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ASSESSMENT OF SOIL QUALITY AND CARBON SEQUESTRATION POTENTIALS OF RE-VEGETATED COAL MINE SPOIL AT MAIGANGA, AKKO LOCAL GOVERNMENT AREA, GOMBE STATE, NIGERIA

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Abstract

Soil quality and carbon sequestration potential are critical components of sustainable agricultural management that are increasingly being considered in policy decisions related to food security, environmental management, and climate change mitigation. This study aimed to evaluate the soil quality and carbon sequestration potential of revegetated coal mine spoil at Maiganga, Akko Local Government Area, Gombe State, Nigeria. Seven dominant tree species (Mangifera indica, Azadirachta indica, Eucalyptus camaldulensis, Acacia Senegal, Jatropha curcas, Syzygium gyneense, and Anacardium occidentale) were identified growing on the reclaimed coal mine spoil. Twelve composite soil samples were collected using an auger under the canopy of each of the seven dominant tree species on the reclaimed coal mine spoil, including reference samples from an unplanted site in the study area, at depths of 0–30 cm and 30–60 cm. A total of 96 composite soil samples were collected and analyzed using standard methods. Results revealed that sand dominated the soil fractions, with soil textural classes ranging from sandy loam to loamy sand. The soil pH ranges from 4.84 to 7.23 and was slightly acidic to neutral in its reactions. Organic carbon (1.86 to 4.79 g/kg) was low with a significantly ($p<0.05$) higher value (4.79 g/kg) recorded in soils under Eucalyptus camaldulensis, while the total nitrogen value of 1.21 to 3.28 g/kg was medium to high, and the available phosphorus (Ap) value of 0.14 to 9.66 mg/kg was significantly ($p<0.05$) different, with the highest AP value (9.66 mg/kg) obtained at the Anacardiun occidentale site. The soil quality percentages ranged from 13 to 20% and soil carbon stock values from 10.07 to 27.55 t C/ha. The soils are poor in quality but have higher potential to sequester carbon, contributing to coal mine spoil remediation, climate change mitigation, and food security..

Key words: *carbon sequestration*, *climate change*, coal mine, re-vegetated, *soil quality*,

Introduction

Coal is an important source of energy that plays a vital role in powering the economies of many countries worldwide (Ahirwal et al., 2018). According to Ahirwal et al. (2018), coal provides 30% of the energy needed for human activities worldwide (International Energy Agency, 2014). The world production of coal is approximately 3.5 × 109 t yr^{-1}, most of which is used to produce 38% of the world's electricity, and is an important energy resource for steel, cement, and thermal power plants (Mukhopadhyay et al. 2016). Land subsidence caused by coal mining alters the properties and structure of the soil, reducing crop yields, limiting vegetation growth, causing soil erosion, altering topographic and hydrologic conditions, and resulting in the loss of topsoil and agricultural land (Wang et al., 2017). Numerous nations, including the USA (Darmody et al., 2014), India (Tripathi et al., 2014), and Nigeria (Maina et al., 2016; Yuguda and Kulawe, 2020), have reported the effects of coal mining on agricultural land. Damage to surface and subsurface drainage, changes in the physico-chemical and biological properties of the soil, soil erosion, and decreased agricultural yields are the primary focus of these studies. The impact of reclamation activities on soil characteristics and ecosystem services has also been documented in several studies (Akala and Lal 2001; Ingram et al. 2005; Mukhopadhyay et al. 2013; Ahirwal et al. 2017; Józefowska et al. 2017; Liu et al. 2017). Significant differences in particle size, SOC, nitrogen, phosphorus, potassium, and cation exchange capacity between China's reclaimed and unreclaimed areas were documented by Zhou et al. (2017). According to the authors, reclaimed mine-degraded lands will resemble an undisturbed ecology after about 20 years (Ahirwal et al., 2018).

The ability of soil to support biological productivity, preserve environmental quality, and promote plant and animal health within ecosystem limits is referred to as soil quality (Doran and Parkin 1994). Because it simultaneously addresses sustainability and productivity, soil quality (SQ) is becoming increasingly important for developing nations (Mulat et al., 2021). To develop improved soil management techniques that enhance environmental sustainability and production, it is crucial to evaluate the current state of soil quality (Mulat et al., 2021). To create the soil quality index (SQI) for soil that has been anthropogenically managed, three Important actions are taken: According to Mukhopadhyay et al. (2016) and Vasu et al. (2016), (i) selecting potential MDS that comprise the smallest group of the numerical dataset to evaluate the soil quality; (ii) performing multivariate statistical screening of selected indicator parameters (i.e., physicochemical and/or biological) that can be used to define SQI; and (iii) combining the indicator score to calculate a final SQI. Carbon sequestration involves transferring atmospheric CO_2 into long-lived pools and storing it securely to prevent immediate re-emission, while soil C sequestration means increasing SOC and soil inorganic carbon stocks through judicious land use and recommended management practices (Lal, 2005). Agroforestry and a variety of cropping systems, mulch farming, conservation tillage, cover crops, and integrated nutrient management—

which includes the use of compost, biosolids, manure, and enhanced grazing—are a few of these techniques. The cumulative historic C loss, estimated at 55 to 78 gigatons (Gt), is almost comparable to the potential carbon sink capacity of managed ecosystems (Lal, 2004). Emissions from fossil fuels offset by attainable SOC potential offer numerous socioeconomic and biological advantages. The amount of soil organic carbon (SOC) in the pool at a depth of one meter varies from 30 tons/ha in arid climates to 800 tons/ha in cold climate organic soils. One ton of soil carbon added to degraded farmland soils could improve global food security by increasing crop output by 20 to 40 kg/ha for wheat, 10 to 20 kg/ha for maize, and 0.5 to 1 kg/ha for cowpeas (Lal, 2004). Coal mining has been shown to have an impact on the Maiganga environment, particularly on agricultural land (Maina et al., 2016; Yuguda and Kulawe, 2020). However, the harm to surface and subsurface drainage, the disposition of heavy metals, the impact on human health, and the decrease in crop yields are the main topics of these early studies. Although various tree species have been planted to reclaim a portion of the Maiganga coal mine, the effectiveness of each species in enhancing soil quality and sequestering carbon in the post-mining ecosystem (PME), much remains unclear. Furthermore, the type of tree and its environmental adaptability determine whether a species can enhance the quality of the soil. Thus, the premise behind this study is that re-vegetation with various tree species is necessary for soil quality and carbon sequestration in the PME. Therefore, assessment of changes in mine soils and post-mining ecosystem (PME) functions is vital for managing soil quality that has been degraded due to mining activities. This study is based on the hypothesis that soil quality and C sequestration in the PME depend on revegetation using tree species. Thus, the purpose of this field study was to (i) assess changes in soil quality under different tree species of revegetated post-mining sites, (ii) estimate the C sequestration potential of the revegetated sites, and (iii) assess the physical and chemical properties of soils of the re-vegetated sites.

Materials and Methods

Study Area

The study area is located in Maiganga village, the southwestern part of Kumo, the headquarters of Akko Local Government Area of Gombe State, Nigeria (Fig. 1). It lies between longitude 090 59' 24.1” N and latitude 110 09' 12.4"E and covers a land area of about 20129.47 acres (48.16 km²). The study area is seasonally wet from April to October and dries from October to March. The average annual rainfall ranges from 850 mm to 1000 mm, while the mean maximum monthly temperature is 37°C, occurring from March to October, while from December to February the temperature lowers to 21°C. Relative humidity follows a similar pattern, from 94% in August and dropping to less than 10% during the Harmattan in December/January. The geology of the area comprises two major rock formations, the Gombe sandstones, which occupy the NE-SW part of the area, and the Pindiga Formation, which is on the southern part of the study area. The main economic activity of the people is agriculture, including the cultivation of crops such as maize, beans, soybeans, guinea corn, groundnuts, rice, millet, and sorghum.

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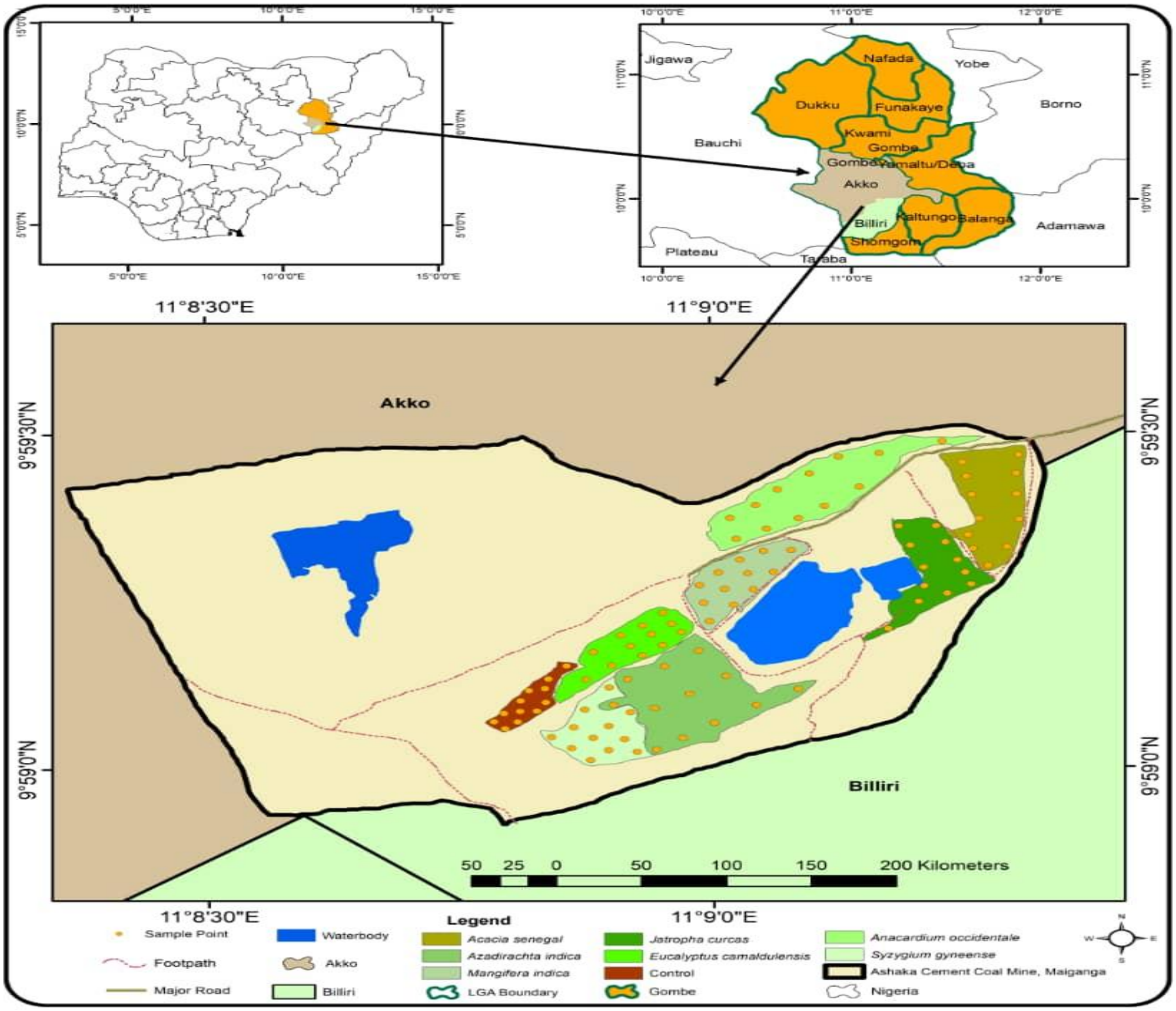

Fig. 1: Map of Nigeria showing Gombe State, Akko Local Government Area and Sampling points

Pre-Fieldwork

A reconnaissance survey was conducted using satellite imagery, a Digital Elevation Model (DEM), and a handheld GPS device in collaboration with the mining company. This led to the identification of the various revegetated areas and subsequent delineation and mapping. The seven dominant tree species identified; Mangifera indica (09 59 13.7 N and 11 09 0.1 E), Azadirachta indica (09 59 6.3 N and 11 08 57.9 E), Eucalyptus camaldulensis (09 59 8.8 E and 11 08 57 E), Acacia Senegal (09 59 53 N and 11 08 54.3 E), Jatropha curcas (09 59 23.1 N and 11 09 5.2 E), Syzygium gyneense (09 59 6.9 N and 11 08 53.3 E), and Anacardium occidentale (09 59 16.6N and 11 09 2.1 E), all growing on the reclaimed coal mine spoil, including an unplanted site (09 59 4 N and 11 08 47.1 E).

Field Work/Soil sampling

Soil samples were collected using an auger under the canopy of the seven dominant tree species on the reclaimed coal mine spoil, including reference soil samples from an unplanted site in the study area. For each tree species, including the unplanted site, twelve replicate soil samples were collected at the depths of 0–30 cm and 30–60 cm. Each composite soil sample was prepared by mixing three sub-samples collected randomly from three different spots under the respective tree canopy, including the unplanted site. A total of 96 composite soil samples were collected.

Laboratory Analysis

Composite soil samples from each plot were air-dried, lightly crushed, and passed through a 2 mm sieve. The fractions smaller than 2 mm were used for soil physicochemical analyses. Particle size distribution was determined using the hydrometer method (Gee and Bauder, 1979). Bulk density was determined using the core sampler method (Blake and Hartge, 1986). The measurement of soil pH was conducted using the pH meter method in the supernatant suspension of a 1:2 soil-to-water ratio (Agbenin, 1995). Electrical conductivity of the saturated soil extract was determined at a 1:2 soil/water ratio, and the suspension was then read using a Wheatstone bridge meter at 25°C (Agbenin, 1995). Organic carbon was determined using the dichromate wet oxidation method of Walkley and Black (Nelson and Sommers, 1982). Available phosphorus was determined using the Bray 1 method (IITA, 1979), and total nitrogen was determined by the Kjeldahl method (Bremner and Malvaney, 1982). The exchangeable bases (Ca, Mg, K, and Na) were extracted by saturating the soil samples with neutral ammonium acetate (1N NH_4OAc) solution. After extraction, exchangeable Ca and Mg were measured using an atomic absorption spectrophotometer, and the exchangeable Na and K were determined by a flame photometer. The ammonium acetate method was used to determine the Cation Exchange Capacity (CEC) (Agbenin, 1995).

Evaluation of Soil Quality

Soil quality was evaluated using the Tropical Soil Quality Index (TSQI) as described by Arifin et al. (2012) to determine the soil quality index under the forest tree species. This method is largely suitable for tropical soils, as it considers the acidic nature of the soil in choosing a method of soil analysis. The method uses a scoring system of 0–2, where soil properties with sufficient levels receive a higher score (2 or 1), while those with low levels receive zero (0).

Evaluation of Soil Carbon Stock

Elemental stocks were calculated from measured elemental concentrations (SOC), bulk density corrected for fine earth material, and at 30 cm depths based on IPCC guidelines as follows:

SOC = (OC x d X Bd x 10000) / 1000 (t C/ha)

Where SOC = soil carbon stock of soil (t C ha^{-1}), Org C = organic carbon content (g kg^{-1}), d = soil depth, Bd = Bulk density at the depth (Mg m^{-3}),10,000 m^2 = 1 ha,and 1000 kg= 1 ton.

Data Analysis

Descriptive statistics were used to assess the normal distribution of results for all parameters analyzed in the laboratory (Agbenin, 1995). All results collected from the laboratory analysis were subjected to analysis of variance (ANOVA), using GenStat Statistical Software 17th edition. Means that are significantly different were separated using Least Significant Difference (LSD) at the 5% level of probability.

Results and Discussions

Soil physical properties across the study area

Table 2 displays the mean particle-size distribution data for the different tree species, including the unplanted site. The sand fraction dominates the particle size distribution among the different land use types. The results of Jimoh et al. (2019), who also recorded a high mean sand content (80.50%) in soils of Gombe State University, are in line with the study's discovery of sand fraction predominance. The parent material composition of the soils may be the cause of the sand fraction's dominance throughout the research area (Brady and Weil, 2017). Additionally, as many sand particles were generated from aeolian deposits that were blown across several thousand kilometers, their prevalence in arid and semiarid regions is not unusual (Mortimore, 1989). The mean sand values also varied significantly ($p<0.05$) across all revegetated areas, including the unplanted site, ranging from 57% to 83%. The land planted with Jatropha curcas had the significantly ($p<0.05$) lowest sand value, at 57% (Table 2). Variations in the degree of pedogenic processes, such as clay lessivage, eluviation and illuviation, sorting of soil materials by biological activities, or surface erosion by runoff or their combination, may be the cause of the significant ($p<0.05$) variation in mean sand distribution throughout the study area (Usman et al., 2017).

The research area's mean silt content showed that soils under Jatropha curcas had the highest silt percentage (27%), while soils under Anacardium occidentale had the lowest (9%) and that the differences were significant ($p<0.05$). The high silt concentration of all the soils under study is a noteworthy characteristic (Table 2). In their research, Abba et al. (2016) also noted a greater silt concentration. The makeup of the parent material and the stage of soil development may be responsible for the high silt concentration found in this investigation. Although silts provide suitable soil components for cultivation, they are prone to structural issues. As a result, building up organic matter is important to support the soils, particularly beneath revegetated fields. In comparison to sand and silt, the mean proportion of clay in all the soils under study had the lowest percentage of clay content (Table 2). These low clay content values were consistent with previous research by Jugulde and Salem (2023), who examined soils in Dadinkowa, Gombe State. The highest clay value was found in both fields planted with Jatropha curcas and Syzygium gyneense (16%). The mean clay values across the entire revegetated land, including the unplanted site, varied significantly ($p<0.05$) and ranged from 8 to 16% (Table 2). According to Usman et al. (2017), pedogenic processes such as clay lessivage, eluviations, and illuviation may be the cause of the significant ($p<0.05$) variance in the percentage distribution of clay throughout the studied area. Additionally, the findings showed that the research area's soil textural class varied from sandy loam to loamy sand (Table 2).

The mean bulk density (BD) values for the entire revegetated land, including the unplanted site, ranged from 1.59 to 1.66 g/cm³ and varied significantly ($p<0.05$). The unplanted site had the significantly ($p<0.05$) highest BD (1.66 g/cm³) (Table 2). Lowest organic matter content, compaction due to mechanical traction, or possibly both, may be the cause of the highest BD value seen in soils beneath the unplanted site. However, because root penetration may be impeded in soil with a bulk density value exceeding 1.75 g/cm³, the values found in these investigations are typically regarded as safe (Ashenafi et al., 2010). According to Donahue et al. (1990), bulk densities below 1.40 g/cm³ for clay and 1.60 g/cm³ for sandy soils are ideal for healthy plant growth. The mean values of particle density (PD) varied significantly ($p<0.05$) throughout the research area, ranging from 2.52 to 2.69 g/cm³. The land under Anacardiun occidentale and Acacia Senegal had the greatest mean PD values (2.69 g/cm³) and the lowest (2.52 g/cm³), respectively (Table 2). According to Brady and Weil (2017), the organic matter content, the type of minerals present, or a combination of the two could be the cause of the variation in mean PD values found in this investigation. Nevertheless, the particle density values found in this investigation were deemed adequate (Kachinskii, 1965). The soil's ability to retain water is directly impacted by its porosity and pore size distribution, which are reflections of bulk density values (Brady and Weil, 2017). Across the entire study area, the mean total porosity (TP) values ranged from 36 to 40% and were significantly ($p<0.05$) different, with the highest mean TP values (40%) obtained in Anacardiun occidentale, while the unplanted site, Acacia senegal, and Eucalyptus camaldulenses are at par and recorded the lowest mean TP value of 36% (Table 2). The significantly ($p<0.05$) higher mean total porosity value recorded in the Anacardiun occidentale site may be attributed to loosening of soil materials by plant roots (Ahukaemere and Akpan, 2012), soil organic matter content, or both. According to Kachinskii (1965), the best soils should have porosities of over 50%; good soils, between 45% and 50%; satisfactory soils, 40-45%; unsatisfactory soils, fewer than 40%; and poor soils, below 30%. It was also reported that the optimum total pore space value for crop production should be >50% (Brady and Weil, 2017). In terms of porosity rating, soils revegetated with Anacardium occidentale are classified as satisfactory soils (Kachinskii, 1965). There is every likelihood that upon organic matter buildup over time, especially under revegetated lands, the soil's bulk density will decrease, leading to an increase in percentage pore distribution, thereby enhancing the soil's physical condition for optimum plant growth.

Soil Chemical Properties across the study area

Throughout the whole study area, the mean soil pH (H2O) values varied statistically ($p<0.05$) from 4.84 to 7.23, with the Acacia Senegal site recording the lowest pH value (4.84) and the Eucalyptus camaldulensis sites obtaining the highest value (7.23) (Table 3). According to

Esu (1991), the pH mean values in the research area fall into the range of very strongly acidic to neutral in reaction. The loss of cations through the leaching process may be the cause of the significantly ($p<0.05$) lowest pH values recorded at the Acacia Senegal location (Brady and Weil, 2017). Nonetheless, the findings showed that the majority of the soils under investigation had reactions that ranged from slightly acidic to neutral. One reliable measure of the saltiness of a soil solution is its electrical conductivity (EC) (Brady and Weil, 2017). Throughout the entire study area, the mean soil EC values varied from 0.09 to 0.37 d/sm and were found to be significantly ($p<0.05$) different. The site planted with Acacia senegal had the highest mean EC value (0.37 d/sm), while the site planted with Mangifera indica had the lowest mean value (0.09 d/sm) (Table 3). Variable degrees in the leaching process may be the cause of the variation in EC mean values throughout the research area. But according to Esu (1991), the entire research area is non-saline. The low EC values found in this study are consistent with previous findings by Jugulde and Salem (2023), who studied Dadin Kowa soils. Indicating that, for now, salinization is not a pedogenic process throughout the research area, because the range of EC values observed in this study falls below the crucial threshold of 4 d/sm to be classified as a saline soil (FAO, 1993). The amount of organic matter in the soils, which acts as a storage for nutrients like N, P, and S, is indicated by organic carbon (OC) soil content. Throughout the entire study area, the mean soil organic carbon (OC) values varied significantly ($p<0.05$), ranging from 1.86 to 4.79 g/kg. The land re-vegetated with Eucalyptus camaldulensis had the highest OC value of 4.79 g/kg (Table 3). The relative accumulation of plant materials, which in turn led to the relative buildup of organic matter, may be the reason for the highest mean value of OC found in soils beneath Eucalyptus camaldulensis. Additionally, the study area's mean range of OC values is typically regarded as low (Esu, 1991). Frequent harvesting and removal of woody material from the system for household purposes, rather than allowing it to be recycled back into the soils, may be the cause of the low OC across the revegetated lands (Demessie et al., 2012). The low OC level combined with a large percentage of sand particles will cause the soil to aggregate poorly, retain water poorly, and have poor physical stability (Salako, 2003). As erosion is a frequent occurrence in the research area, this has made the soil more vulnerable to it. However, the mean range of values of OC reported across the study area was lower than the 11.79 g/kg reported by Abba et al. (2016) and the 5.3 g/kg reported by Jimoh et al. (2019) in soils under date palm plantation in Gombe State University.

Across the study area, the mean soil total nitrogen (TN) values varied from 1.21 to 3.28 g/kg and were found to be significantly ($p<0.05$) different. The Syzygium gyneense site had the lowest mean TN value (1.21 g/kg), while the Jatropha curcas site had the highest (3.28 g/kg) (Table 3). Additionally, according to the Esu (1991) rating scale, the range of mean TN values found in this study is often classified as medium to high in soil content. The significantly ($p<0.05$) lowest mean TN value found in soils under the Syzygium gyneense site may be explained by the fact that TN is mobile in soils and, is therefore lost through various mechanisms, including ammonia volatilization due to high temperatures, subsequent denitrification, chemical and microbial fixation, leaching, and runoff, all of which reduce the amount of residual/available N in soils (Akpan et al., 2017). The study's medium-to-higher soil nitrogen levels suggest a faster rate of organic carbon mineralization and the subsequent release of nutrients such as nitrogen. Further, the mean range of values of TN reported across the study area was higher than the 1.01 g/kg reported by Abba et al. (2016) and the 1.3 g/kg reported by Ibrahim and Umar (2012). The mean available phosphorus (AP) values across the entire study area ranged from 0.14 to 9.66 mg/kg and were significantly ($p<0.05$) different, with the highest AP value (9.66 mg/kg) obtained at the Anacardiun occidentale site, while the lowest value (0.14 mg/kg) was recorded at the Unplanted site (Table 3). In general, the research areas mean range of AP values is considered low (Esu, 1991). The parent material composition of the soils or low organic matter content, or both, may be the cause of the generally low mean AP value found in the investigated soils. Additionally, the mean range of Ap values found in this study is considerably lower than those found in prior investigations by Jimoh et al. (2019), Abba et al. (2016), and Ibrahim and Umar (2012), in some soils of Gombe State.

Soil Exchangeable Properties across the study area

Throughout the entire study area, the mean soil exchangeable calcium (Ca) values varied significantly ($p<0.05$) and ranged from 0.001 to 0.026 cmol (+)/kg. Soils under Azadirachta indica had the lowest mean Ca values (0.001 cmol (+)/kg), while soils under Mangifera indica had the highest (0.026 cmol (+)/kg). Additionally, the mean Ca values found throughout the research region were deemed to be low in general (Esu, 1991). Fekadu et al. (2018) attributed the low content and variation in mean Ca values to a high and variable leaching process, or variable mining of Ca by the different plants, from the rooting zone (Brady and Weil, 2017). The mean range of Ca levels found in this study is also considerably lower than the 3.38 cmol (+)/kg previously reported by Jimoh et al. (2019) in soils under date palm plantation in Gombe State University. The mean soil exchangeable magnesium (Mg) values of the studied soils ranged from 0.001 to 0.012 cmol (+)/kg soil and were found to be significantly ($p<0.05$) different, with soils re-vegetated with Mangifera indica recording the highest mean Mg value of 0.012 cmol (+)/kg (Table 4). One possible explanation for the higher mean magnesium values found in Mangifera indica soils is a minimal leaching process. According to the Esu (1991) rating system, the mean Mg range of values found in this investigation was likewise deemed low. The nature of the parent material may have an impact on the study's apparent low magnesium content readings (Brady and Weil, 2017). Across the entire study area, the mean soil exchangeable sodium (Na) values varied significantly ($p<0.05$), ranging from 0.023 to 0.043 cmol (+)/kg soil. The land re-vegetated with Syzygium gyneense had the highest Na value (0.043 cmol (+)/kg) (Table 4). Higher leaching losses compared to the other locations may be the cause of the unplanted site's soils having a much lower Na concentration (0.023 cmol (+)/kg). Further, Esu's (1991) rating scale also assigns a low rating to the range of mean Na values obtained in this study. Brady and Weil (2017) ascribed these low levels to the parent material's characteristics. The mean soil exchangeable potassium (K) content across the entire study area ranged from 0.058 to 0.108 cmol (+)/kg and was significantly ($p<0.05$) different, with land under Syzygium gyneense recording the highest mean K value of 0.108 cmol (+)/kg (Table 4). The mean K values across the study area were rated as being low as per the Esu (1991) rating scale. The relatively low amount of K recorded in this study might be due to saturation of these soils with base-enriched groundwater (Esu, 1982). However, the low potassium content of the soils under Syzygium gyneense may be attributed to higher leaching losses. The mean soil total exchangeable bases (TEB) values over the entire study area varied significantly ($p<0.05$) and ranged from 0.09 to 0.17 cmol (+)/kg soil, with land under Syzygium gyneense reporting the highest mean TEB value of 0.17 cmol (+)/kg. Furthermore, Usman's (2005) rating system assigned a low rating to the TEB levels found in this study. The kind of clay concentration may be connected to the noticeably ($p<0.05$) elevated mean TEB value found in soils under Syzygium gyneense. Higher amounts of exchangeable cations were associated with more clay (Brady and Weil, 2017). Over the whole study area, the mean soil cation exchange capacity (CEC) varied significantly ($p<0.05$), ranging from 16.02 to 25.75 cmol (+)/kg. The highest mean CEC was recorded on land re-vegetated with Jatropha curcas (25.75 cmol (+)/kg). According to the Esu (1991) rating scale, the range of mean soil CEC values found in this study is evaluated as high. The increased CEC value found on land covered by Jatropha curcas may be explained by the organic matter content or the kind and amount of clay (Ukabiala, 2012). Additionally, the comparatively high CEC values found in this investigation show that the soils under research have a good capacity for buffering and retaining nutrients.

Soil Quality Evaluation across the study area

For soil quality evaluation, eight (8) soil parameters were ranked from 0 to 2, which include bulk density, pH, total carbon, total nitrogen, available phosphorus, exchangeable potassium, magnesium, and calcium (Table 1). A score of 0 was allocated to a parameter with a low nutrient rate, while 1 to 2 was allocated to a parameter with an optimum nutrient rate (Table 1). The scores from the sites were compared with the ideal soil parameter ranking to make deductions on how much influence the individual tree species had on soil quality status (Table 5). Table 5 shows that the maximum total score obtainable was 15, which is 100% quality. However, when a comparison on soil quality across the study area was made, the values varied from 13 to 20%, with Acacia senegal and Eucalyptus camaldulensis recording the lowest SQ percentage (13%). From the study, the most severe limitation to soil quality across the study area was BD, OC, AP, K, Mg, and Ca, which were very limited. Total nitrogen was moderate, while pH recorded a better soil quality across the study area. This result is contrary to an earlier report by Arifin et al. (2012), who reported 59.09% as the percentage of soil quality for Malaysia’s secondary forests, and Jimoh et al. (2019), who reported 53-60% as the percentage of soil quality for soils under date palm plantations. At the right moment, all the tree species studied were found to be limited in their soil quality enhancement.

Soil Carbon Stock across the study area

The research's findings indicate that the amount of carbon sequestered by the various tree species in the study area varied (Table 6). Throughout the research area, the soil organic carbon stock (SOC) values vary from 10.07 to 27.55 t C/ha (Table 6). Additionally, the findings showed that Eucalyptus camaldulensis (27.55 t C/ha), Jatropha curcas (26.24 t C/ha), and Acacia senegal (20.40 t C/ha) are the top-performing tree species in terms of carbon sequestration. A mean SOC value of 21.11 t C/ha was previously reported by Jimoh et al. (2019) in soils under date palm plantation in Gombe State. According to Lal (2004), an increase of 1 ton of soil carbon in degraded cropland soils may increase crop yield by 20 to 40 kg/ha for wheat, 10 to 20 kg/ha for maize, and 0.5 to 1 kg/ha for cowpeas, and could enhance world food security. Lack of adequate protection for the revegetated lands, however, is one of the main issues with this sustainable agricultural management technique. Locals constantly invade the plantation by pruning the palm branches and frequently harvesting and transporting woody material out of the system for domestic uses rather than allowing it to be recycled back into the soils.

Conclusions and Recommendations

Based on the above results, the soil texture was predominantly sandy loam, while the total pore spaces were highly inadequate. The soil pH was very strongly acidic to neutral in reaction, organic carbon was low, and total nitrogen was medium to high in soil content, while available P content of soils was generally low across the study area. The exchangeable cations depict relatively low values across the study area. However, the value of soil CEC was high.The values of soil organic carbon stock (SOC) across the study area range from 10.07 t C/ha to 27.55 t C/ha, with Eucalyptus camaldulensis, Jatropha curcas, and Acacia Senegal as the best-performing tree species. The soil quality percentage range of values across the study area depicts a very poor soil quality status. The use of tree species in reclaiming mine spoil has high potential to improve the soil's quality for sustainable production and mitigate global warming and climate change, and therefore, the adoption of agroforestry in the study area is advocated. For sustained development, the plantations should be protected from trespassers, and their fertility and quality condition should be adequately monitored regularly.

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The selected soil parameters were summed up to give a total SQI calculated as:

Total SQI = Σ individual soil properties index value

$$TSQI\ \% = \frac{\text{Total SQI}}{\text{Max possible total SQI for properties measured}} \times 100$$

Table 1. *Selected soil properties for Tropical Soil Quality Index (TSQI)*

S/N	Parameters	Level	Interpretation	Index
1	BD	> 1.5	Possible adverse effects	0
		≤1.5	Adverse effects unlikely	1
2	Acidity	3.01-4.00	Strongly acidic, only acid tolerant crops can grow	0
		4.01-5.5	Moderate acid, growth of acid intolerant plant is affected	1
		5.51-7.2	Slightly acid to near neutral, optimum for many plant species	2
		7.21-8.5	Slightly to moderately alkaline, optimum except for those who prefer acid soils	1
		>8.5	Strongly alkaline, alkaline tolerant plants	0
3	Total carbon (g/kg)	> 50	High excellent buildup of organic C with all associated benefits	2
		10- 50	Moderate adequate levels	1
		< 10	Low – could indicate a possible loss of organic Carbon	0
4	Total nitrogen g/kg)	> 5	High – excellent reserve of nitrogen	2
		1-5	Moderate – adequate levels	1
		< 1	Low – could indicate loss of organic N	0
5	Available P (mg/kg)	> 30	High – excellent reserve of Available P	2
		15-30	Moderate – adequate levels for plant growth	1
		< 15	Low – P deficiencies likely	0
6	Exch. K (cmol (+)/kg)	>1.28	High – excellent reserve of exchangeable K	2
		0.26-1.28	Moderate – adequate levels for most plants	1
		< 0.26	Low – possible deficiencies	0
7	Exch. Mg (cmol (+)/kg)	> 4.17	High – excellent reserve exchangeable Mg	2
		0.42-4.17	Moderate – adequate levels for most plants	1
		< 0.42	Low – possible deficiencies	0
8	Exch. Ca (cmol (+)/kg)	> 5.00	High – excellent reserve, probably calcareous soil	2
		0.51-5.00	Moderate – adequate levels for most plants	1
		0.05 -0.5	Low – possible deficiencies	0
		<0.05	Very low – severe Ca depletion, adverse effects likely	0

Source: Arifin *et al.* (2012)

Table 2: Physical properties of soils across the study area

Location	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Texture**	**BD (g/cm^3)**	**PD (g/cm^3)**	**TP (%)**
Unplanted site	79a	13de	8c	LS	1.66a	2.61b	36bc
Acacia Senegal	70b	19bc	11bc	SL	1.62ab	2.52b	36bc
Azadirachta indica	70b	18bcd	12ab	SL	1.59b	2.54b	37bc
Eucalyptus camaldulenses	70b	16cd	14ab	SL	1.64ab	2.59b	36bc
Mangifera indica	70b	16cd	14ab	SL	1.65ab	2.60b	38b
Anacardiun occidentale	83a	9e	8c	LS	1.63ab	2.69a	40a
Jatropha curcas	57c	27a	16a	SL	1.62ab	2.56b	37bc
Syzygium gyneense	62c	22ab	16a	SL	1.60b	2.56b	37bc
LSD	**4.89**	**6.65**	**3.46**		**0.06**	**0.09**	**1.84**

LS= Loam Sand, SL= Sandy Loam, BD= Bulk density, PD= Particle density, TP= Total porosity

Table 3: Chemical properties of soils across the study area

Location	**pH**	**EC**	**OC(g/kg)**	**TN (g/kg)**	**AP (mg/kg)**
Unplanted site	6.78b	0.23abc	2.40cd	2.11ab	0.14d
Acacia Senegal	4.84e	0.37a	3.06bcd	1.25b	4.68b
Azadirachta indica	6.72bc	0.12bc	1.86d	1.71b	0.62d
Eucalyptus camaldulenses	7.23a	0.11bc	4.79a	1.80b	1.73cd
Mangifera indica	6.87 b	0.09c	2.85bcd	2.05ab	2.69bcd
Anacardiun occidentale	6.56cd	0.18bc	2.92bcd	1.71b	9.66a
Jatropha curcas	6.40d	0.11bc	4.20ab	3.28a	4.42bc
Syzygium gyneense	7.10a	0.27ab	3.65abc	1.21b	8.68a
LSD	**0.20**	**0.17**	**1.49**	**1.45**	**2.94**

Table 4: Exchangeable properties of soils of the study area

Location	Ca	Mg	Na	K	TEB	CEC
Unplanted site	0.017b	0.011a	0.023c	0.058b	0.11cd	17.15d
Acacia Senegal	0.001c	0.001b	0.037ab	0.092ab	0.13bcd	16.02d
Azadirachta indica	0.001c	0.001b	0.025c	0.063b	0.09d	17.95cd
Eucalyptus camaldulenses	0.004c	0.003b	0.032abc	0.081ab	0.12cd	20.33bcd
Mangifera indica	0.026a	0.012a	0.034abc	0.082ab	0.15abc	22.63ab
Anacardiun occidentale	0.009c	0.003b	0.028bc	0.070b	0.11cd	22.11abc
Jatropha curcas	0.019ab	0.011a	0.042ab	0.102a	0.17a	25.75a
Syzygium gyneense	0.025ab	0.010a	0.043a	0.108a	0.11cd	17.15d
LSD	**0.008**	**0.005**	**0.014**	**0.034**	**0.049**	**4.489**

Table 5: Soil quality evaluation across the study area

Parameters	Max. Score	UPS	ACS	AZI	EUC	MGI	ANO	JTC	SYG
Bulk density (BD)	1	0	0	0	0	0	0	0	0
Soil reaction (pH)	2	2	1	2	1	2	2	2	2
Organic carbon (OC)	2	0	0	0	0	0	0	0	0
Total nitrogen (TN)	2	1	1	1	1	1	1	1	1
Avai. Phosphorus(AP)	2	0	0	0	0	0	0	0	0
Potassium (K)	2	0	0	0	0	0	0	0	0
Magnessium (Mg)	2	0	0	0	0	0	0	0	0
Calcium (Ca)	2	0	0	0	0	0	0	0	0
Total Score	**15**	**3**	**2**	**3**	**2**	**3**	**3**	**3**	**3**
% Score	**100**	**20**	**13**	**20**	**13**	**20**	**20**	**20**	**20**

Unplanted site UPS, Acacia Senegal ACS, Azadirachta indica AZI, Eucalyptus camaldulenses EUC, Mangifera indica ,MGI, Anacardium occidentale ANO, Jatropha curcas JTC, Syzygium gyneense SYG

Table 6: SOC status across the study area

Sites	OC (kg/kg)	Depth (m)	**BD** g/cm^3	SOC (t C/ha)
Unplanted site	0.0030	0.30	1.66	14.94
Acacia Senegal	0.0042	0.30	1.62	20.40
Azadirachta indica	0.0021	0.30	1.59	10.07
Eucalyptus camaldulenses	0.0056	0.30	1.64	27.55
Mangifera indica	0.0033	0.30	1.65	16.34
Anacardiun occidentale	0.0033	0.30	1.63	16.14
Jatropha curcas	0.0054	0.30	1.62	26.24
Syzygium gyneense	0.0040	0.30	1.6 0	19.20