Journal of Environmental Protection, 2022, 13, 220-232
https://www.scirp.org/journal/jep
ISSN Online: 2152-2219
ISSN Print: 2152-2197

Effects of Charcoal Production on Soil Physicochemical Properties in Moro Local Government Area of Kwara State, Nigeria

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How to cite this paper: Adio, A.A., Saliu, A.O., Akanbi-Gada, M.A. and Najeemdeen, B.A. (2022) Effects of Charcoal Production on Soil Physicochemical Properties in Moro Local Government Area of Kwara State, Nigeria. *Journal of Environmental Protection*, **13**, 220-232.
https://doi.org/10.4236/jep.2022.132014

Received: November 15, 2021
Accepted: February 15, 2022
Published: February 18, 2022

Abstract

Charcoal production is a major economic activity in rural Kwara State, North-Central Nigeria. Given that it generally involves the use of traditional earth kilns, this study was designed to investigate the effects of charcoal production on the physical and chemical properties of soil. Replicate soil core samples were collected within a depth of 0 - 20 cm from 19 charcoal kiln sites (CKS) and 19 adjacent control sites (ACS) across five administrative districts in the study area. These samples were subjected to laboratory analysis to determine their physical and chemical qualities and then t-test was used to statistically compare the CKS and ACS soils. There was no significant difference in soil texture between both sites. However, CKS soil pH and electrical conductivity significantly increased ($p < 0.01$) by 9.12% and 17.80%, respectively. Conversely, charcoal production led to a significant decrease ($p < 0.001$) of extractable acidity at a rate of 24.05%. Total organic carbon, organic matter, total nitrogen, carbon to nitrogen ratio, and available phosphorus increased slightly ($p > 0.05$) due to charred biomass introduced to soils by the process of charcoal production. The CKS cation exchange capacity, Ca and Mg increased significantly ($p < 0.0001$) by 40.11%, 57.15% and 89.16%, respectively. Charcoal production significantly reduced Fe by 28.54%, while the concentration of other heavy metals remained similar between both sites. The findings showed that charcoal production using traditional earth kilns improves soil physical and chemical properties for agriculture purposes. However, further studies are suggested to understand its effects on vegetation cover and soil biota.

Keywords

Charcoal Production, Earth Kiln, Soil Properties, Guinea Savanna, Soil

Properties

1. Introduction

Woodfuel production is an essential ecological service provided by dry forests and woodlands. Increased population and continuous outrageous increases in the pricing of alternative energy sources, particularly kerosene, have given significance to the charcoal business, which is currently spreading rapidly across Nigeria [1].

As a result of the country's significant poverty rate, more than 60% of the Nigerian people relied on fuelwood and charcoal as their primary energy sources for cooking [2]. Charcoal production through selective logging of favoured hardwood species, has the potential to change the physiognomic composition of residual or re-growth woods, resulting in their deterioration and degradation [3]. Annual deforestation is expected to be around 400,000 hectares, compared to 1.043 hectares of replanting and report has it that the annual rate of deforestation increased from 0.7 percent in 1980-1990 to 0.9 percent in 1990/1995 and 2.6 percent in 1990/2000 [4]. Forest resource loss can result in decreased income and food-generating capability for forest-dependent people, increased soil and canal siltation, loss of species and genetic diversity, and increased carbon emissions, all of which contribute to global warming [5] [6]. Fish smoking, garri frying, maize/plantain roasting, blacksmithing, and other small-scale processing operations employ charcoal. Despite efforts to deter its end use, nearly 80% percent of the African population use charcoal as the main source of energy for cooking [7]. Due to its cultural preference [8], this fuel will continue to be a part of the fuel ladder for many countries. According to Food and Agriculture Organization [9], the charcoal production in Africa grew by 12.6% between 2010 and 2016 and in West Africa by 14.3%.

However, if rainfall occurs after the harvest of charcoal, the biomass materials will be converted to biochar for soil amendment, resulting in a large increase in microbial efficiency (measured in units of CO_2 emitted per microbial biomass carbon in the soil) and basal respiration [10]. As reported by previous researchers, increased soil nutrients and organic matter are the resultant effects of charcoal production [11] [12]. Oguntunde *et al.* reported significant increase in soil pH, base saturation, electrical conductivity, exchangeable Ca, Mg, K, Na and available P in the soil at kiln sites as compared to the adjacent soils, an implication of its value not only as a soil conditioner but also a fertilizer [13] [14]. Positive effects on soil properties, soil fertility and productivity have also been reported [15].

The goal of this study was to determine the influence of charcoal production on the physical and chemical properties of soil in Moro Local Government Area of Kwara State, Nigeria.

2. Materials and Methods

2.1. Study Area

The study was conducted in Moro Local Government Area of Kwara State in North-Central Nigeria in Figure 1. It is situated around latitude N8.94225˚, longitude E4.77804˚, and an altitude of about 300 m above sea level. The area lies within the guinea savanna ecoregion with marked seasonality. It is characterized by a mean annual rainfall of 1200 mm with a wet season that spans April to October and a dry season from November to March. It has a warm average annual temperature of 26.2˚C rising to a peak of 30˚C in March [16] [17] [18]. A reconnaissance conducted in August 2019 as part of this study revealed evidence of various activities in the charcoal value-chain across the study area including kilns, charcoal storage depots, retail points, and haulage. Hence, charcoal business is an important economic activity in the study area.

2.2. Sampling Strategy

A total of 19 kilns were purposefully selected from five administrative districts within the study area (Table 1) between July and September 2020. The inclusion criteria include kilns not older two months [11] as well as security accessibility to a sampling point due to the recent ban on charcoal production and activities of the task force set up by the State Government [19] [20]. Locals involved in charcoal production activities were recruited in this regard. Soil core samples were collected using a soil auger from a depth of 0 - 20 cm at each sampling point. The soil cores were taken in duplicates from each kiln (coded CKS for charcoal kiln soil) and from an adjacent control site (coded ACS for adjacent

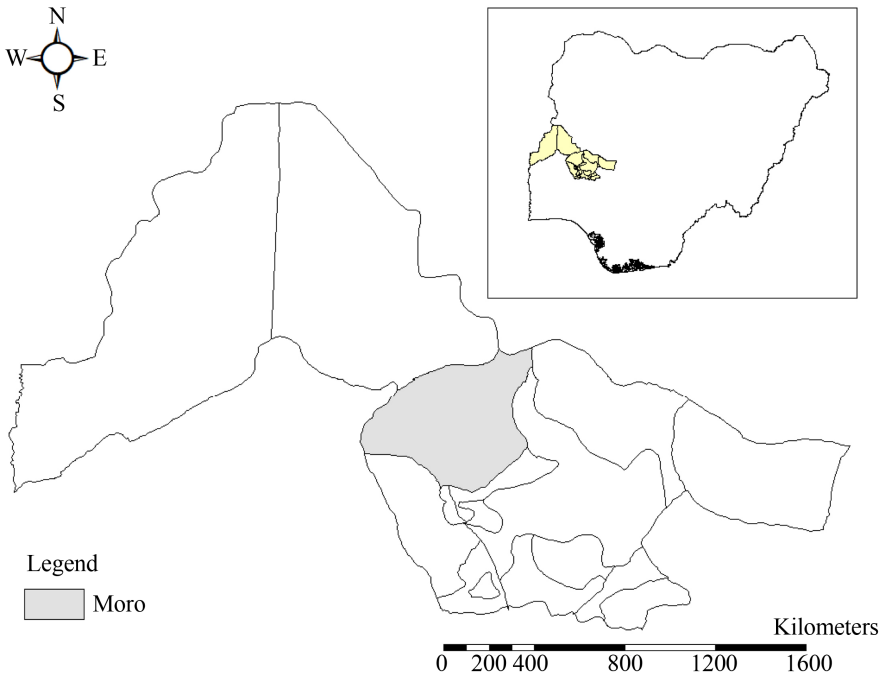

Figure 1. Map of Kwara State showing the study area (Inset: Nigeria).

Table 1. Geospatial attributes of sampling points.

S/N	District	Northing (˚)	Easting (˚)	Elevation (m)	Kiln age (month)	Surrounding activity
1.	Malete	8.73989	4.48416	345	<2	Bush
2.	Malete	8.72132	4.40890	350	<1	Bush
3.	Malete	8.68605	4.44361	360	<1	Bush
4.	Malete	8.71582	4.46188	337	<1	Residential
5.	Bode Saadu	8.86875	4.72266	283	<2	Beside national highway (Ilorin-Jebba)
6.	Bode Saadu	8.86140	4.73695	239	<2	Farmland
7.	Shao	8.63240	4.53079	313	<1	Military shooting range
8.	Shao	8.62874	4.52861	311	<1	Farmland
9.	Shao	8.62375	4.53147	327	<1	Bush
10.	Shao	8.61744	4.54881	270	<1	Bush
11.	Shao	8.61912	4.54478	283	<1	Bush
12.	Olooru	8.64077	4.60747	296	<1	Bush
13.	Olooru	8.63487	4.61488	276	<1	Bush
14.	Olooru	8.65491	4.59971	300	<1	Bush
15.	Olooru	8.65433	4.60109	301	<1	Bush
16.	Olooru	8.65743	4.59025	298	<1	Residential
17.	Lanwa	8.76171	4.74598	277	<1	Bush
18.	Lanwa	8.76514	4.74586	280	<1	Farmland
19.	Lanwa	8.77400	4.74685	278	<1	Bush

control soil) about 5 - 15 cm from the edge of the reference kiln. Therefore, 38 CKS along with complimentary 38 ACS were collected in polythene bags and transported to the laboratory.

2.3. Laboratory Analysis

The soil samples were air-dried at the laboratory and sieved through a 2 mm mesh before analysis to determine the physicochemical properties of the soil samples including soil particle size, bulk density, pH, electrical conductivity, extractable acidity, total nitrogen, available phosphorus, total organic carbon, organic matter, calcium ion, magnesium ion, sodium ion, potassium ion, cation exchange capacity, and heavy metals (copper, manganese, iron, lead, chromium, cadmium).

An improved hydrometer method was used to determine the percent distribution of sand, silt, and clay particles in the soil samples [21] [22]. Soil pH was determined by an electrometric method using a 1:2.5 soil to water ratio, wherein 20

g of soil was added to 50 ml of distilled water and the value measured with the electrode of a pH meter [22] [23]. Electrical conductivity was determined by adding 100 ml distilled water to 20 g of the soil samples and measured using a conductivity meter [24]. Extractable acidity was determined by centrifuging a mixture of the soil sample with $BaCl_2$-TEA buffer solution then an aliquot of the supernatant solution was titrated with acid [25]. Total nitrogen was determined using the micro-Kjeldahl procedure. Available phosphorous was determined using the Olsen method. Total organic carbon was determined with the Walkey-Black wet oxidation method [25].

To determine exchangeable Ca^{2+}, Mg^{2+}, K^+, Na^+ and effective cation exchange capacity (CEC) in soil, 30 ml of 1 N NH_3OAC was added to 5 g of the soil sample and was shaken using a mechanical shaker for 2 hrs. The solution was then centrifuged carefully at 2.00 rpm for 5 - 10 mins and the supernatant was carefully decanted into a 100 mL volumetric flask. Another 30 mL of NH_4OAC solution was added and the flask was shaken for 30 minutes. It was then centrifuged, and the supernatant was transferred into the same volumetric flask. The step was repeated thrice, and the supernatants were transferred into the same volumetric flask which was used to mark up with the NH_4OAC solution. The concentrations of these cations were determined using flame photometer and atomic absorption spectrophotometer [25] [26] [27].

A wet digestion method was used to prepare soil samples for determining the concentration of heavy metals (Cu, Mn, Pb, Fe, Cr, and Cd) using atomic absorption spectrophotometry. A mixture of 1 g soil sample, 5 ml concentrated HCl and 15 ml HNO_3 was heated on a hot plate in a fume-hood at a temperature between 50˚C - 60˚C until the brownish fume color was expelled. The mixture was allowed to cool at room temperature then 5 ml of distilled water added. The resulting mixture was filtered into a clean plastic container using Whatman filter paper and made up to 50 ml in a standard flask with distilled water. Each digested sample was transferred into plastic containers for heavy metal analysis using a BUCK Scientific ACCUSYS 211 Atomic Absorption Spectrophotometer.

2.4. Data Analysis

The difference in the soil parameters between CKS and ACS was assessed using the Student's t test with the critical significance level (a) set at 0.05. The relative change in each soil parameter between both site categories was determined using the formula below.

$$\text{Relative Change}(\%) = \frac{P_c - P_a}{P_a} \times 100\% \quad (1)$$

where P_c and P_a are the CKS and ACS soil parameter, respectively.

3. Results and Discussion

3.1. Effect of Charcoal Production on Soil Physical Properties

The variation of the physical properties of the soil at ACS and CKS are presented

in Figure 2, while Table 2 outlines the mean ± standard error of the mean, relative change, and statistical difference of these properties. Although the silt and clay fractions of the soil were not significantly different between both sites, they exhibited slight decrease of 3.25% and 1.03% at the charcoal kiln sites, respectively. However, the sand fraction increased by 1.59% at the charcoal sites. These findings are consistent with those of previous researchers [11] [28]. The marked increased in soil temperatures due to charcoal production might have led to the fusion of silt and clay particles into sand-sized ones [29] [30]. This coarsening process may adversely affect the water holding capacity of the severely heated soil surface [31].

There was also no significant difference in the soil bulk density, however, it slightly reduced by 0.68% at the charcoal kiln sites. Nigussie and Kissi suggest that this could be due to the complex pore structure of charcoal residues left on the kiln site as well as the increased sand fraction at these sites as discussed above [28].

3.2. Effect of Charcoal Production on Soil pH, Electrical Conductivity, and Extractable Acidity

Soil pH exhibited a very high significant difference ($p < 0.001$) between the charcoal kiln sites and adjoining control sites (Table 3). The soil in the study area

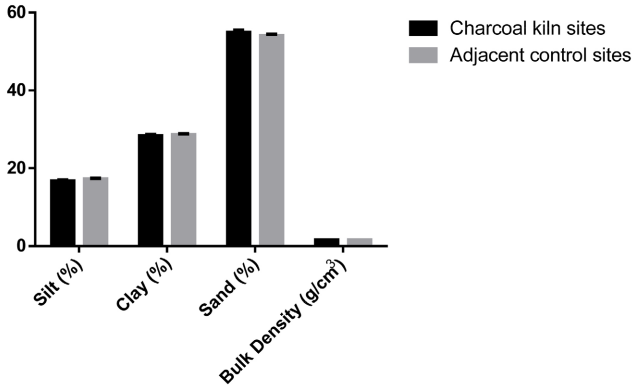

Figure 2. Mean ± SE of physical properties of soil at charcoal kiln sites and adjacent control sites.

Table 2. Selected summary statistics, relative change, and statistical significance of physical properties of soil at charcoal kiln sites and adjacent control sites.

	Silt (%)	Clay (%)	Sand (%)	Bulk density (g/cm^3)
Adjacent control sites (ACS)	17.30 ± 0.13	28.63 ± 0.25	54.07 ± 0.36	1.58 ± 0.01
Charcoal kiln sites (CKS)	16.74 ± 0.29	28.34 ± 0.33	54.93 ± 0.56	1.57 ± 0.01
Relative change (%)	−3.25	−1.03	1.59	−0.68
p-value	ns	ns	ns	ns

ns = not significant.

Table 3. Selected summary statistics, relative change, and statistical significance of soil pH, electrical conductivity, and extractable acidity at charcoal kiln sites and adjacent control sites.

	pH	Electrical conductivity (mmhos/cm^3)	Extractable acidity (meq/100g)
Adjacent control sites (ACS)	7.81 ± 0.06	21.41 ± 1.10	0.88 ± 0.02
Charcoal kiln sites (CKS)	8.52 ± 0.05	25.22 ± 0.88	0.67 ± 0.02
Relative change (%)	9.12	17.80	−24.05
p-value	<0.001	<0.01	<0.001

is typically neutral, however, charcoal production appears to have increased the pH by 9.12% in agreement with the findings of Nigussie and Kissi, and Chima *et al.* [32] [33]. The ash residue at the charcoal kilns has been suggested to be responsible for this increase in pH. Furthermore, the porous nature of charcoal increases exchange of bases (cation exchange capacity) of soils. Thereby improving the possibility of Al and Fe to bind with the exchange site [34] [35].

The electrical conductivity of the soil exhibited a high significant difference ($p < 0.01$), increasing by about 17.8% at the charcoal kiln sites relative to the adjacent control sites. This is also indicative of the presence of ash, which is known to have abundance of exchangeable cations. Similar patterns of difference in soil electrical conductivity have been reported by previous researchers [11] [32].

Figure 3, extractable acidity showed a very high significant difference ($p < 0.001$) between the charcoal kiln sites and the adjacent control sites. In variance to pH and electrical conductivity, the extractable acidity of the soil reduced by about 24% at the charcoal kiln sites. Nigusiie and Kissi [32] reported a significant negative correlation between extractable acidity and pH/electrical conductivity.

3.3. Effect of Charcoal Production on Organic Carbon, Organic Matter, Total Nitrogen, and Available Phosphorus

Charcoal production did not significantly affect the soil organic carbon, organic matter, total nitrogen, carbon to nitrogen ratio, and available phosphorus relative to the adjacent control sites. Ogundele *et al.* reported similar findings for organic carbon and nitrogen in a nearby ecosystem [36]. However, in Figure 4, the observed increase in carbon, nitrogen and organic matter in soils directly beneath the kilns may be due to charcoal residue. Similarly, the increase in available phosphorus by 19.9% in the charcoal kiln soil may be due to wood ash that is characterized by high phosphorus content [28] (Table 4).

3.4. Effect of Charcoal Production on Cation Exchange Capacity and Exchangeable Bases

Charcoal production significantly affected the cation exchange capacity ($p < 0.001$), increasing its value by 40.11% relative to the adjacent control sites. This

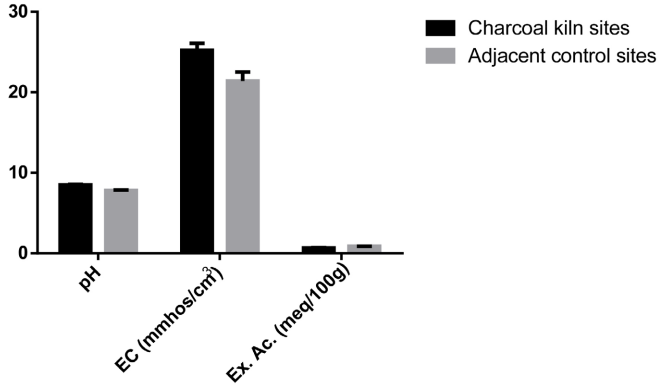

Figure 3. Mean ± SE of soil pH, electrical conductivity, and extractable acidity at charcoal kiln sites and adjacent control sites.

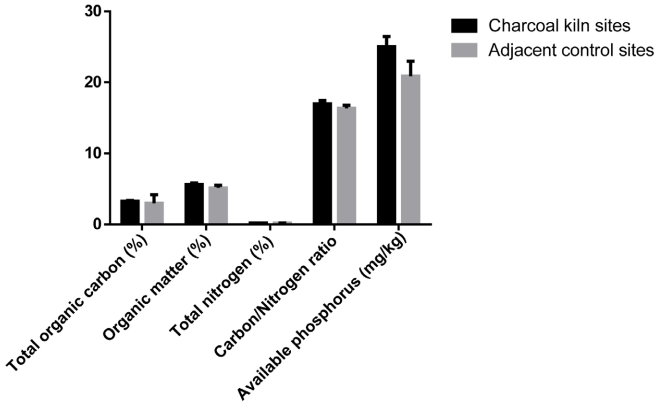

Figure 4. Mean ± SE of soil organic carbon, organic matter, total nitrogen and available phosphorus at charcoal kiln sites and adjacent control sites.

Table 4. Selected summary statistics, relative change, and statistical significance of organic carbon, organic matter, total nitrogen and available phosphorus of soil at charcoal kiln sites and adjacent control sites.

	TOC (%)	OM (%)	TN (%)	C/N	AvP (mg/kg)
Adjacent control sites (ACS)	2.98 ± 0.22	5.14 ± 0.38	0.19 ± 0.02	16.37 ± 0.42	20.88 ± 2.11
Charcoal kiln sites (CKS)	3.26 ± 0.12	5.62 ± 0.21	0.20 ± 0.01	16.98 ± 0.45	25.04 ± 1.39
Relative change (%)	9.11	9.33	6.19	3.70	19.90
p-value	ns	ns	ns	ns	ns

TOC = Total Organic Carbon, OM = Organic Matter, TN = Total Nitrogen, AvP = Available Phosphorus, C/N = Carbon to Nitrogen ratio, ns = not significant.

conforms with the findings and suggestion of Nigussie and Kissi that this increase could be due to charcoal residue and other charred matter at the kiln sites [32]. Addition of biochar to soil has also been shown to increase cation exchange capacity [37].

In Figure 5, two of the exchangeable bases (Ca and Mg) significantly increased ($p < 0.001$) at the charcoal kiln sites by 57.15% and 89.16%, respectively. However, Na slightly increased by 3.30% while K reduced by 0.29%. The release of minerals has been correlated with the deposition of ash due to its richness in basic cations [38]. Awodun *et al.*, Kishor *et al.*, and Nigussie and Kissi all reported a significant increase in exchangeable bases at their respective burn sites [32] [39] [40]. Furthermore, our non-significant findings on exchangeable Na and K are similar to those of Ogundele *et al.* [36]. This could be due to the proximity of our study locations (Table 5).

3.5. Effect of Charcoal Production on Heavy Metals

Most of the heavy metals investigated did not significantly change between both sites. Only Fe exhibited a significant ($p < 0.001$) reduction of 28.54% at the charcoal kiln sites. Mn and Cr also slightly reduced by 16.28% and 6.35%, respectively. Lehmann [41] explained that the bioavailability of heavy metals is reduced when COO, OH and other functional groups on the surface of biochar form complexes with heavy metals in Figure 6. Pb and Cd were largely below the detection limits of the methods used in this study. This could be because the study areas are rural with minimal industrial activities (Table 6).

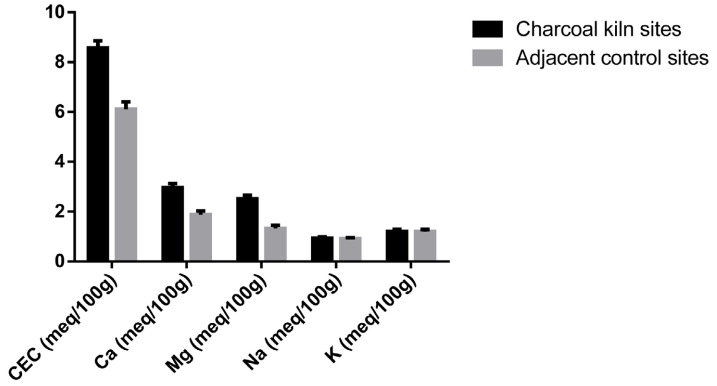

Figure 5. Mean ± SE of cation exchange capacity and exchangeable bases at charcoal kiln sites and adjacent control sites.

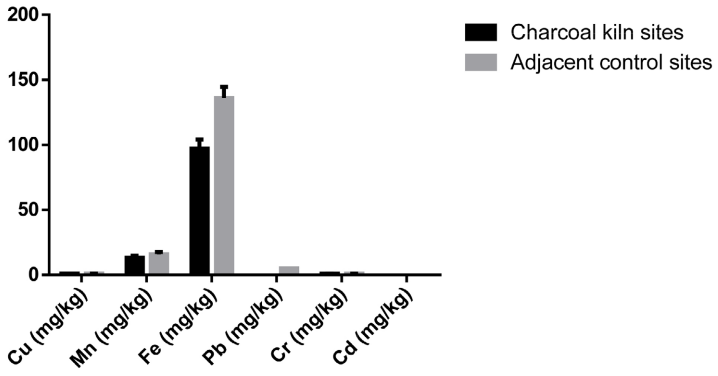

Figure 6. Mean ± SE of heavy metals at charcoal kiln sites and adjacent control sites.

Table 5. Selected summary statistics, relative change, and statistical significance of cation exchange capacity and exchangeable bases of soil at charcoal kiln sites and adjacent control sites.

	CEC (meq/100g)	Ca (meq/100g)	Mg (meq/100g)	Na (meq/100g)	K (meq/100g)
Adjacent control sites (ACS)	6.11 ± 0.29	1.88 ± 0.15	1.33 ± 0.12	0.91 ± 0.04	1.20 ± 0.09
Charcoal kiln sites (CKS)	8.56 ± 0.29	2.96 ± 0.17	2.51 ± 0.14	0.94 ± 0.04	1.20 ± 0.09
Relative change (%)	40.11	57.15	89.16	3.30	−0.29
p-value	<0.0001	<0.0001	<0.0001	ns	ns

CEC = Cation Exchange Capacity, ns = not significant.

Table 6. Selected summary statistics, relative change, and statistical significance of heavy metals at charcoal kiln sites and adjacent control sites.

	Cu (mg/kg)	Mn (mg/kg)	Fe (mg/kg)	Pb (mg/kg)	Cr (mg/kg)	Cd (mg/kg)
Adjacent control sites (ACS)	1.17 ± 0.11	15.92 ± 1.73	136.03 ± 8.63	5.00 ± 0.00	1.06 ± 0.08	ND
Charcoal kiln sites (CKS)	1.23 ± 0.09	13.33 ± 1.39	97.20 ± 6.88	ND	0.99 ± 0.09	ND
Relative change (%)	4.70	−16.28	−28.54	NA	−6.35	NA
p-value	ns	ns	<0.001	ns	ns	ns

ND = Not Detected, NA = Not Applicable, ns = not significant.

4. Conclusion

Charcoal production did not significantly affect soil physical properties, although a slight increase in sand percentage was observed at kiln sites while silt, clay and bulk density reduced to a small degree in relation to the adjacent control sites. Soil pH and electrical conductivity significantly increased at the kiln sites. However, total extractable acidity reduced significantly due to its negative correlation with pH and electrical conductivity. Total organic carbon, organic matter, total nitrogen, carbon to nitrogen ratio, and available phosphorus increased slightly due to charred biomass introduced to soils by the process of charcoal production. The increased quantity of ash at the kiln sites led to a significant increase in the cation exchange capacity and most of the exchangeable bases in the affected soils. Charcoal production also reduced the bioavailability of heavy metals. Conclusively, charcoal production does not appear to cause irreversible adverse effects on soil physical and chemical properties. However, further studies will be useful in understanding the effects of charcoal production

on vegetation cover and soil biota.

Acknowledgements

This study was conducted under the Institutional Based Research (IBR) of Kwara State University, funded by the Tertiary Education Trust Fund (TETFund), Nigeria.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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