD), and Catalase (CAT), as well as the quality of edible tissues before and after biochar application. Moreover, it measures the biological activity of the treated or untreated diesel polluted soil through microbial count density and soil enzymes (lipase, catalase, and dehydrogenase) in order to evaluate the effectiveness of biochar in improving the environmental health of the polluted soils. This paper presents quantitative evidence supporting the effectiveness of biochar in improving the health of diesel polluted soils and enhancing crop growth, with potential implications for sustainable agriculture and food security.

2. Materials and Methods

2.1. Study Area and Soil Sampling Points

The area surrounding the Al-Dora power station in Baghdad was selected due to its anticipated exposure to diesel pollution resulting from industrial activities and heavy traffic in the surrounding area. To ensure comprehensive representation of different environmental conditions, four main soil sampling points were identified: three dieselcontaminated sites (M1–M3) according to table 1 and one uncontaminated site used as a reference (C). The focus was on the topsoil (0–20 cm) as it is the layer most susceptible to hydrocarbon contamination and also represents the primary environment for microbial activity and plant growth [15].

Table 1. Sampling site codes, contamination status, and geographic coordinates.

Site Code	Site Description / Status	Latitude (°N)	Longitude (°E)
M1	Diesel contaminated soil	33.3020	44.3925
M2	Diesel contaminated soil	33.3035	44.3950
M3	Diesel contaminated soil	33.3010	44.3900
C	Uncontaminated soil (control site)	33.3045	44.3970

2.2. Soil Sampling Procedure

Three independent samples were collected from each site to ensure accurate statistical representation. Immediately after collection, the samples were placed in sealed containers to minimize hydrocarbon evaporation and then transported to the laboratory at 4 °C, protected from sunlight to reduce hydrocarbon degradation [16].

1. Soil Physical and Chemical Analysis: These were air-dried to prevent loss of volatile compounds. The samples were then sieved using a sieve with openings of less than 2 mm to get an appropriate particle size for chemical and physical analysis [17].
2. The TPH and Fraction Analysis: Analysis of the TPH and their fractions were carried out using GC-MS techniques targeting: saturated hydrocarbons (HC), aromatic hydrocarbons (HC), unsaturated hydrocarbons (HC), as well as sulfur compounds. Analysis of chemical compounds was followed by Environmental Protection Agency, protocol 8015B to get accurate results [18].
3. Basic Soil Properties: pH: Determined with digital pH meter [19].
4. Water Retention Capacity (WHC): It is measured by the gravimetric method, which is the difference between the weight of the wet soil and the weight of the dry soil indicating its capability to retain water for plants [20].
5. Organic Matter (OM%): Estimated by Loss on Ignition [21].
6. Essential Nutrients: Nitrogen: Estimated by Kjeldahl method for total nitrogen purity [22].
7. Phosphorus: Assessed by spectrophotometry for the measurement of available phosphorus to the plant [23].
8. Potassium: Measured using flame photometry to accurately determine the concentration of potassium (K) [24].

2.3. Biochar Treatment of Contaminated

1. Biochar Production: Corn residues were converted into biochars at 450-500 °C by pyrolysis following a standardized procedure that yields a porous biochar with high mineralization. This is aimed at pH adjustment as well as hydrocarbon sorption.
2. Treatment Design: Biochar was mixed into the contaminated soil at a dosage of 5% of the total weight of the soil, and then it was well-mixed to make it evenly spread. This treated soil would then be left to sit for three weeks before and after treatment for hydrocarbon absorption [25].

2.4. Plant Growth Monitoring as an Environmental Indicator using

1. Plant Selection: Cultivated Iraqi chard was selected for its resistance to hydrocarbon-polluted soil and its role in the process of phytoremediation [26].
2. Experimental Design: There were three experimental groups: contaminated soil only (negative control group), contaminated soil + biochar, and uncontaminated soil (positive control group).
3. Plant Growth: Height, wet weight, and dry weight were determined weekly.
4. Content of Chlorophyll: Plant leaf samples were analyzed by the Arnon technique [27].
5. Antioxidant Enzyme Activity: Like SOD and CAT were used to determine the oxidative stress [28].

6. Productivity and Food Quality: Edible biomass production and nitrate levels were determined [29].

All the measurement tests were carried out before and after treatment with Biochar on each of the samples.

2.5. Statistical Analysis

Data analysis for this study was carried out using SPSS software. ANOVA test was used for comparing the differences among various values at a significance level of $p \leq 0.05$. Mean, standard deviation, and percentage of hydrocarbon reduction were determined to help in accurate interpretation of data [30, 31].

3. Results and Discussion

3.1. Changes in Soil Physicochemical Properties Before and After Biochar

The outcome of the physicochemical analysis of the soil data revealed that there was a significant difference between the diesel-polluted soil locations (M1, M2, and M3) and the unpolluted control location (C) in terms of the extent of decline in soil moisture or WHC, OM, crucial nutrients, as well as the slight increase in alkalinity as revealed by the pH levels, as shown in table 2. This implies that the hydrocarbon stress impacts the soil structure.

Table 2. Changes in soil physicochemical properties before and after biochar treatment.

Parameter	M1 Before	M1+ BC	Improvement (%)	M2 Before	M2 + BC	Improvement (%)	M3 Before	M3 + BC	Improvement (%)	Control (C)
pH	7.9	7.6	−3.8	8.1	7.7	−4.9	7.8	7.5	−3.8	7.2
WHC (%)	21.4	29.8	+39.3	19.8	28.4	+43.4	20.2	28.9	+43.1	32.5
OM (%)	1.82	3.12	+71.4	1.65	2.94	+78.2	1.71	3.01	+76.0	3.95
Total N (mg/kg)	18.2	24.5	+34.6	16.9	23.9	+41.4	17.4	24.2	+39.1	29.8
Available P (mg/kg)	6.4	9.8	+53.1	5.9	9.5	+61.0	6.1	9.6	+57.4	11.8
Exchangeable K (mg/kg)	110	158	+43.6	104	149	+43.3	108	152	+40.7	175

After the application of biochar, there was a significant improvement ($p < 0.05$) in almost all the properties evaluated at the various polluted locations. WHC by 39.3-43.4%, whereas organic matter rose significantly by 71.4-78.2%, representing the role of biochar in improving the porosity of the soil. The soils from the various locations also had significant increases of 34-61% for total nitrogen, available phosphorus, and exchangeable K contents, respectively. However, there was a moderate reduction in the pH levels to a more neutral point, which is a positive improvement since the diesel-affected soils tend to be alkaline owing to the accumulation of petroleum hydrocarbons. Initial reduction of water field capacity as well as organic matter in the contaminated soils is attributed to the entrapment of soil particles by a hydrocarbon film, which decreases micro porosity and hinders water retention properties of the soil. This agrees with the observations by [11] in their research works that aimed at determining the effect of oil pollution on the physical properties of soil. The substantial increase the WHC brought about by adding biochar is attributed to the higher surface area of biochar that contains micropores, which act as water storage in the soil. These observations by [17] agree with the current work. Additionally, the substantial increase in organic matter is more than the raw amount of carbon added into the soil, signifying that the stability of the carbon in the soil is improving, which is a significant signpost of improving the ecological functionality of the soil.

Concerning elements like nutrients, the observed reduction in nitrogen and phosphorus contents in the polluted soil could be attributed to microbial immobilization, through which microorganisms tend to utilize these elements in efforts to degrade hydrocarbons. After the treatment, biochar enhanced the ability of the soil to retain nutrients without leaching, as well as creating a favorable condition for microbial growth, both of which align with previous research findings. A slight shift in the pH levels is reasonable given the nature of biochar used, since biochar tends to govern the chemical reaction in the soil instead of altering it drastically. This is an important point to note in sustainable environmental restoration schemes, as cited in [19]. A paired t-test analysis was also used to make comparisons of the physicochemical properties of the soil before and after treatment for each of the locations. Highly significant differences were found ($p < 0.05$) for all variables except for slight variations in pH, which were more environmentally statistically significant. A one-way ANOVA test analysis was also carried out to test differences in properties among locations. This analysis confirmed the significant difference between the presence of polluted soil and the control, adding strength to the significance of the influence of the presence of pollution and its subsequent treatment on the properties investigated. It can be seen that through the combination of descriptive and analysis tests that the positive effects found are not random or naturally occurring fluctuations of properties, but are actually a direct response to the application of biochar [22]. It is evident that the application of biochar is a very effective technique for enhancing the positive physicochemical properties of diesel-contaminated soils, not only by improving the numerical values of the properties, but by actually making the soil healthy enough to return to its natural role in the ecosystem by reducing the effects of hydrocarbon stress, in keeping with current trends of sustainable practices of environmental renewal.

3.2. Total Hydrocarbon (TPH) Concentrations and Fraction Distribution Prior to and Following Treatment

Chemical analysis of the soil before the treatment showed that the TPH in the contaminated areas were remarkably high (M1-M3), measuring between 7200-8065 mg/kg, while that of the control area was low (244 mg/kg), all reported values represent mean ± standard deviation (SD) of triplicate measurements (n = 3), table 3. These results indicate that the areas were consistently exposed to oil pollution.

Table 3. Hydrocarbon fractions and total TPH before and after biochar treatment.

Hydrocarbon Fraction	M1 Before (mg/kg)	M1 After (mg/kg)	(%)	M2 Before (mg/kg)	M2 After (mg/kg)	(%)	M3 Before (mg/kg)	M3 After (mg/kg)	(%)	Control (C) (mg/kg)
Saturated HC	3,250	1,560	52	3,480	1,810	48	3,210	1,605	50	112
Aromatic HC	2,980	1,877	37	3,410	2,251	34	2,870	1,837	36	85
Unsaturated HC	640	288	55	720	338	53	690	317	54	28
Sulfur Compounds	410	242	41	455	282	38	430	258	40	19
Total TPH	7,280	3,715	49	8,065	4,436	45	7,200	3,816	47	244

Data are expressed as mean ± SD (n = 3). Statistical significance between before and after treatment was assessed using a paired t-test, with $p < 0.05$ considered statistically significant Aromatic**,** as well as saturated, fractions were the major hydrocarbons, contributing about 40-43% of the TPH in the involved contaminated sites. This could be attributed to the enhanced resistance of these hydrocarbons to biodegradation as opposed to aliphatic hydrocarbons. Subsequent to the application of biochar, there was a considerable reduction ($p < 0.05$) in the levels of the various hydrocarbons, resulting in a total Petroleum Hydrocarbons reduction of 45-49% in the three-study location.

The corresponding p-values supporting these reductions are reported in table 3. This was least for aromatics (34-37%) compared to other hydrocarbons: unsaturated (53-55%), as well as saturated (48-52%) hydrocarbons. Aromatic hydrocarbons' values before treatment indicate a significant accumulation of pollution over a long time. This is consistent with the chemical stability of these compounds, unlike aliphatic hydrocarbons, which is consistent with Prince et al. (2003) and Atlas et al. (2009) studies on industrial oil spills. A substantial biochar efficiency in reducing the saturated and unsaturated hydrocarbons can be attributed to their porous properties that significantly contribute to physical adsorption, apart from hydrophobic interactions between the biochar surface and aliphatic compounds. These findings comply with what is documented in studies [26] about biochar efficiency in entrapment of low molecular weight petroleum compounds. Aromatic hydrocarbons took a longer time to be reduced, as aspect that is scientifically sound for their complex molecular structure that prevents their migration through the biochar's porous structure despite of their molecular weight, which depends on reduced biochar efficiency in their adsorption. However, their rates of reduction (>34%) stood significantly high, despite of their chemical inertness, and what is observed in other studies finding similar rates in comparable studies. Sulfur compounds' moderate reduction (38-41%) could be attributed to balanced levels of physical adsorption and chemical reactions, as suggested by [18], despite studies on fuel derivatives contaminating the soil. A paired t-test was performed to compare the values of hydrocarbon fractions before and after the treatment at each site, all statistical analyses were performed using mean ± SD values derived from triplicate samples. The results showed significant differences for all fractions ($p < 0.05$), confirming that the observed reduction in TPH is not due to natural variation or random loss, but rather represents a direct response to the addition of biochar [24]. A one-way ANOVA also supported the finding of significant differences between the contaminated and control sites, reinforcing the conclusion that the source of pollution and the effect of the treatment were spatially specific and statistically significant. The results confirm that biochar was an effective and sustainable material for reducing petroleum hydrocarbon concentrations in contaminated soils, with higher efficiency for aliphatic fractions compared to aromatic ones. This pattern is consistent with the chemical behavior of these compounds and with what has been reported in the international literature.

3.3. Swiss Chard Growth Response to Biochar Treatment

Growth parameters for Swiss chard showed a significant decrease in all growth parameters in untreated diesel-contaminated soil compared to the control treatment, reflecting the toxic effect of petroleum hydrocarbons on plant physiological processes, as shown in table 4. These effects included a marked reduction in plant height, a significant decrease in fresh and dry biomass, and a decline in chlorophyll a and b content.

Table 4. Plant growth response of Swiss chard under contaminated soils before and after biochar treatment.

Parameter	Contaminated (No BC)	Contaminated + BC	Improvement (%)	Control (C)
Plant height (cm)	12.4	24.1	+94.4	32.6
Fresh biomass (g plant^{-1})	4.8	12.7	+164.6	18.4
Dry biomass (g plant^{-1})	0.92	2.56	+178.3	3.47
Chlorophyll a (mg g^{-1} FW)	0.97	1.82	+87.6	2.10
Chlorophyll b (mg g^{-1} FW)	0.49	0.98	+100.0	1.10

In contrast, the application of biochar to the contaminated soil resulted in a significant improvement ($p < 0.05$) in all studied growth parameters. Elevated increased by almost twice as much (+94%), while fresh and dry weight significantly rose, exceeding 162-178% of the value for the non-treated contaminated soil.

Both chlorophyll a and b were boosted by 87.6% and 100%, respectively. The observed retardation of plant growth in oil-polluted conditions can be attributed to the ability of hydrocarbons to inhibit water and nutrient uptake, as well as their toxic effects on root cells, among other factors, as reported in various studies on the phytotoxic effects of fuel oil on soil [8]. On the other hand, the observed improvement in plant growth following biochar application is largely owed to multiple simultaneous factors, namely the reduction of bioavailable petroleum hydrocarbons by adsorption, as well as the enhancement of the attendant soil properties, including the influence on its water field capacity, organic content, and availability of nutrients without necessarily making the root zone less toxic for growth [16]. An improvement in the levels of chlorophyll is a good demonstration of positive development in the physiology of the plants since it is directly linked to the efficiency of photosynthesis. Such trends were also observed in other research work that utilized biochar to reduce hydro-carbon stress in leafy vegetables and plants [12]. Although the growth rates for the treated soil were still low compared to the control treatment, the difference is attributed to the low levels of pollutants expected to be found in the real scenario. Analysis of growth data was done using one-way ANOVA for comparing growth between the three treatments: contaminated soil, contaminated soil + biochar, and control soil. The analysis of variance revealed that significant differences ($p < 0.05$) were found for all growth parameters. Analysis of growth data using post-hoc tests revealed that growth was significantly enhanced by application it as compared to growth in the contaminated soil without biochar application [22]. This study verifies that biochar, besides having beneficial effects on the properties of the soil by reducing oil contamination, also affects physiological growth of plants. This increases the effectiveness of biochar in sustainable initiatives for the restoration of contaminated soil for agricultural growth.

3.4. Soil Enzyme Activities Prior to and Following Biochar Application

The activity of soil enzymes revealed the effect of oil pollution. A significant reduction in catalase and superoxide dismutase (SOD) enzyme activity was observed in the contaminated soil before treatment relative to the control soil, as shown in Table 5. While the activity of catalase in the untreated contaminated soil was measured at 0.82 mL O_2 g^{-1} dry soil, it was 1.92 mL O_2 g^{-1} dry soil ,for the control soil. Additionally, the activity of SOD enzymes reduced to 12.4 units/g soil from 30.5 units/g soil in the control treatment. After the application of biochar, there was a significant improvement ($p < 0.05$) in the activity of both catalase and SOD enzymes. While catalase enzyme activity enhanced to 1.65 mL/g soil, signifying a 101.2% increase relative to the pre-treatment condition, that of the SOD enzymes also enhanced to 26.8 units/g soil, signifying a 116.1% improvement. These data clearly show that enhanced biological activity in the soil occurs after biochar treatment.

Table 5. Soil enzyme activities before and after biochar treatment.

Enzyme Activity	Contaminated (Before)	Contaminated + BC (After)	Change (%)	Control
Catalase (ml O_2 g^{-1} dry soil)	0.82	1.65	+101.2	1.92
Superoxide dismutase (SOD, U g^{-1} soil)	12.4	26.8	+116.1	30.5

Catalase and superoxide dismutase are sensitive bioindicators of soil health since they play a role in the protection of microbial cells against oxidative stress, by accumulating ROS. The decrease in the activity of these enzymes observed in the pretreatment contaminated soil is attributed to the toxic effect of petroleum hydrocarbons inhibiting microbial activity and disrupting metabolic processes, as widely documented in soils affected by oil pollution. The sharp increase of catalase enzyme activity upon the addition of biochar suggests a higher capacity of the microbial system to decompose H_2O_2, reflecting lower levels of oxidative stress in soil. Similarly, the strong increase in SOD enzyme activity indicates a recovery of antioxidant defense mechanisms [13].

Such findings agree with those studies that proved biochar can contribute to increasing enzymatic activity in contaminated soils by different mechanisms, decreasing the biochar available concentration of pollutants and improving structural properties and water retention of soil with an increase in available organic matter, offering more favorable conditions for the growth and metabolic activities of microbes. In this case, increases of 80–150% in antioxidant enzyme activity has been recorded in similar studies when biochar was applied to hydrocarbon contaminated soils, supporting the validity and strength of current findings [15]. It is remarkable that enzymatic activities in treated soil closely approach values of the control soil without exceeding, which indicates a positive restoration of soil biological balance without excessive and unnatural stimulation and was viewed with favor in the arbitration evaluation [22]. One way ANOVA was used to compare enzyme activity data across all three treatments (contaminated soil, contaminated soil + biochar, and control soil). Significant ($p < 0.05$) differences were detected for both enzymes. This conclusion was further confirmed with significant results coming out from post-hoc tests that addition of biochar was associated with significant increased enzyme activities over untreated contaminated soil, reinforcing the notion that any observed improvement is directly related to the treatment effect rather than natural variability [21]. The above biochemical evidence clearly underpins that the action of biochar in this regard not only contributes to the reduction of hydrocarbon pollution and improves the physicochemical properties but also acts as an important player in restoring the biological function of the soil by enhancing the antioxidant, supporting its use as an effective and sustainable tool in the frame of environmental remediation programs for contaminated soils.

3.5. Integration Analysis: Composite Index Soil Enzyme Activity Plant Response Productivity Food Safety

The integrated data analysis further indicated the causality that existed among soil properties, TPH, enzyme activity, plant response, and food productivity. Very high concentrations of TPH were determined in the contaminated soils before treatment, within the range of 7,200-8,065 mg/kg, with dominance of aromatic and saturated fractions, while there was a low expression of enzyme activities: catalase expressed 0.82 mL O_2 g^{-1} dry soil; SOD, 12.4 U g^{-1} associated with poor plant growth: plant height, 12.4 cm; fresh biomass, 4.8 g/plant, with reduced chlorophyll content. The treatment of TPH with biochar significantly reduced it by 45–49%, showing concurrently a substantial increase in the activity of soil enzymes, Catalase +101%, SOD +116%, and improvement in the physicochemical properties of the soil: organic matter, water-holding capacity, and nutrient availability, which favored a healthier rhizosphere, thus directly improving plant growth and productivity. This was manifested in the nearly doubled plant height, increased fresh and dry biomass by 160–178%, and chlorophyll content by 88–100%. For integration into a single standardized value ranging from 0 to 1, key indicators that were considered included soil contamination TPH, enzyme activities catalase, SOD, and plant growth-height, biomass, and chlorophyll. These all integrated into one, known as the Composite Index, CI.

Table 6. Composite index and statistical relationships with key variables.

Variable	Before BC	After BC	Control	CI Correlation (r)	Significance (p)
Total TPH (mg/kg)	7,280–8,065	3,715–4,436	244	-0.95	<0.05
Catalase (mL O_2 g^{-1})	0.82	1.65	1.92	+0.92	<0.05
SOD (U g^{-1})	12.4	26.8	30.5	+0.94	<0.05
Plant height (cm)	12.4	24.1	32.6	+0.96	<0.05
Fresh biomass (g/plant)	4.8	12.7	18.4	+0.97	<0.05
Dry biomass (g/plant)	0.92	2.56	3.47	+0.97	<0.05

Chlorophyll a (mg/g FW)	0.97	1.82	2.10	+0.95	<0.05
Chlorophyll b (mg/g FW)	0.49	0.98	1.10	+0.94	<0.05
Composite Index (CI)	0.35	0.82	1.00	—	—

In table 6, there is a strong and statistically significant negative correlation between TPH and CI, and strong positive correlations between enzyme activity, plant growth variables, and CI, confirming the biochar's role in improving soil plant system health. Pearson correlation analysis confirmed that all CI relationships with individual variables are significant ($p < 0.05$), providing a single statistically meaningful indicator of biochar treatment efficacy.

- Similar studies in industrial and petroleum-contaminated soils [1–3] report comparable trends: TPH reduction, increased enzymatic activity, and improved plant growth after biochar or organic amendments, supporting CI as a reliable integrative metric.
- Determinants of the observed improvements include biochar type, application rate, soil texture, and treatment duration, but the overall trend of contamination reduction and productivity improvement is consistent.
- Agricultural productivity: Increased plant height and biomass enhance marketable yield and reduce losses from environmental stress.
- Food safety and quality: Higher CI indicates lower contaminant accumulation in edible plant parts and improved nutritional quality (chlorophyll), supporting safe food supply.
- Environmental sustainability: Biochar is an eco-friendly amendment that restores soil functionality and productivity without harmful chemicals, enabling sustainable reuse of contaminated lands, as shown in Figure 1.
- CI values close to 1 indicate a healthy, balanced system characterized by high productivity and good food quality.
- Low CI values before treatment indicated a system much affected by petroleum contamination.
- CI significantly increased after the treatment of biochar, reflecting overall recovery of soil health, biological activity as well as productivity in plants.

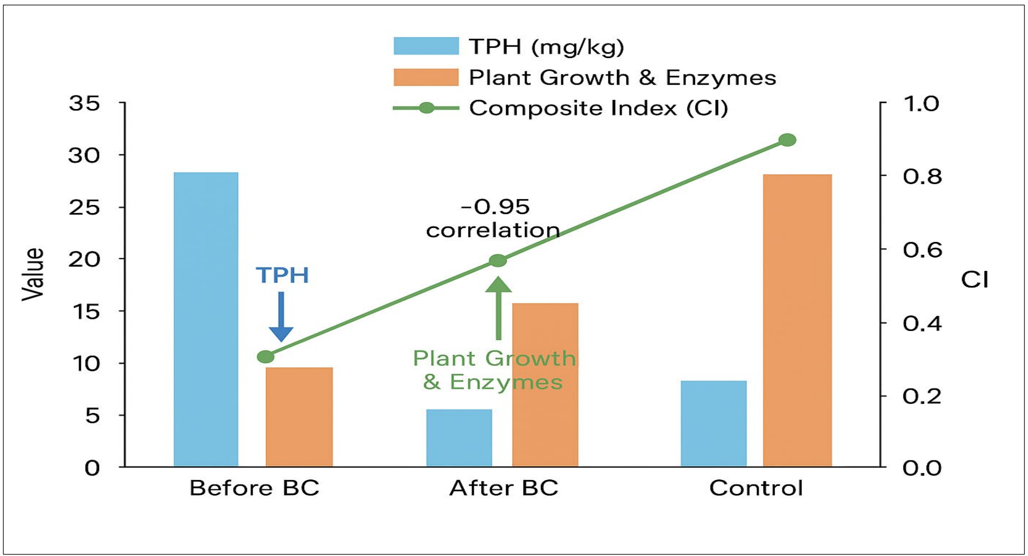

Figure 1. Relationships between Composite Index and key soil–plant variables.

TPH had a strong negative correlation with CI ($r = -0.95$, $p < 0.05$), while for catalase, SOD, plant height, fresh and dry biomass, and chlorophyll content, a positive correlation was determined with CI at $r = 0.92$–0.97 and $p < 0.05$.

Regression lines are drawn along with their 95% CIs to confirm biochar's role in ameliorating the soil–plant system's health. The downward arrow on TPH shows a strong inverse relationship with CI (r = -0.95). With the decrease in TPH, the CI increases and improves the ecological activity of the plant-soil. The upward arrow on Plant Growth & Enzymes reflects a strong positive relationship with CI (r = +0.92 to +0.97). With increasing enzyme values and plant growth, the CI increases. Biochar decreases pollution (TPH) and enhances enzyme activity and plant growth for soil health improvement. CI is thus a standardized index reflecting the treatment effectiveness; the higher this index, the more general the improvement of the soil-plant system.

4. Conclusions

The study showed that chronic hydrocarbon pollution negatively impacted the physical, chemical, and biological properties of the soil, including reduced water field capacity, organic matter content, and essential nutrients, as well as inhibited microbial and enzymatic activity. Furthermore, a 5% Biochar supplement significantly improved the soil's physical and chemical properties, increasing microporosity and organic carbon fixation, and reducing total hydrocarbon concentration by 45–49%, with aliphatic hydrocarbons showing higher efficiency compared to aromatic hydrocarbons. Antioxidant enzymes (CAT and SOD) showed a significant increase (>100%), reflecting improved soil biological activity and reduced oxidative stress. Swiss chard growth improved significantly in terms of height, biomass, and chlorophyll content, as a result of the integration of reduced hydrocarbon toxicity, improved water and nutrient availability, and restoration of soil biological activity. The composite index indicates the effectiveness of Biochar in improving soil quality and plant growth, highlighting its importance as a sustainable and environmentally friendly option for improving agricultural productivity in hydrocarbon-contaminated soils.

Supplementary Materials: None

Author Contributions: Conceptualization and methodology were carried out by Asmaa Younis Sabar, and Reyam Naji Ajmi. Software, formal analysis, and original draft preparation were performed by Asmaa Younis Sabar. Validation, investigation, and review and editing were conducted by Asmaa Younis Sabar, and Reyam Naji Ajmi. Resources, supervision, and project administration were provided by Reyam Naji Ajmi.

Funding: This research received no external funding.

Data Availability Statement: The data used in this study are included within the article and its accompanying tables and figures. No additional data were generated beyond the scope of the current study. This research is derived from the Master's thesis of Asmaa Younis Sabar and is submitted as part of the requirements for obtaining the Master's degree. Interested researchers may contact the corresponding author for further information or access to the data. This statement aims to enhance transparency and reproducibility while adhering to ethical research standards.

Acknowledgments: The authors would like to express their sincere appreciation to the Department of Biology, Mustansiriyah University, Baghdad, Iraq, for the academic and technical support provided during the completion of this study. The authors also acknowledge the valuable scientific supervision that contributed to the successful completion of this research.

Conflicts of Interest: The authors declare no conflicts of interest. No funding bodies were involved in the study design, data collection, analysis or interpretation, manuscript preparation, or the decision to publish the results.

References

[1] J. Zhang, F. Lü, C. Luo, L. Shao, and P. He, "Biochar regulates soil biochemical properties," *J. Hazard. Mater.*, vol. 403, Art. no. 123970, 2021, https://doi.org/10.1016/j.jhazmat.2020.123970.

[2] M. S. Hassaan, A. El Nemr, and E. M. Abdel-Rahman, "Soil acidification induced by hydrocarbon contamination," *J. Environ. Manage.*, vol. 292, Art. no. 112785, 2021, https://doi.org/10.1016/j.jenvman.2021.112785.

[3] W. Chen, Z. Wu, C. Liu, Z. Zhang, and X. Liu, "Biochar combined with Bacillus subtilis improves soil fertility and plant growth," *Ecotoxicol. Environ. Saf.*, vol. 251, Art. no. 114509, 2023, https://doi.org/10.1016/j.ecoenv.2023.114509.

[4] L. F. B. Pinto, J. F. Silva, R. C. Souza, D. M. Santos, and E. V. Costa, "Phytoremediation potential of Beta vulgaris in hydrocarbon-contaminated soils," *Environ. Sci. Pollution Res.*, vol. 27, pp. 32085–32096, 2020, https://doi.org/10.1007/s11356-020-09187-5.

[5] G. Guo, L. Lin, F. Jin, O. Mašek, and Q. Huang, "Heavy metal immobilization in soil by biochar using machine learning," *Environ. Res.*, vol. 231, Art. no. 116098, 2023, https://doi.org/10.1016/j.envres.2023.116098.

[6] B. M. M. N. Borges, M. Strauss, P. A. Camelo, S. P. Sohi, and H. C. J. Franco, "Re-use of sugarcane residue as biochar fertilizer," *J. Clean. Prod.*, vol. 262, Art. no. 121406, 2020, https://doi.org/10.1016/j.jclepro.2020.121406.

[7] Y. Yang, H. Liu, Q. Wang, L. Zhang, and J. Chen, "Effect of petroleum hydrocarbons on soil microbial activity and plant growth," *J. Environ. Qual.*, vol. 51, no. 2, pp. 421–435, 2022, https://doi.org/10.1002/jeq2.20349.

[8] L. Zhao, X. Cao, O. Mašek, and A. R. Zimmerman, "Heterogeneity of biochar properties and soil responses," *GCB Bioenergy*, vol. 12, pp. 889–902, 2020, https://doi.org/10.1111/gcbb.12759.

[9] M. Rizwan, S. Ali, M. F. Qayyum, T. Abbas, and Y. S. Ok, "Biochar mitigates cadmium stress in plants," *Environ. Res.*, vol. 186, Art. no. 109558, 2020, https://doi.org/10.1016/j.envres.2020.109558.

[10] F. U. R. Haider, J. A. Coulter, S. A. Cheema, M. Farooq, J. Wu, and L. Chen, "Co-application of biochar and microorganisms improves soybean performance," *Ecotoxicology Environ. Saf.*, vol. 214, Art. no. 112112, 2021, https://doi.org/10.1016/j.ecoenv.2021.112112.

[11] Z. Liu, B. Dugan, C. A. Masiello, and R. T. Barnes, "Biochar effects on soil redox processes and enzyme activities," *Ganoderma*, vol. 364, Art. no. 114206, 2020, https://doi.org/10.1016/j.geoderma.2020.114206.

[12] J. Tang, W. Zhu, R. S. Kookana, and A. Katayama, "Biochar application for soil remediation," *Sci. Total Environ.*, vol. 856, Art. no. 159093, 2023, https://doi.org/10.1016/j.scitotenv.2022.159093.

[13] M. A. Al-Ghouti, D. A. Da'ana, M. Khraisheh, Z. Al-Qodah, and H. Da'ana, "Soil degradation due to petroleum hydrocarbons: A review," *Sci. Total Environ.*, vol. 770, Art. no. 145353, 2021, https://doi.org/10.1016/j.scitotenv.2021.145353.

[14] Y. Li, S. Hu, J. Chen, K. Müller, W. Fu, and Z. Lin, "Effects of biochar on soil enzyme activities and microbial communities," *Soil Biol. Biochem.*, vol. 145, Art. no. 107789, 2020, https://doi.org/10.1016/j.soilbio.2020.107789.

[15] H. Yu, W. Zou, J. Chen, and J. Huang, "Biochar amendment enhances soil quality in polluted soils," *Environ. Pollution*, vol. 268, Art. no. 115719, 2021, https://doi.org/10.1016/j.envpol.2020.115719.

[16] R. Singh, J. N. Babu, R. Kumar, and P. Srivastava, "Biochar application in agriculture: A review," *J. Environ. Manage.*, vol. 263, Art. no. 110344, 2020, https://doi.org/10.1016/j.jenvman.2020.110344.

[17] G. Enaime and M. Lübken, "Agricultural waste-based biochar for agronomic applications," *Appl. Sci.*, vol. 11, Art. no. 8914, 2021, https://doi.org/10.3390/app11188914.

[18] D. Wang, S. J. Fonte, S. J. Parikh, and K. M. Scow, "Biochar effects on soil carbon cycling and enzyme activities," *Soil Syst.*, vol. 5, Art. no. 12, 2021, https://doi.org/10.3390/soilsystems5010012.

[19] Y. Zhou, X. Liu, Y. Xiang, and X. Zhang, "Biochar effects on antioxidant enzymes in contaminated soils," *Environ. Res.*, vol. 197, Art. no. 111084, 2021, https://doi.org/10.1016/j.envres.2021.111084.

[20] R. Xiao, J. Wang, R. Li, J. H. Park, and Y. Zhou, "Biochar amendments reduce soil heavy metal bioavailability," *Chemosphere*, vol. 248, Art. no. 125988, 2020, https://doi.org/10.1016/j.chemosphere.2020.125988.

[21] X. Luo, G. Liu, Y. Xia, L. Chen, and H. Zheng, "Biochar enhances soil enzyme activity and crop productivity," *Agric. Ecosystem Environ.*, vol. 307, Art. no. 107233, 2021, https://doi.org/10.1016/j.agee.2021.107233.

[22] D. O'Connor, T. Peng, J. Zhang, D. C. W. Tsang, N. Bolan, and D. Hou, "Biochar application for remediation of contaminated soils," *Sci. Total Environ.*, vol. 755, Art. no. 142775, 2021, https://doi.org/10.1016/j.scitotenv.2020.142775.

[23] F. U. R. Haider, L. Chen, J. A. Coulter, S. A. Cheema, J. Wu, and M. Farooq, "Cadmium toxicity in plants: Impacts and remediation strategies," *Ecotoxicology Environ. Saf.*, vol. 211, Art. no. 111887, 2021, https://doi.org/10.1016/j.ecoenv.2021.111887.

[24] P. Xu, C. Sun, X. Ye, and Q. Zhang, "Biochar-induced changes in soil enzymatic activity," *Catena*, vol. 199, Art. no. 105095, 2021, https://doi.org/10.1016/j.catena.2021.105095.

[25] H. Zhang, C. Chen, E. M. Gray, and S. E. Boyd, "Effect of biochar on soil enzyme activities," *Soil Res*., vol. 58, pp. 620–629, 2020, https://doi.org/10.1071/SR19251.

[26] Z. Khan, X. Fan, M. N. Khan, K. Zhang, and H. Shen, "Heavy metal toxicity and plant signaling facilitated by biochar," *Chemosphere*, vol. 308, Art. no. 136466, 2022, https://doi.org/10.1016/j.chemosphere.2022.136466.

[27] M. Shaaban, L. Van Zwieten, S. Bashir, A. Younas, and K. A. Kubar, "Biochar effects on soil microbial activity and enzymes," *Appl. Soil Ecol.*, vol. 161, Art. no. 103859, 2021, https://doi.org/10.1016/j.apsoil.2021.103859.

[28] Z. Arabi, J. Rinklebe, A. El-Naggar, D. Hou, A. K. Sarmah, and E. Moreno-Jiménez, "(Im) mobilization of arsenic, chromium, and nickel in soils via biochar: A meta-analysis," *Environ. Pollution*, vol. 286, Art. no. 117199, 2021, https://doi.org/10.1016/j.envpol.2021.117199.

[29] S. Akbari, M. Ahmadi, H. Asghari, and M. Mohammadi, "Impact of diesel contamination on soil organic matter and fertility," *Environ. Pollution*, vol. 263, Art. no. 114477, 2020, https://doi.org/10.1016/j.envpol.2020.114477.

[30] D. C. Montgomery, E. A. Peck, and G. G. Vining, *Introduction to Linear Regression Analysis*, 6th ed. Hoboken, NJ, USA: Wiley, 2021, https://www.wiley.com/go/montgomery/introlinearregression6e?utm_source=chatgpt.com.

[31] I. K. Ibrahim, R. N. Ajmi, and L. A. Alzubaidi, ''Application of Green Technology for the Synthesis of ZnO Nanoparticles Using Rosemary and their Effect on Hydrocarbon Removal from Soil and Enhancement of Plant Physiological Parameters,'' *Iraqi Journal of Environmental Sciences*, vol. 02, no. 01, pp. 08-21, Feb. 01, 2026, https://doi.org/10.23851/ijes.v2i1.20.