

Date	Submitted	Accepted	Published
	13 th January 2025	7 th April 2025	30 th July 2025

CHANGES IN UPLAND ULTISOLS AMENDED WITH DIGESTATE FORTIFIED BIOCHAR: EFFECTS ON BASIL (*OCIMUM BASILICUM*) GROWTH PERFORMANCE

Zama EF^{1,2*}, Cooke RA¹, Ngwabie NM² and CT Ngwa²



Eric Zama

*Corresponding author email: ezama@illinois.edu

ORCID: <https://orcid.org/0000-0002-6099-5623>

¹Department of Agricultural and Biological Engineering, University of Illinois at Urbana-Champaign, 1304 W Pennsylvania Ave, Urbana, IL 61801, USA

²Department of Agricultural and Environmental Engineering, College of Technology, University of Bamenda, P.O. Box 39, Bamili, Cameroon



ABSTRACT

With an ever-growing world population, sustainable farming practices are critically needed to meet rising food demands. This study explored the use of digestate-fortified biochar, to improve the quality of upland Ultisols (upland degraded soil) and enhance basil (*Ocimum basilicum*) growth. Biochar (BC) was obtained from corncobs, while fortified biochar (MBC) was produced by incubating a 2:1 (w/v) mixture of BC and municipal digestate for 21 days. A slightly acidic upland soil (pH = 6.1) collected from a degraded area of the Western Highlands of Cameroon, was amended with both BC and MBC in a pot experiment at the rate of 1 kg/m² and changes in the physicochemical properties of the soil were assessed. Basil was grown in three pots (that is, pots with soil only (control), pots with soil and pristine biochar amendment (SBC), and pots with soil and fortified biochar amendment (SMBC)). The pots were set up in three replicates and three growth parameters (stem growth rate, leaf surface area, and leaf numbers) of the plant were monitored for 8 weeks. Results indicated that key properties of the soil were remarkably influenced by the addition of fortified biochar. For example, soil pH increased from 6.1 to 7.8, offering a favourable condition for basil growth. The soil became coarser, possibly due to the addition of coarse biochar particles, and soil porosity was enhanced from 66 % to 77% while density reduced from 0.91 to 0.60 g/m³), improving soil aeration and root penetration. The clay content of soil increased slightly from 17.0 to 21.0, likely due to fine biochar particles mimicking clay while organic matter increased substantially, from 8.97 % to 28.3% with MBC addition, reflecting an enhancement in soil fertility. Biochar (BC) addition reduced nitrogen content possibly through immobilization, while MBC boosted nitrogen and phosphorus availability by factors of 1.8 and 1.3, respectively. Additionally, the Cation Exchange Capacity (CEC) increased by a factor of 3.1, with MBC showing superior nutrient retention and soil quality enhancement. These improvements in soil quality, significantly enhanced basil growth ($p < 0.001$), with stem growth rates reaching 1.2 inch/week by week 8. A strong positive correlation was observed between the measured and modelled growth data ($r^2 > 0.98$), highlighting the effectiveness of digestate-fortified biochar as a soil amendment for enhancing soil quality and crop yields, thus supporting sustainable agricultural production.

Key words: Ultisols, digestate-fortified biochar, soil properties, basil plant, growth performance, upland soil

Citation: Zama EF, Cooke RA, Ngwabie NM and CT Ngwa Changes in upland ultisols amended with digestate fortified biochar: effects on basil (*Ocimum basilicum*) growth performance. *Afr. J. Food Agric. Nutr. Dev.* 2025; **25(6)**: 26942-26964 <https://doi.org/10.18697/ajfand.143.25705>



INTRODUCTION

Natural soil fertility across many areas in the world has significantly declined due to increased soil use and land use changes [1,2]. Upland Ultisols are soils that typically have low organic matter, poor soil quality, and are more susceptible to water and nutrient loss [3], yet it is the most important cropland system supporting more than 38% of the global population. Increasing human population with increasing demand for food forces an increase in agricultural activities and exerts greater pressure on these marginal soils. It is estimated that 36 billion tons of soil are being lost every year globally, due to farming, deforestation, and other land use changes [4], and 3.2 billion people, particularly smallholder farmers in rural communities, are directly impacted by land degradation [5].

The largest and most intensively degraded areas in the world are in China (6.3% of land area), Brazil (4.6% of land area) and African Equatorial territories (3.2% of land area). In Cameroon for example, Nguemezi *et al.* [6] attribute declining crop productivity to soil infertility associated with low levels of available phosphorus and heavy rains that increase nutrient leaching. As much as 46.49% of soils with moderate fertility in this region require fertilizer applications and short-term adjustments to promote successful agricultural growth. However, intensive use of chemical fertilizers is known to contribute to soil pollution, which further degrades the environment, producing acute and chronic effects on both plants and animals [7].

Future directions for restoring degraded lands mandate the adoption of recommended sustainable management practices. Achieving productive lands requires a complete reversal of current unsustainable agricultural practices and making sure that restorative actions surpass degradation actions. Approaches could include reducing soil erosion, maintaining good soil carbon and nitrogen levels, increasing the activity and diversity of soil organisms across all sizes, and improving soil structure and pore formation. Conservation agriculture, which accounts for roughly 15.3% of global cropland, has the potential to prevent the loss of over a billion tons of soil annually [4]. In an effort to conserve the soil, small holder farmers in some developing countries practice intercropping and crop rotation, or agroforestry together with intercropping. These farmers typically use a mix of organic manures, such as fowl droppings and inorganic fertilizers, primarily N-P-K (20-10-10) [8]. However, apart from cost and timely availability, one of the difficulties faced by farmers using inorganic fertilizers is the inability for soils to hold the fertilizer in place long enough for plants to absorb. With heavy rains the fertilizer is often leached, causing subsurface and surface water pollution.



Worldwide, interest in the use of biochar for environmental and agricultural improvement has grown significantly [9,10]. The use of biochar in agriculture has been suggested as a promising method to enhance crop productivity due to its ability to retain nutrients and water in soil for prolonged exposure to plants [11]. Biochar's high porosity often accounts, in part, to its ability to retain water and nutrients in soil, long enough for plants to absorb [12]. Biochar therefore reduces the cost involved in irrigation and fertilization by shortening their frequency and intensity [13]. Previous studies have used biochar from many different biomass materials and at different temperatures and sizes to improve on the quality of soils for crop growth. Adding biochar to soil increases its cation exchange capacity (CEC), which helps to reduce nutrient loss through leaching [13,14]. It also increases soil pH which helps in suppressing the activity of enzymes that convert nitrite to nitrous oxide [15]: a process that increases nitrogen availability in the soil.

Although biochar has been tested in many studies and its potential to improve agricultural soil has been largely reported, different soil types and crop species are known to respond differently to biochar incorporation, and this may affect the effectiveness of biochar as a soil amendment. The specific physical and chemical interactions between biochar and upland soil remain inadequately understood, including how biochar influences soil pH, cation exchange capacity (CEC), porosity, density, texture, organic content, and the availability of nutrients over time. Basil (*Ocimum basilicum*) is a widely cultivated herb, tolerant to acidic soils, although challenges such as nutrient deficiencies and aluminum toxicity may affect its growth. Understanding how soil amendments influence basil growth in such conditions is essential for optimizing cultivation practices. This study aimed to examine the key influence of digestate biochar amendment on basil growth in a typical acidic upland soil. Digestate was sourced from a wastewater treatment plant in Bamenda, Cameroon and was used to fortify biochar, and the composite was applied as a soil amendment to improve upland soil properties and enhance basil (*Ocimum basilicum*) growth. It was hypothesized that this combination with digestate would introduce a new dimension of nutrient enrichment and organic matter supplementation beneficial for basil growth in an acidic upland soil.

MATERIALS AND METHODS

Biochar preparation and fortification with digestate

Biochar was made from corncobs in dry pyrolysis using a Thermo Scientific Lindberg/Blue M Moldatherm 1100 °C box furnace. Pyrolysis was done at 550 °C and the temperature of the furnace was raised at 10 °C min⁻¹ and kept at the desired temperature for 4 h. Corncobs were chosen for this study because they constitute a major source of agricultural waste worldwide, making up 12.2% [16] and needing innovative ways of treatment and disposal. Their conversion into biochar, not only



contributes to waste treatment, but also valorises this large agricultural waste product and contributes to environmental sustainability. Pyrolysis was done at 550° C to maximise the concentration of nutrients and enhance properties like the cation exchange capacity (CEC) which is often significantly higher in biochar produced at lower temperatures [17]. The resulting biochar was ground to pass through a 2 mm mesh sieve and labelled BC. Digestate fortified biochar was made from a mixture of pristine biochar (BC) and digestate in a 2:1 (w/v) mixture and aerobically incubated for 21 days (3 weeks) at 28° C in the greenhouse. Digestate was sourced from a municipal wastewater treatment plant in Bamenda, Cameroon. The choice of digestate was hinged on its high nutrient content, organic matter enrichment, and its potential to enhance soil microbial activity, relevant for crop growth. Unlike other organic amendments such as compost or manure, digestate is a by-product of anaerobic digestion, which has undergone a stabilization process while retaining essential nutrients like nitrogen, phosphorus, and potassium in bioavailable forms. The mixture of biochar and digestate was regularly stirred, to ensure maximum interaction between the biochar and digestate. The combination of ratio, temperature and regular stirring was optimally balanced to ensure the biochar-digestate system attained equilibrium within the set time [18]. Samples were drawn from the incubated mixture every week to measure the change in nutrient composition and structure of the biochar as a function of time. After 3 weeks, the incubated biochar, labelled MBC, was dried in an oven at 70 °C for 1 week. It was ground to pass through 2 mm sieve, and stored for further use.

Soil and biochar characterization

Samples of BC and MBC were characterized at the Materials Research Laboratory Central Research Facilities, University of Illinois at Urbana-Champaign, USA. The pH of soil was measured from a suspension of soil and deionized water in the ratio 1:2.5 (w/v) while the pH of biochar was obtained from a 1:10 (w/v) biochar-DI water suspension according to the International Biochar Initiative standard protocol. The mixtures were shaken for 2 h using a BT Lab Systems' Orbital Shaker, and the pH of the filtrates was measured using a Mettler Toledo 320-S pH meter. *Biochar porosity* was determined with the Micromeritics 3Flex Analyzer and SmartVac Degasser. *Particle size* distribution (sand, clay and silt), was determined by the Robinson-Kôhn pipette method while *soil textural classes* were identified using the USDA Textural Triangle based on the proportions of different textural fractions. *Cation Exchange Capacity (CEC)* in both soil and biochar was measured using the ammonium acetate (CH₃COONH₄) method at neutral pH. *Organic carbon* was measured using the Walkley and Black method, where organic carbon is oxidized by potassium dichromate (K₂Cr₂O₇) in an acidic medium (H₂SO₄) [19] and organic matter was estimated by calculating the values of soil organic carbon by 1.724 (van Bemmelen factor). *Available phosphorus* was measured using the Bray II method,



which involves extracting phosphorus in an acidic medium (0.1 N HCl), followed by complexation with ammonium fluoride (0.03 N NH_4F) and aluminium. The *total nitrogen* in biochar was determined by the Kjeldahl method with a Kjeltect system 1002 Distilling Unit [20].

Scanning Electron Microscope (SEM) (Thermo Scientific Axia ChemiSEM) with energy dispersive x-ray spectroscopy (EDS) was used to examine the structure of biochar. The samples were scanned in high vacuum mode at a working distance of 10 mm, an accelerating voltage of 15 kV, and a spot size of 3.0. The EDS analysis helped estimate the elemental composition of the biochar surfaces. To identify existing crystalline species (minerals) on the biochar, *X-ray diffraction (XRD)* analysis was performed using the Bruker D8 Advance Powder X-ray Diffractometer, which operated at a voltage of 40 kV and a current of 40 mA, under $\text{CuK}\alpha$ radiation. Data was collected at 2θ angles ranging from 10° to 80° and interpreted using a database from the International Centre for Diffraction Data [21]. The Thermo Nicolet™ iS50 FTIR Spectrometer was used to scan functional groups composition on the surfaces of biochar over a range of 400 to 4000 cm^{-1} at a resolution of 4 cm^{-1} .

Biochar and the growth performance of basil (*Ocimum basilicum*)

Upland soil, typically with a sandy-loam texture, was collected from the dry areas of the Western Highlands Region of Cameroon. These soils are often high in acidity and prone to erosion. Due to unsustainable farming practices in this area, some portions experience weathering and leaching, particularly on older, higher-elevation landscapes. The area is characterized by two distinct seasons (the dry season and the rainy season) and key crops such as maize, beans, potatoes, plantains, and coffee, are cultivated extensively. Soil was collected from a depth of 30cm. The soil was air-dried at room temperature with regular turning and removal of debris through a 2 mm sieve. Pristine biochar (BC) and digestate-fortified biochar (MBC) were added to the soil at the rate of 1 kg/m^2 and each thoroughly mixed for consistency. The mixtures were each placed in 37.7 litres (40 cm diameter) pots in three replicates and the following experimental set ups were made: (1) pots with no biochar amendment (control), (2) pots with soil and pristine biochar amendment (SBC), and (3) pots with soil and digestate fortified biochar amendment (SMBC). The pots were placed outdoors under natural environmental conditions.

Basil (*Ocimum basilicum*), widely used as herb in cuisines across the world, and known to be fast growing and resistant to most pest and diseases was used in this study. The seeds of this plant were bought from a local farmer's shop and germinated separately by sowing them in well-drained soil. The sown seeds were lightly covered with soil, keeping them moist until germination occurred within 5–8 days. The seedlings were then transplanted into the experimental pots (5 seedlings per pot). Seedlings were transplanted when they were averagely 6 cm tall with at

least two sets of true leaves. The plants were grown for 8 weeks and three non-destructive growth parameters (leaf surface area, stem growth rate, and number of leaves), were measured on a weekly basis. While the Leaf Surface Area (LSA) was measured using the millimeter graph paper method proposed by Pandey & Singh, [22], the Stem Growth Rate (SGR), was calculated from Eqn. 1. Soil samples were collected at the end of the eighth week to measure the impact of the biochar amendment on soil properties.

$$SGR = \frac{S_1 - S_2}{T} \text{-----(1)}$$

where: S1 and S2 = stem lengths for first measurement and second measurements respectively. T = number of days between each measurement.

Statistical analysis and data modelling

Using OriginPro, statistical analysis and data modelling were done mainly on the basil growth data (stem growth rate, leaf surface area and number of leaves). A two-tailed t-test was used to assess significant differences in basil growth on SBC and SMBC compared to those grown on control (soil alone). A significance level (p-value) of less than 0.05 was considered indicative of statistical significance in the growth parameters. Additionally, a sigmoid curve function (Eqn. 2) was used to model the growth data, allowing for a comparative analysis between the observed growth data and modelled data.

$$y = \frac{L}{1 + \exp(-k(x - x_0))} + b \text{-----(2)}$$

where: L = curve's maximum value, k = steepness of the curve, x0 = x-value of the sigmoid midpoint and b = shift parameter (intercept)

RESULTS AND DISCUSSION

Biochar fortification with digestate

Incubating biochar with digestate for 21 days increased available phosphorus from 5.69 mg/kg to 26.9 mg/kg (Table 1), underscoring the phosphorus-enriching effects of the fortification process which turned the biochar into a nutrient carrier. The CEC of fresh biochar increased from 24.0 Me/100g to 43.0 Me/100g (Table 1) after incubation, suggesting an augmentation in the biochar's surface charge which helps to retain essential nutrients like potassium (K⁺), calcium (Ca²⁺), magnesium (Mg²⁺), and ammonium (NH₄⁺) in soil, preventing leaching, and ensuring a steady supply of nutrients to plants [23].



Figure 1: Detail view of (a) BC and (b) MBC pore structure under the scanning electron microscope (SEM) indicating pores filled with digestate after incubation for 21 days

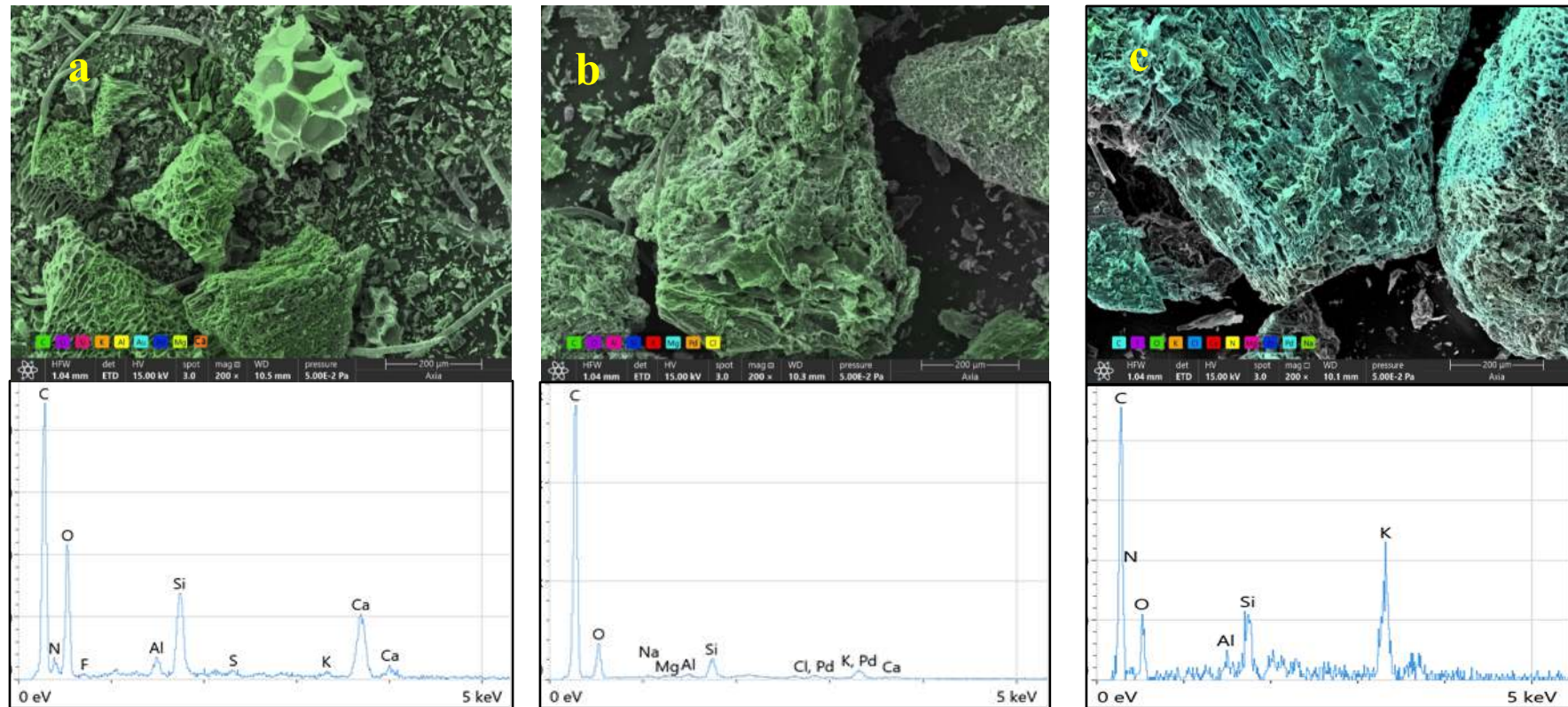


Figure 2: SEM images and EDX spectra of (a) BC, (b) biochar after the first week of incubation (MBC-W1) and (c) biochar after 3 weeks of incubation (MBC-W3) showing the differences in elemental composition as a result of the biochar treatment with digestate. Peak intensity corresponds to the element's relative abundance in the biochar, while the width of each peak corresponds to the energy resolution of the EDX detector

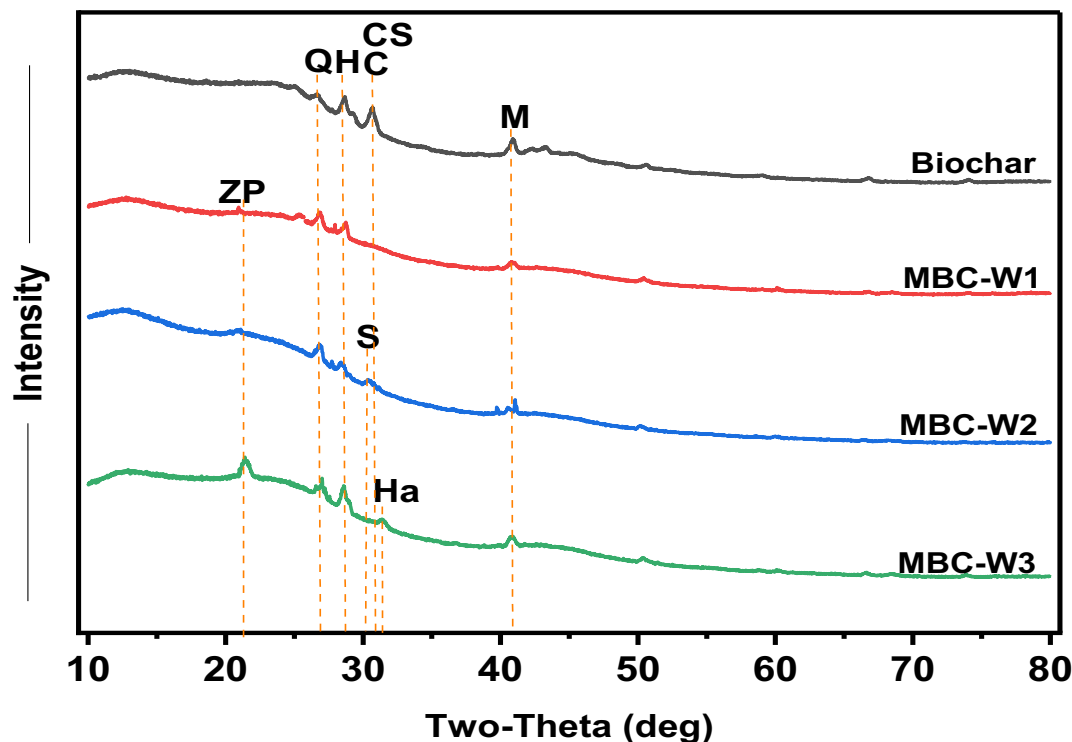


Figure 3: XRD analysis of biochar (BC) and fortified biochar after week 1 (MBC-W1), week 2 (MBC-W2) and week 3 (MBC-W3). Q (quartz), M (magnetite), H (hematite), Ha (Hydroxyapatite), S (struvite), ZP (zinc phosphate), C (calcite), CS (calcium silicate)

Scanning Electron Microscope (SEM) images, open pore biochar became more compact with partially clogged pores after incubation (Fig. 1a and 1b). Clogged pores may have reduced biochar performance due to a reduction in surface area. However, EDX analysis (Figs 2a, 2b, and 2c) confirmed significant nutrient enrichment with strong nitrogen and potassium peaks (Fig. 2c) which may have countered the effects of the clogged pores. Biochar incubation therefore increased its ability to retain and recycle nutrients [24]. Results of the EDX analysis were corroborated by XRD analysis where minerals like corundum, kaolinite, and magnesium carbonate, as well as phosphorus-containing minerals such as hydroxyapatite, struvite, and zinc phosphate, became apparent (Fig. 3) in week 3 of incubation compared to week 1 where only traces of hydrated zinc phosphate ($Zn_3(PO_4)_2 \cdot 4H_2O$) at $2\theta = 25.0^\circ$ could be seen (Fig 3). It could be noticed that Silicon containing minerals were abundant, partly because corncobs have high silicon contents (about 27 - 60%) [25], and extracted silica from corncobs is mostly amorphous which often changes to crystalline when corncobs are pyrolyzed at temperatures greater than 500 °C [26].

Fourier Transform Infrared (FTIR) Spectroscopic analysis equally showed evidence of silicates with Si-O-Si rocking vibrations around 460 cm^{-1} on both BC and MBC (Fig. 4). Such vibrations are often low-frequency vibrations involving a rocking motion of bridged oxygen

atoms perpendicular to the silicate plane [27]. There was a broad peak around 1040 cm^{-1} on MBC (Fig. 4) corresponding to stretching vibrations of asymmetric organophosphates (-P-O-C). This peak, was absent on the fresh biochar, providing further evidence that incubation with digestate enriched the biochar with these vital functional groups. Nitrogen-containing functional groups, such as aromatic nitro alkanes (NO_2), and nitriles ($\text{C}\equiv\text{N}$) were also abundant on the MBC with characteristic asymmetrical bonds stretching around 1530 cm^{-1} and 1550 cm^{-1} . The bond vibrations around 1040 cm^{-1} and 1550 cm^{-1} became more intense on week 3, suggesting that as incubation time increased, there was more interaction between biochar and digestate and more functional groups (including phosphates and nitrates) adsorbed onto the biochar surfaces with potential implications on the adsorption of essential nutrients like phosphates and nitrates [28].

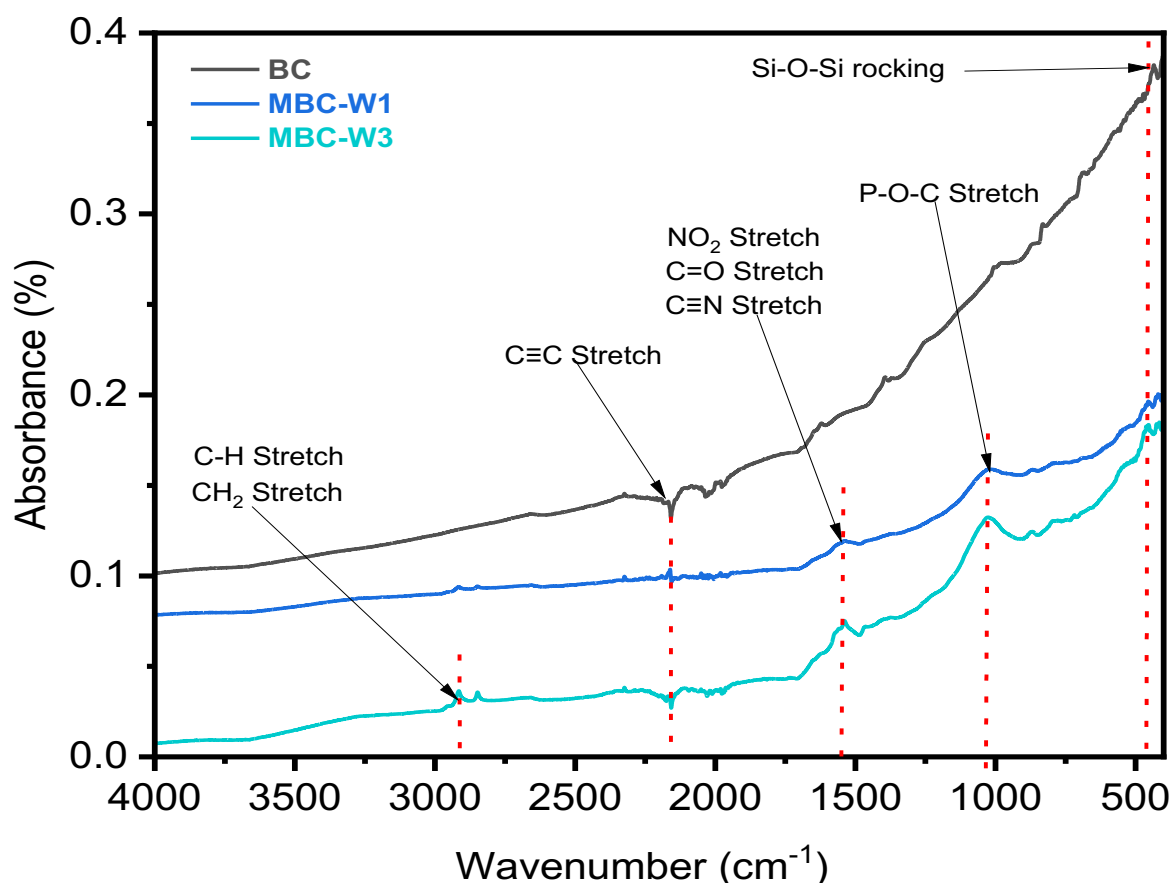


Fig. 4: FTIR patterns of pristine biochar (BC), and fortified biochar after week 1 (MBC-W1) and week 3 (MBC-W3) of incubation indicating the presence and behavior of various functional groups and types of bond vibrations on the biochar

The response of soil properties to biochar addition

Soil pH

The pH of soil increased from 6.1 to 7.9 and 7.8 when BC and MBC were added respectively (Table 2), implying a notable liming effects of the biochar. Despite this increase, the resulting

pH remained within the optimal range for basil growth (6.0 to 8.0), suggesting that the soil conditions remained suitable for the crop.

Changes in soil structure

The upland soil type was mainly sandy loam with up to 69% sand content (Table 2). Sandy loam soils are characteristically well-drained and well-suited for gardening and basil cultivation, especially when soil fertility is enhanced. The addition of biochar appeared to increase the proportion of coarse particles, with measured sand content reaching 75%. This was likely due to the coarse nature of biochar particles, which may have contributed to the perception of increased sand content without actually altering the soil's inherent texture. Similarly, the highest measured clay content (21%) was observed when MBC was added, possibly due to the presence of fine biochar and digestate particles mimicking clay-like behaviour, though they are not true clay minerals. Additionally, the slight decrease in silt content from 14% to 12% could be attributed to increased soil aggregation, where finer particles bind together to form larger aggregates, affecting soil structure rather than texture [29]. Biochar is well known for enhancing soil structure by promoting the formation of stable aggregates, which can help reduce erosion, improve aeration, and facilitate root penetration, ultimately enhancing the physical properties of sandy loam soils [30].

Total Porosity and apparent density

Biochar (BC) and fortified biochar (MBC) exhibited highly porous structures of 90% and 80% respectively, and their incorporation into the soil increased the overall porosity of soil from 66% to 76% and 77%, respectively (Table 2). Previous studies have demonstrated a 2 to 12 % increase in sandy loam soil porosity when corncob biochar was added at the rate of 4% [31] and the total porosity of soil increases proportionately with the amount of biochar added [32]. This notable enhancement in soil porosity and available biochar facilitates better water retention and air penetration in the soil. Sandy soils, known for low water retention, particularly benefit from this enhancement, potentially alleviating water and nutrient scarcity concerns in soils with similar characteristic as upland soils. There was an observed decrease in soil density from 0.91 g/m³ to 0.63 g/m³ and 0.60 g/m³ following the addition of BC and MBC, respectively (Table 2). Similar studies have noted that biochar application generally decreases soil density by at least 16% [33], and up to 31% which aerates the soil and aids water movement, root penetration, and overall plant growth.

Organic carbon (OC) and matter (OM) content

As seen on Table 2, the addition of BC and MBC raised soil organic carbon from 5.2% to 11.9% and 24.6% and the overall organic matter from 8.97% to 15.7% and 28.3% respectively. These results demonstrate that biochar treatment with digestate can enhance soil organic content by up to fourfold, which is crucial for improving soil fertility. Organic carbon, a key component of organic matter, plays a vital role in enhancing soil structure, nutrient retention, and microbial activity, all of which are fundamental for crop growth. Moreover, increased organic matter not only supports soil fertility but also contributes to



carbon sequestration and stimulates beneficial microbial activity, ultimately promoting sustainable soil health [34].

Total nitrogen (N)

Biochar (BC) and fortified biochar (MBC) amendment had contrasting effects on soil nitrogen suggesting distinct influences on the nitrogen dynamics in the upland soil. Biochar (BC) amendment led to a reduction in soil nitrogen from 0.51% to 0.41% indicating a nitrogen immobilization effect while MBC slightly increased soil nitrogen from 0.51% to 0.88%, suggesting that fortified biochar likely contributed additional nitrogen to the soil. A reduction in nitrogen content upon addition of BC may have been caused by biochar's high carbon-to-nitrogen ratio, which can result in a temporary hold-up of nitrogen as microorganisms decompose organic matter. In 2014, Harter *et al.* [35] observed a decrease in NH_4^+ concentration in soil after biochar application, suggesting that this might result from increased NH_4^+ assimilation or its oxidation to NO_3^- . NH_4^+ sorption to the oxygenated carbonyl and carboxyl groups on biochar reduced its availability for nitrification.

Available phosphorus (P)

Biochar (BC) and fortified biochar (MBC) amendments increased soil available phosphorus from 59.1 mg/kg to 110 mg/kg and 74 mg/kg respectively (Table 2). Previous reports found that applying coffee husk biochar produced at 500°C at a rate of 15 t ha⁻¹ led to an 84.3% boost in available phosphorus [36]. However, available P was unexpectedly lower in MBC amendment compared to BC amendment possibly because of the presence of organic compounds in digestate which can bind phosphorus, making it less available in the short term, and the presence of ammonium or other cations in the digestate which might cause phosphorus to precipitate as a less soluble compound, reducing its immediate availability.

Cation exchange capacity (CEC)

The Cation Exchange Capacity (CEC) of soil is a key determinant of the soil's quality as it measures the soil's ability to retain and exchange nutrients. When soil was amended with BC and MBC, there was a remarkable enhancement in the soil's CEC increasing from 16.4 Me/100g to 22.3 Me/100g and 50.7 Me/100g respectively (Table 2). The elevated CEC is beneficial for nutrient retention, availability, and exchange in a typical sandy loam soil such as the one used in this study, highlighting the potential of MBC as a valuable soil amendment. Elsewhere, soil amendments with biochar at rates greater than 10 t ha⁻¹ produced similar effect [37].



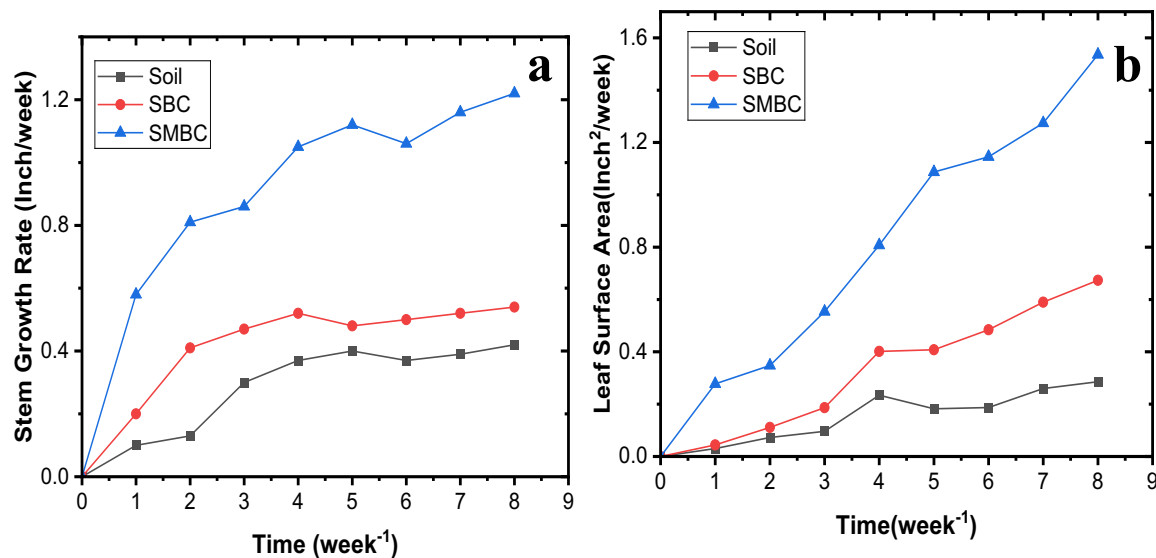


Figure 5: Influence of BC and MBC on the growth performance of basil (*Ocimum basilicum*). Soil was the control substrate. (a) stem growth rate and (b) leaf surface area were used to measure the growth

Effects of BC and MBC on the growth performance of basil

Plants were grown on three media (unamended soil, BC amended soil and MBC amended soil) and the stem growth rate (SGR), leaf surface area (LSA) and number of leaves (NL) were the non-destructive growth parameters used to assess the influence of biochar on basil growth. Compared to unamended soil (with SGR of 0.31 inch/week), plants grown on BC amended soil (SBC) and MBC amended soil (SMBC) showed significantly ($p < 0.001$) higher growth rates (reaching 0.46 and 0.99 inch/week, respectively) (Fig. 5a). Similarly, a t-test revealed a significant difference (p -value = 0.03) in the LSA of plants grown on SMBC and those grown on unamended soil, whereas no significant difference (p -value = 0.07) was observed for those grown on SBC compared to unamended soil. The superior performance of SBC and SMBC may have been influenced by increases in organic matter, available phosphorus and total nitrogen following the addition of biochar. High CEC in MBC influenced nutrient uptake and water retention in the amended soils fostering optimal conditions for basil growth.

Growth rates were significantly higher during the first two weeks across all three media (Fig. 5), likely due to the initial abundance of nutrients and readily available exchangeable bases. However, by weeks 7 and 8, growth rates declined as nutrient availability diminished. This underscores the role of biochar in nutrient retention and supply. In a similar study, active exchangeable bases doubled when biochar was applied at rates of 2% and 3%, leading to substantial increases in plant height (38% and 48%), leaf length (15% and 24%), leaf number (15% and 27%), and leaf width (36% and 50%), respectively [38].

Unlike the SGR and LSA, the number of leaves (NL) showed no significant difference (p -value = 0.28) between the plants grown on the three media. This was probably because measurements were done on a weekly basis and it took averagely 8 days for new leaves to



fully develop on the basil plants. Fig. 6 shows the average number of leaves developed by the plants within the eight weeks of growth.

Modelling the growth of basil

Modelling the basil plant growth data using a sigmoid function (Eqn. 2) revealed a characteristic "S-shaped" growth pattern particularly for the stem growth rate (Fig. 7). This growth pattern indicated that the growth rate starts slowly, accelerates rapidly around the midpoint of week 2, and then levels off as it approaches the maximum growth rate. The fitted curves closely align with the observed data. The growth pattern for LSA and NL did not typically follow the characteristic "S-shaped" model compared to the SGR. This was normal given that growth parameters such as SGR, LSA, and NL are driven by the distinct biological processes underlying each growth parameter [39,40]. For a plant like basil, each parameter has unique growth dynamics, environmental responses, physiological stages, and resource allocation strategies, leading to varied growth patterns that are captured by their respective sigmoid curves. These findings provide a clear understanding of the growth dynamics of basil and can inform optimal cultivation practices for maximizing basil plant development.



Figure 6: Number of leaves was used as another parameter to measure basil growth performance under the influenced of BC and MBC. Soil was the control substrate

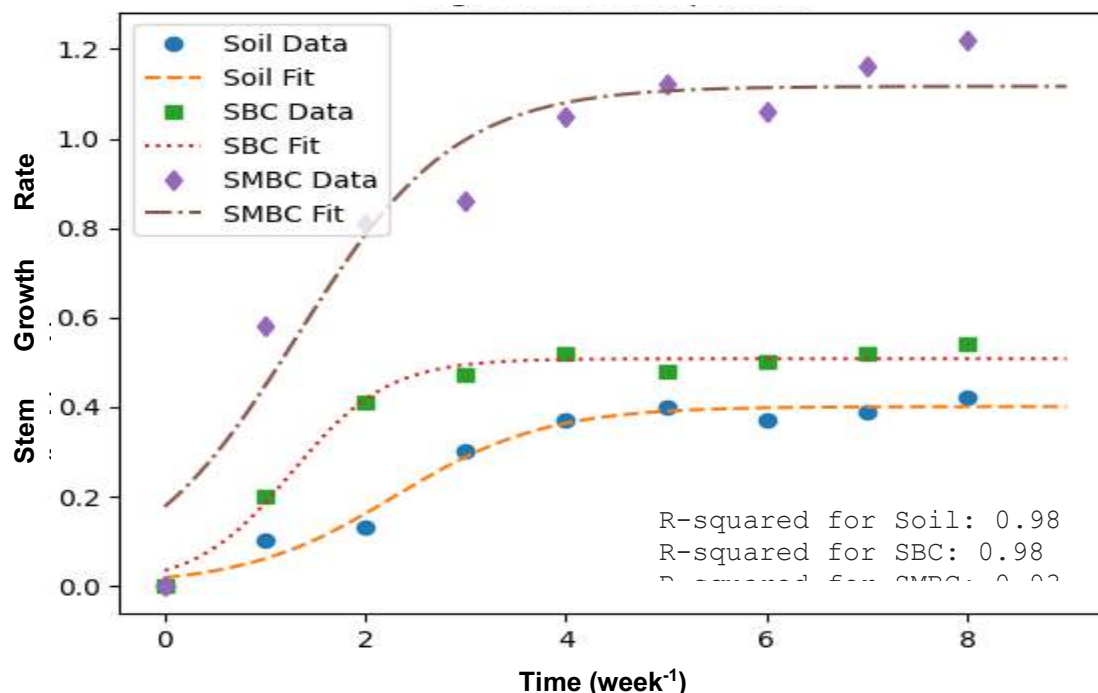


Figure 7: Sigmoid curves, used to model the basil plant growth data. The plots visualize both the data and the fitted curves, enabling a clear comparison between observed and modelled growth

CONCLUSION AND RECOMMENDATIONS FOR DEVELOPMENT

This study demonstrated the potential of digestate-fortified biochar to ameliorate key properties of upland soils, resulting in enhanced soil fertility and increased basil growth. The superior performance of digestate-fortified corncob biochar in improving soil quality was likely due to the additional nutrients and organic matter introduced by the digestate and availability of exchangeable bases and suitable pH. The increased soil organic matter, not only has potential benefits for soil fertility improvement, but also enhances carbon sequestration, and improves soil microbial activity. Improved soil aggregation, increased organic matter, and increases available phosphorus and total nitrogen played central roles in the superior performance of MBC. An improvement in the CEC of fortified biochar positively affected nutrient uptake and water retention in biochar-amended soils fostering optimal conditions for basil growth. Fitting a sigmoid function to the plant growth data, helped with valuable insights into the growth dynamics of the basil plant. Findings from this study provided insights into a sustainable agricultural technology that can enhance soil quality and crop productivity in the long run, with broader positive implications on global food security.

Funding information

This research was supported in part by the intramural research program of the U.S. Department of Agriculture, National Institute of Food and Agriculture, Hatch (accession



number: 7005794). The work was also equally supported in part by the International Institute of Education, Scholar Rescue Fund (IIE-SRF).

ACKNOWLEDGEMENTS

Data analysis was carried out in part in the Materials Research Laboratory Central Research Facilities, University of Illinois at Urbana-Champaign, USA.

Conflict of Interest

The authors declare no conflict of interest



Table 1: Physicochemical properties of the digestate, pristine biochar (BC), and fortified biochar (MBC)

Material	Organic Materials (%)		Nutrients content			CEC (me/100 g)	pH	Apparent Density (g/cm ³)	Total Porosity (%)
	OC	OM	Total N (%)	C/N	Available P (mg/kg)				
Digestate	37.3	64.9	2.39	12	102	39.8	7.3	0.92	
BC	42.4	80.8	1.46	29.0	5.69	24.0	9.20	0.26	90.0
MBC	44.7	89.3	2.54	18.0	26.9	43.0	9.10	0.35	80.0



Table 2: Physicochemical properties of the soil, and its amendments (pristine biochar amended soil (SBC) and digestate-fortified biochar amended soil (SMBC))

Material	Texture (%)				Organic Materials (%)		Nutrients content			CEC (me/100 g)	pH	Apparent Density (g/cm ³)	Total Porosity (%)
	Clay	Silt	Sand	Textural class	OC	OM	Total N (%)	C/N	Available P (mg/kg)				
SOIL	17.0	14.0	69.0	Sandy loam	5.20	8.97	0.51	10.0	59.1	16.4	6.10	0.91	66.0
SBC	13.0	12.0	75.0	Sandy loam	11.9	15.7	0.41	22.0	110	22.3	7.90	0.63	76.0
SMBC	21.0	12.0	67.0	Sandy clay loam	24.6	28.3	0.88	20.0	74.0	50.7	7.80	0.60	77.0



REFERENCES

1. **Willy D K, Muyanga M, Mbuvi J and T Jayne** The effect of land use change on soil fertility parameters in densely populated areas of Kenya. *Geoderma*, 2019; **343**: 254-262.
2. **Reynolds JF, Smith DMS, Lambin EF, Turner BL, Mortimore M, Batterbury SP, Downing TE, Dowlatabadi H, Fernández RJ, Herrick JE, Huber-Sannwald E and B Walker** Global desertification: building a science for dryland development. *Science* 2007; **316(5826)**: 847-851.
3. **Adeli A, Brooks JP, Read JJ, Feng G, Miles D, Shankle MW, Barksdale N and JN Jenkins** Management strategies on an upland soil for improving soil properties. *Communications in Soil Science and Plant Analysis*. 2020; **51(3)**: 413-429.
4. **Borrelli P, Robinson DA, Fleischer LR, Lugato E, Ballabio C, Alewell C, Meusburger K, Modugno S, Schütt B, Ferro V and V Bagarello** An assessment of the global impact of 21st-century land use change on soil erosion. *Nature Communications*. 2017; **8(1)**: 1-13.
5. **Berry L, Olson J and L Boukerrou** Resource mobilization and the status of funding of activities related to land degradation. Florida Center for Environmental Studies, paper commissioned by Global Mechanism with support from the GEF 2006.
6. **Nguemezi C, Tematio P, Yemefack M, Tsozue D and TB Silatsa** Soil quality and soil fertility status in major soil groups at the Tombel area, South-West Cameroon. *Heliyon*. 2020; **6(2)**.
7. **Nadarajan S and S Sukumaran** Chemistry and toxicology behind chemical fertilizers. In: *Controlled Release fertilizers for Sustainable Agriculture*. 2021; 195-229.
8. **Nkengafac NJ, Nkempi L, Mubeteneh TC, Herman DN and NE Forghab.** Soil fertility management practices by smallholder farmers in the Bamboutos mountain ecosystem. *World*. 2021; **9(2)**: 58-64.
9. **Bano A, Aziz MK, Prasad B, Ravi R, Shah MP, Lins PV, Meili L and KS Prasad** The multifaceted power of biochar: A review on its role in pollution control, sustainable agriculture, and circular economy. *Environmental Chemistry and Ecotoxicology*. 2025; **7**: 286-304.



10. **Afshar M and S Mofatteh** Biochar for a sustainable future: Environmentally friendly production and diverse applications. *Results in Engineering*. 2024; **23**:102433.
11. **Tsai CC and YF Chang** Poultry litter biochar as a gentle soil amendment in multi-contaminated soil: quality evaluation on nutrient preservation and contaminant immobilization. *Agronomy*. 2022; **12(2)**: 405.
12. **Glaser B, Lehmann J and W Zech** Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—a review. *Biology and fertility of soils*. 2002; **35**: 219-30.
13. **Ama G** Phosphorus fertilizing Potential of Biochar derived from agricultural residues: A review. *J. Environ. Res*. 2021; **5**:1-5.
14. **Lehmann J** Bio-energy in the black. *Frontiers in Ecology and the Environment*. 2007; **5(7)**: 381-7.
15. **Zhang R, Zhong Z and Y Huang** Combustion characteristics and kinetics of bio-oil. *Frontiers of Chemical Engineering in China*. 2009; **3**: 119-24.
16. **Castorina G, Cappa C, Negrini N, Criscuoli F, Casiraghi MC, Marti A, Rollini M, Consonni G and D Erba** Characterization and nutritional valorization of agricultural waste corncobs from Italian maize landraces through the growth of medicinal mushrooms. *Scientific Reports*. 2023; **13(1)**: 21148.
17. **Gaskin J, Steiner C, Harris K, Das KC and B Bibens** Effect of low-temperature pyrolysis conditions on biochar for agricultural use. *Transactions of the ASABE*. 2008; **51(6)**: 2061-9.
18. **Viaene J, Peiren N, Vandamme D, Lataf A, Cuypers A, Debeer L and B Vandecasteele** Application of biochar to anaerobic digestion versus digestate: Effects on N emissions and C stability. *Science of the Total Environment*. 2024; **915**: 170124.
19. **Gelman F, Binstock R and L Halicz** Application of the Walkley–Black titration for the organic carbon quantification in organic-rich sedimentary rocks. *Fuel*. 2012; **96**: 608-10.
20. **Kirk PL** Kjeldahl method for total nitrogen. *Analytical chemistry*. 1950; **22(2)**:354-8.
21. **International Centre for Diffraction Data** PDF Card No. 01-089-7717. <https://www.icdd.com> Assessed 20th December 2024.

22. **Pandey SK and H Singh** A simple, cost-effective method for leaf area estimation. *Journal of botany*. 2011; **2011(1)**: 658240.
23. **Hailegnaw NS, Mercl F, Pračke K, Száková J and P Tlustoš** Mutual relationships of biochar and soil pH, CEC, and exchangeable base cations in a model laboratory experiment. *Journal of Soils and Sediments*. 2019; **19**: 2405-16.
24. **Wang C, Luo D, Zhang X, Huang R, Cao Y, Liu G, Zhang Y and H Wang** Biochar-based slow-release of fertilizers for sustainable agriculture: A mini review. *Environmental Science and Ecotechnology*. 2022; **10**: 100167.
25. **Sarkar J, Mridha D, Sarkar J, Orasugh JT, Gangopadhyay B, Chattopadhyay D, Roychowdhury T and K Acharya** Synthesis of nanosilica from agricultural wastes and its multifaceted applications: A review. *Biocatalysis and Agricultural Biotechnology*. 2021; **37**: 102175.
26. **Taherymoosavi S, Verheyen V, Munroe P, Joseph S and A Reynolds** Characterization of organic compounds in biochars derived from municipal solid waste. *Waste Management*. 2017; **67**: 131-42.
27. **Fidalgo A and LM Ilharco** The defect structure of sol-gel-derived silica/polytetrahydrofuran hybrid films by FTIR. *Journal of Non-Crystalline Solids*. 2001; **283(1-3)**: 144-54.
28. **Macedo JC, Gontijo ES, Herrera SG, Rangel EC, Komatsu D, Landers R and AH Rosa** Organosulphur-modified biochar: an effective green adsorbent for removing metal species in aquatic systems. *Surfaces and interfaces*. 2021; **22**: 100822.
29. **Pastorelli R, Casagli A, Rocchi F, Tampio E, Laaksonen I, Becagli C and A Lagomarsino** Effects of Anaerobic Digestates and Biochar Amendments on Soil Health, Greenhouse Gas Emissions, and Microbial Communities: A Mesocosm Study. *Applied Sciences*. 2024; **14(5)**: 1917.
30. **Hammerschmiedt T, Holatko J, Sudoma M, Kintl A, Vopravil J, Ryant P, Skarpa P, Radziemska M, Latal O and M Brtnicky** Biochar and sulphur enriched digestate: Utilization of agriculture associated waste products for improved soil carbon and nitrogen content, microbial activity, and plant growth. *Agronomy*. 2021; **11(10)**: 2041.
31. **Obia A, Mulder J, Hale SE, Nurida NL and G Cornelissen** The potential of biochar in improving drainage, aeration and maize yields in heavy clay soils. *PLoS One*. 2018; **13(5)**: e0196794.

32. **Liu D, Feng Z, Zhu H, Yu L, Yang K, Yu S, Zhang Y and W Guo** Effects of Corn Straw Biochar Application on Soybean Growth and Alkaline Soil Properties. *BioResources*. 2020; **15**(1).
33. **Walters RD and JG White** Biochar in situ decreased bulk density and improved soil-water relations and indicators in Southeastern US Coastal Plain Ultisols. *Soil Science*. 2018; **183**(3): 99-111.
34. **Shenbagavalli S and S Mahimairaja** Characterization and effect of biochar on nitrogen and carbon dynamics in soil. *International Journal of Advanced Biological Research*. 2012; **2**(2): 249-55.
35. **Harter J, Krause HM, Schuettler S, Ruser R, Fromme M, Scholten T, Kappler A and S Behrens** Linking N₂O emissions from biochar-amended soil to the structure and function of the N-cycling microbial community. *The ISME Journal*. 2014; **8**(3): 660-74.
36. **Bayu D, Dejene A, Alemayehu R and B Gezahegn** Improving available phosphorus in acidic soil using biochar. *Journal of Soil Science and Environmental Management*. 2017; **8**(4): 87-94.
37. **Van Zwieten L, Kimber S, Morris S, Chan KY, Downie A, Rust J, Joseph S and A Cowie** Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and soil*. 2010; **327**: 235-46.
38. **Jaborova D, Ma H, Bellingrath-Kimura SD and S Wirth** Impacts of biochar on basil (*Ocimum basilicum*) growth, root morphological traits, plant biochemical and physiological properties and soil enzymatic activities. *Scientia Horticulturae*. 2021; **290**: 110518.
39. **Li X, Schmid B, Wang F and CT Paine** Net assimilation rate determines the growth rates of 14 species of subtropical forest trees. *PLoS one*. 2016; **11**(3): e0150644.
40. **Larsen DH, Woltering EJ, Nicole CC and LF Marcelis** Response of basil growth and morphology to light intensity and spectrum in a vertical farm. *Frontiers in Plant Science*. 2020; **11**: 597906.

