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The effect of pyrolysis conditions on the quality of biochar produced from beans shaft applied as an enhancer for beans plant growth

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Abstract

Biochar has emerged as an innovative material with promising applications in soil remediation, carbon sequestration, and sustainable agriculture. Derived from the thermal decomposition of biomass under oxygen-limited conditions, biochar's properties are highly dependent on the conditions under which it is produced. This article investigates the influence of pyrolysis conditions on the quality of biochar produced from beans shaft, a readily available agricultural residue and the possible effect of these conditions on enhancing plant growth. Biochar from beans shaft was pyrolysed at different temperatures of 350 °C, 500 °C and 700 °C and at different reaction times of 40 min and 80 min. The effect of these pyrolysis conditions was assessed by carrying out elemental and structural analysis of the produced biochar. The results reveal that the biochar produced at 350 °C and 40 min retained reactive functional groups that made it a viable and effective tool for enhancing plant growth. Further results showed that at higher temperatures (above 350 °C), the pore size of biochar increased which makes biochar well-suited for soil bioremediation. However, specifically for plant growth, producing biochar at low temperatures and short reaction times produced the best result. This study provides clear evidence that biochar quality is highly sensitive to pyrolysis conditions. Also, careful control of pyrolysis conditions is essential to produce biochar with tailored properties for specific applications.

Keywords: Pyrolysis; Beanshaft; Biochar quality; Plant growth rate; Beans; Soil bioremediation

1. Introduction

Recently, environmental sustainability has become a global challenge as a result of the negative impact of industrialization, urban development and intensive agriculture. The aforementioned activities have led to degradation and contamination of the soil. Soils contaminated with toxic chemicals, heavy metals, pesticides, and herbicides threaten ecosystem stability, public health and agricultural productivity. Consequently, different soil remediation techniques have been adopted to improve soil quality [1, 2]. However, the traditional soil remediation techniques are expensive, disruptive and lack long-term sustainability [3]. Against this backdrop, biochar has garnered attention as a low-cost and eco-friendly option with the potential to remediate contaminated soils and improve soil fertility.

Biochar is produced through the thermal decomposition of biomass in limited oxygen, a process termed pyrolysis. One of the abundant and readily available biomass source used for the production of biochar are agricultural residues. In Nigeria, a tropical rainforest area in sub-Saharan Africa, beans shaft, a by-product of beans processing is a widely available agricultural residue [4]. Beans shaft is characterized by a balance of organic carbon, essential nutrients (such as nitrogen, phosphorus, and potassium), and lignocellulosic materials which makes it particularly suitable for conversion into biochar. When subjected to pyrolysis, the beans shaft transforms into a carbon-rich material with enhanced adsorptive properties and a porous structure, ideal for immobilizing contaminants in soil. Moreover, utilizing

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beans shaft not only mitigates waste disposal issues but also aligns with the principles of the circular economy by transforming an agricultural byproduct into a valuable resource.

Despite the wide use of biochar in environmental sustainability through carbon sequestration, being a bioremediation agent, adsorbent, biofilter and agricultural enhancer among other uses, its effectiveness is a function of its physicochemical properties [5] including functional group abundance, surface area, elemental composition and porosity. These properties are directly linked to the operating conditions used during pyrolysis. For example, temperature, residence time, and heating rate can influence the extent of carbonization, the development of aromatic structures, and the retention or loss of reactive functional groups on the biochar surface. Understanding these relationships is critical for tailoring biochar to specific remediation tasks, such as immobilizing heavy metals in contaminated soils or adsorbing organic pollutants.

Although there have been studies centred on studying the effect of pyrolysis conditions on the quality or physicochemical properties of biochar applied for different purposes [6-9], studies centred on the effect of these conditions on the quality of biochar produced as a soil amendment agent is limited [10], and their direct effect on the growth rate of plant especially beans is lacking. Hence, this study aims to elucidate the effects of different pyrolysis conditions on the quality of biochar derived from beans shaft and to assess its potential for direct support of plant growth. More specifically, the study aims to:

Study the effect of pyrolysis temperature variation and residence time on the surface area, porosity, chemical composition, and functional group retention of biochar.

Study the effectiveness of biochar produced under the above varying conditions on plant growth.

Optimizing biochar production from readily available agricultural residues such as beans shaft offers a promising alternative that can help restore soil health, improve water retention, and support beneficial microbial activity while sequestering carbon and mitigating climate change.

2. Materials and Methods

2.1. Materials

Two bags of beans shaft were sourced from local markets in Epe and Ibadan, Nigeria.

2.2. Preparation of beans shaft

The beans shaft was initially weighed and air-dried until a constant weight was achieved. This is to reduce the moisture content of the beans shaft. It took 5 days to dry the beans shaft to constant weight. The dried beans shaft was then ground into smaller particle sizes using a commercial grinding machine. The reduction in particle size ensured a more homogeneous feedstock, which is critical for consistent pyrolysis and optimal heat penetration.

2.3. Pyrolysis procedure

250 g of beans shaft was placed into initially weighed stainless steel containers. These containers ensured thermal stability during the heating process. The weighed beans shaft were then pyrolysed in a muffle furnace at specific temperatures ranging from 350 °C to 700 °C and times 40-80 min. These temperature variations were selected based on prior studies to explore their effects on biochar production. The furnace was preheated to the desired temperatures before placing the different samples. At the end of the pyrolysis time, the biochar samples were immediately transferred to a desiccator to prevent the biochar from absorbing moisture. The samples were then weighed after it was cooled in the desiccator.

2.4. Analytical Methods

After pyrolysis, the biochar samples were analysed to characterize their physicochemical properties. The following analyses were carried out:

2.4.1. Beans shaft proximate analysis:

To characterize the beans shaft used for pyrolysis, the following proximate analysis was carried out at the Laboratory of the University of Lagos, Nigeria, according to established methods in literature: moisture content, ash content, total fatty acid, crude fibre, nitrogen, crude protein, and carbohydrate content analysis.

Moisture content determination:

1 g of the beans shaft was weighed in a clean beaker (W_1), placed in an oven and dried to a constant weight for about 2 hr at 105 ^{0}C. After drying, the beaker was then placed in a desiccator and reweighed (W_2) after it cooled down. The percentage moisture content was then calculated using Equation 1.

$$\% \text{ Moisture Content } = \frac{W_1 - W_2}{1\ g} \text{ X } 100 \ \ldots\ldots\ldots (1)$$

Ash content determination

An empty crucible was weighed and 2 g of the beans shaft was weighed into it and reweighed as W_3. The crucible was placed in a muffle furnace at 450 ^{0}C for 4 hr after which it was removed from the furnace and placed in a desiccator and reweighed as (W_4). The ash content was then calculated using Equation 2.

$$\% \text{ Ash Content } = \frac{W_3 - W_4}{2\ g} \text{ X } 100 \ldots\ldots\ldots\ldots (2)$$

Fatty acid content determination:

To determine the fatty acid content, the oil was extracted using diethyl ether and quantified after flash evaporation. 2-3 g of the beans shaft was put into a 250 ml beaker, 50 ml of distilled water was added and placed in a hot steam bath for 30 min. The beaker was removed and its content was separated using a 250 ml separating funnel. 50 ml of 95% diethyl ether was then used to separate the oil from the mixture in the ratio 25:15. 10 ml of the extract was weighed W_5, into a clean beaker. The oil was then flashed off in an oven at 45 ^{0}C, and the weight of the beaker W_6 was taken. The fatty acid content was then calculated using Equation 3.

$$\% \text{ Oil Content } = \frac{W_5 - W_6}{weight\ of\ extract} \text{ X } 100 \ldots\ldots\ldots\ldots (3)$$

Crude fiber determination:

1 g of beans shaft was weighed into a beaker. 50 ml of 1.5 $^w/_v$% sulfuric acid was added and made up to 100 ml by adding water. The content was stirred and allowed to stand for 30 min. The mixture was decanted and 50 ml of 1.5 $^w/_v$% NaOH was added, water was added to make up 100 ml, it was then stirred and allowed to stand for 30 min. The mixture was then filtered into a pre-weighed crucible W_7 and placed into the oven for 1 h at 105 ^{0}C until a constant weight W_8 is achieved. The percentage of crude fiber was then determined using Equation 4.

$$\% \text{ Crude fiber } = \frac{W_7 - W_8}{weight\ of\ sample} \text{ X } 100 \qquad \ldots\ldots\ldots (4)$$

Nitrogen and crude protein determination

This involves three stages, which are digestion, distillation and titration.

- *Digestion Stage*

0.2 g of beans shaft was weighed into a filter paper and gently transferred into a round bottom Kjeldahl flask. 25 ml of concentrated H_2SO_4 was added. 0.3 g of Kjeldahl tablet ($CuSO_4$ + Na_2SO_4 (1:1)) was added to the solution. The mixture was then digested for 1 hr until a clear colourless solution was obtained. This was then made up to 100ml with distilled water in a standard flask.

- *Distillation Stage*

10 ml of the aliquot (digest) was pipetted into a 250 ml distil flask, 50% NaOH was added, and an anti-bumping agent was also added. In another flask, 50 ml of boric acid was prepared and a screen methyl red indicator was added. The distillation was set up with the outlet of the tube inserted into the conical flask containing the boric acid for the collection of NH_3 through the condenser. As the nitrogen gas was being given off as NH_3, the colour changed from red to green.

- *Titration Stage*

The distillate was titrated with 0.1 M HCl and the percentage nitrogen content was obtained using Equation 5. The percentage of crude protein was calculated using Equation 6.

$$\% \text{ nitrogen } = \frac{\text{Tvx0.1 Mx0.00014}}{weight\ of\ sample} \text{ X } 100 \qquad \ldots\ldots \quad (5)$$

Tv = titer value

$$\% \text{ Crude protein} = \% \text{ nitrogen X } 6.25 \qquad \ldots\ldots (6)$$

Determination of carbohydrate

The sum of all earlier determined proximate parameters was obtained and deducted from 100% to give the percentage carbohydrate composition.

2.4.2. Elemental and structural analysis of beans shaft and biochar samples

To gain a better insight into the effect of pyrolysis on each elemental constituent of the beans shaft before and after pyrolysis, the elemental analysis of the beans shaft was carried out using Energy Dispersive X-ray Spectroscopy (EDS) before pyrolysis. Also, the produced biochar samples at different pyrolysis conditions were analysed using Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM) and EDS for their structural and elemental composition to determine the effect of these pyrolysis conditions on the quality of the produced biochar samples.

FTIR analysis

FTIR analysis was carried out at the University of Lagos using FTIR-model Cary 630 by Agilent Technologies USA. Infrared spectroscopy is a non-destructive technique used to analyze materials by studying their interaction with infrared radiation. It provides information about the molecular structure and chemical bonding of a sample, allowing for qualitative and quantitative analysis. The infrared spectrum is unique to each material, making it a valuable tool for identification and concentration determination. By measuring the absorbed frequencies, the spectrum was used to identify functional groups and compounds, as well as impurities and their bonding with the produced biochar.

SEM and EDS analysis

SEM and EDS analysis of the biochar was carried out at the University of Lagos. SEM is a technique used to visualize the surface structure of materials at high magnifications by using a focused electron beam to scan across the sample and detect the signals it produces. EDS was used to identify and map the elements present in the sample. Together, SEM and EDS provide a powerful tool for analyzing both the surface morphology and elemental composition of materials.

2.5. Plant cultivation

To study the effect of the pyrolysis conditions of biochar on the beans plant growth rate, the biochar samples with the best qualities obtained from the elemental, structural and porosity analyses, were used to cultivate bean seeds. The seeds were planted in small disposable cups under direct sunlight and taken indoors at night. The initial weight of the disposable cups was obtained after which soil of a constant weight of 150 g was added to each of the cups. Samples of different biochars were added to soil in the cups in the ratio of 1:10 after which the mixture was thoroughly stirred and 3 bean seeds were carefully planted in the cups. The cups were punctured at different points to allow water drainage. The plants were watered daily and the effect of biochar quality on plant growth rate was monitored by measuring the height of the plants and the number of leaves and sprouts daily.

3. Results and discussion

The proximate and elemental analyses of the beans shaft, FTIR spectra, SEM imaging, and EDS data of the biochar samples collectively illustrate the influence of pyrolysis conditions on the quality of biochar produced from beans shaft and are presented in this section. The effect of these qualities on plant growth rate is also presented in this section.

3.1. Proximate composition of beans shaft

The result of the proximate analysis of the beans shaft is presented in Table 1. The results show that beans shaft has a promising potential for use in biochar production for soil remediation. The low moisture content (6.2% and 6.4% in samples 1 and 2) indicates that the beans peel is fairly dry, which reduces the energy required for drying during pyrolysis, making the process more efficient. The ash content (3.42% and 3.40%) is relatively low, suggesting a good proportion of organic matter available for conversion into biochar, while still contributing essential minerals to the biochar for soil fertility. The total fatty acid content (1.22%) is also low, minimizing the risk of excess volatile emissions during pyrolysis and resulting in more stable biochar.

Table 1 Proximate analysis of beans shaft

Beans shaft	Sample 1	Sample 2
Parameters	1	2
% Moisture Content	6.2	6.4
% Ash Content	3.42	3.40
% Total Fatty Acid	1.22	1.22
% Crude Fiber	2.56	2.58
% Nitrogen Content	3.66	3.64
% Crude Protein	22.88	22.75
% Carbohydrate	63.72	63.65

3.2. The effect of pyrolysis conditions on biochar yield

The result of the yield of biochar produced from beans shaft is presented in Fig.1. The percentage yield of biochar reduces as the temperature and time increase. This is in line with the work of Sun, He [11] who reported a reduction in the yield of biochar from different sources at low temperatures. This might be due to the loss of volatile organic compounds as the temperature increases as justified by the FTIR results in section 3.4.

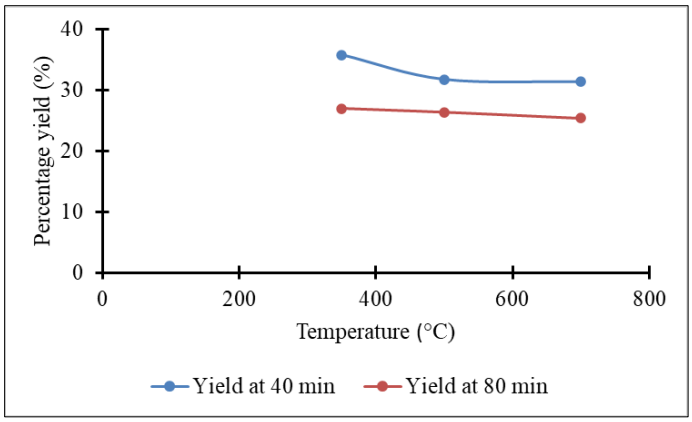

Figure 1 Biochar production result

3.3. Effect of pyrolysis conditions on the elemental composition of the biochar samples

The elemental analysis of these six biochar samples (Table 2) reveals a lot about their potential use in environmental applications, especially for remediating pesticide-contaminated soils. The high carbon content in all samples (60.08% to 72.00%) makes them excellent candidates for stabilizing and trapping harmful organic compounds, including

pesticides, in the soil. Biochar's porous structure, largely due to its high carbon content, acts like a sponge, absorbing and immobilizing pesticides, preventing them from leaching into groundwater and further contaminating the environment.

Oxygen levels in the biochar samples, ranging from 7.20% to 20.25%, suggest the presence of reactive functional groups on the biochar surface. These oxygenated groups enhance the biochar's ability to adsorb toxic substances, including pesticides, by providing more binding sites. This means biochar with higher oxygen content, like samples B and E, may be more effective at capturing and neutralizing pesticides than those with lower oxygen levels.

Phosphorus, found in moderate amounts (5.22% to 12.22%), doesn't directly impact pesticide remediation, but it can improve soil fertility, which is important for restoring plant life in contaminated areas. Once the soil is remediated, the phosphorus-rich biochar can help rejuvenate it, promoting healthier, more resilient crops.

Other elements like magnesium, calcium, and trace amounts of iron, silicon, and copper also contribute to the biochar's remediation potential. Magnesium and calcium improve the structure and pH of the soil, making it more hospitable for beneficial microbes that can help break down pesticides. Silicon, which supports plant disease resistance, could also indirectly benefit the soil remediation process by promoting healthier plants that can thrive in the restored soil.

Although there was no regular trend in the elemental composition of these samples, the high carbon and oxygen content in these biochar samples makes them highly effective for absorbing and stabilizing pesticides in contaminated soils. Samples with higher oxygen levels (B and E) may offer better remediation performance, while phosphorus and other nutrients aid in restoring soil health post-remediation. This dual benefit of remediating toxic compounds and enhancing soil fertility makes biochar a powerful tool in sustainable agriculture and environmental cleanup efforts.

Table 2 Elemental composition of different biochar samples

	A	**B**	**C**	**D**	**E**	**F**
Temperature (°C)	350	500	700	350	500	700
Time (min)	40	40	40	80	80	80
Carbon	68.24	71.54	62.14	69.10	60.08	72.00
Oxygen	10.30	10.30	20.00	7.20	20.25	9.30
Phosphorus	6.22	6.20	7.18	12.22	7.46	5.22
Magnesium	2.98	6.24	3.20	5.00	_	_
Sodium	2.10	2.60	_	2.22	2.09	_
Chlorine	2.02	2.00	0.09	0.50	1.22	0.31
Calcium	1.60	1.62	1.18	0.33	4.40	1.32
Nitrogen	0.50	1.43	3.22	3.20	0.45	5.20
Silicon	3.20	0.52	2.40	0.23	3.90	6.00
Iron	_	_	_	_	0.15	_
Manganese	_	_	0.55	_	_	0.15
Copper	2.14	_	_	_	_	0.50

3.4. Effect of pyrolysis conditions on the functional group composition of biochar samples

The FTIR analysis of biochar samples A, *B*, *C*, *D*, *E*, and *F* (Fig 2) produced at different temperatures (350 °C, 500 °C, and 700 °C) and durations (40 and 80 min), reveal key insights into their functional group composition and implications for environmental remediation. There are a lot of peaks in the FTIR spectra which shows that biochar is a complex mixture. At 350 °C and 40 min, (Sample *A*, Fig. 2*a*) the biochar sample showed the presence of a lot of functional groups in the single bond region. These are groups with hydrogen bonds including hydrate groups, hydroxyl groups, ammonium/amino groups, unsaturated compounds, amino rings and aliphatic compounds. There are also aromatic compounds identified in the triple bond region. For sample *B* (Fig. 2*b*), the number of peaks in the single bond region reduced compared to sample A but still contains functional groups with hydrogen bonds. There is the presence of ammonium/amino groups, hydroxyl groups, and unsaturated compounds, but no aliphatic compounds and aldehydes. There are also ortho- and para-aromatic compounds identified in the fingerprint region which is absent in sample A.

The aliphatic C-H, hydroxyl (O-H), and carbonyl (C=O) groups make these two biochar samples effective for adsorbing polar contaminants like heavy metals and organic pollutants.

As the temperature and pyrolysis duration increase in samples *C*-F (Fig. 2*c-f*), the number of hydrogen groups reduces with the absence of ammonium/amino groups, aldehydes and aromatic compounds. At 700 °C (samples *C* and *F*), the biochar is dominated by stable aromatic structures with minimal aliphatic and oxygen-containing groups, which limits their reactivity with polar contaminants but provides excellent long-term durability. These high-temperature biochars are better suited for nonpolar contaminant adsorption or long-term filtration. Overall, the FTIR analysis suggests that lower-temperature biochar (samples *A* and *B*) is more effective for short-term, reactive remediation, while higher-temperature biochar is more suitable for long-term applications where structural stability is essential.

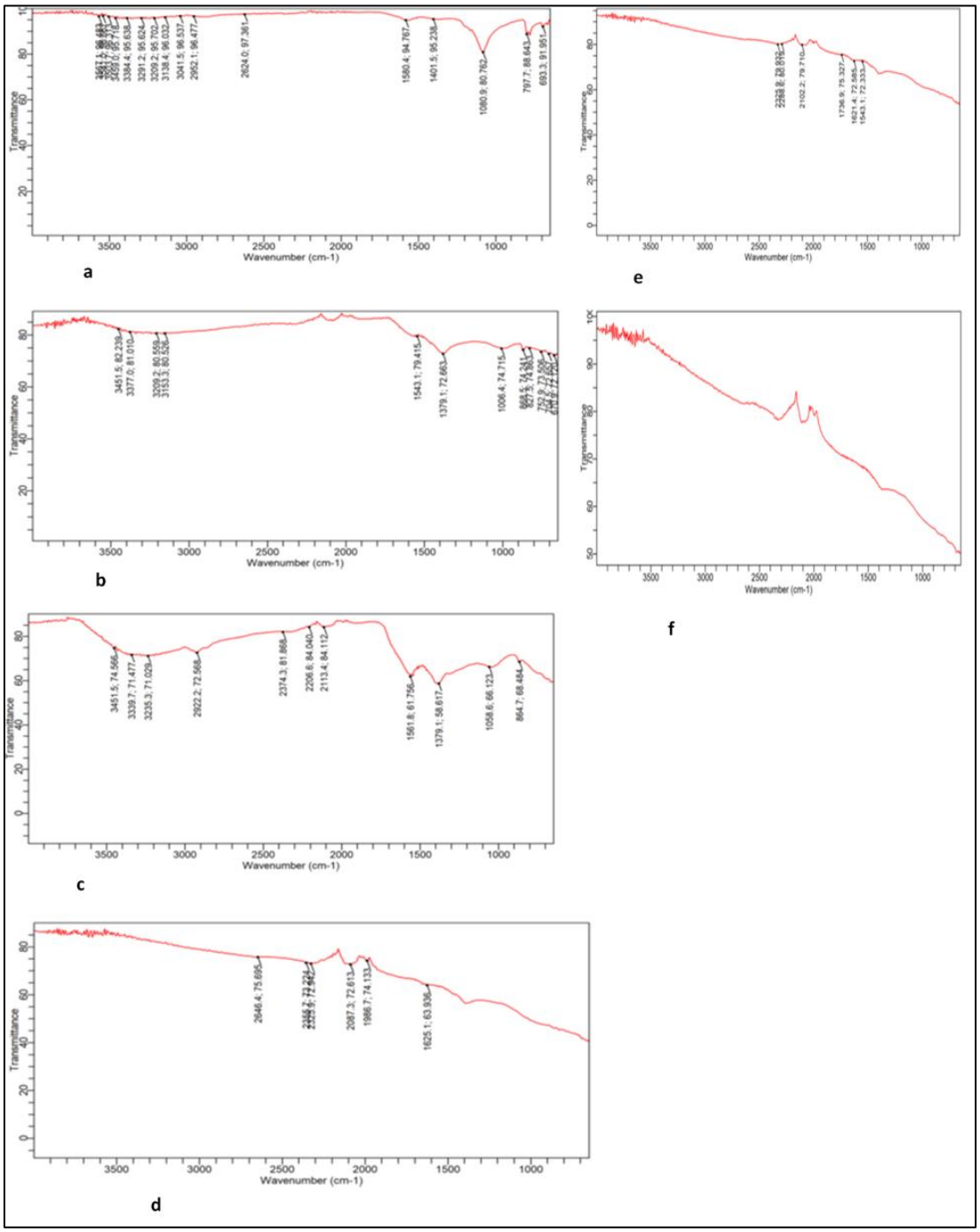

Figure 2 FTIR spectra of the different biochar samples: sample *A* at 350 °C (*a*), 40 min, sample *B* at 500 °C (*b*), 40 min, sample *C* at 700 °C, 40 min (*c*), sample *D* at 350 °C, 80 min (*d*), sample *E* at 500 °C, 80 min (e), sample *F* at 700 °C, 80 min (*f*)

3.5 Effect of pyrolysis conditions on the pore structure of biochar samples

The SEM images of the biochar (Fig. 3) reveal a porous structure with a large surface area and a heterogeneous particle size distribution. The pore size of the different samples increases with increasing temperature at 40 °C with sample *A* (Fig. 3*a*) having the smallest pore size (11.6 μm) followed by sample *B* (Fig. 3*b*, 42 μm) and sample *C* (Fig. 3*c*, 61 μm). However, at a longer pyrolysis time of 80 min, the average pore size increases from 30 μm for sample *D* (Fig. 3*d*) to 44 μm for sample *E* (Fig. 3*e*). Sample *F* (Fig. 3*f*) on the contrary had a lower pore size of 19 μm at the highest temperature (700 °C) and longest duration (80 min). These characteristics suggest that biochar is a promising material for remediation applications. The porous structure and large surface area can provide numerous adsorption sites for contaminants, while the heterogeneous particle size distribution can enhance contaminant removal efficiency.

Consequently, sample *C* exhibited the best pore size area when compared to the other samples. Sample *C* will be a very good adsorbent for the removal of contaminants. However, its effect on plant growth can only be verified when used as a soil enhancer as compared to sample *A* which yielded the best FTIR result.

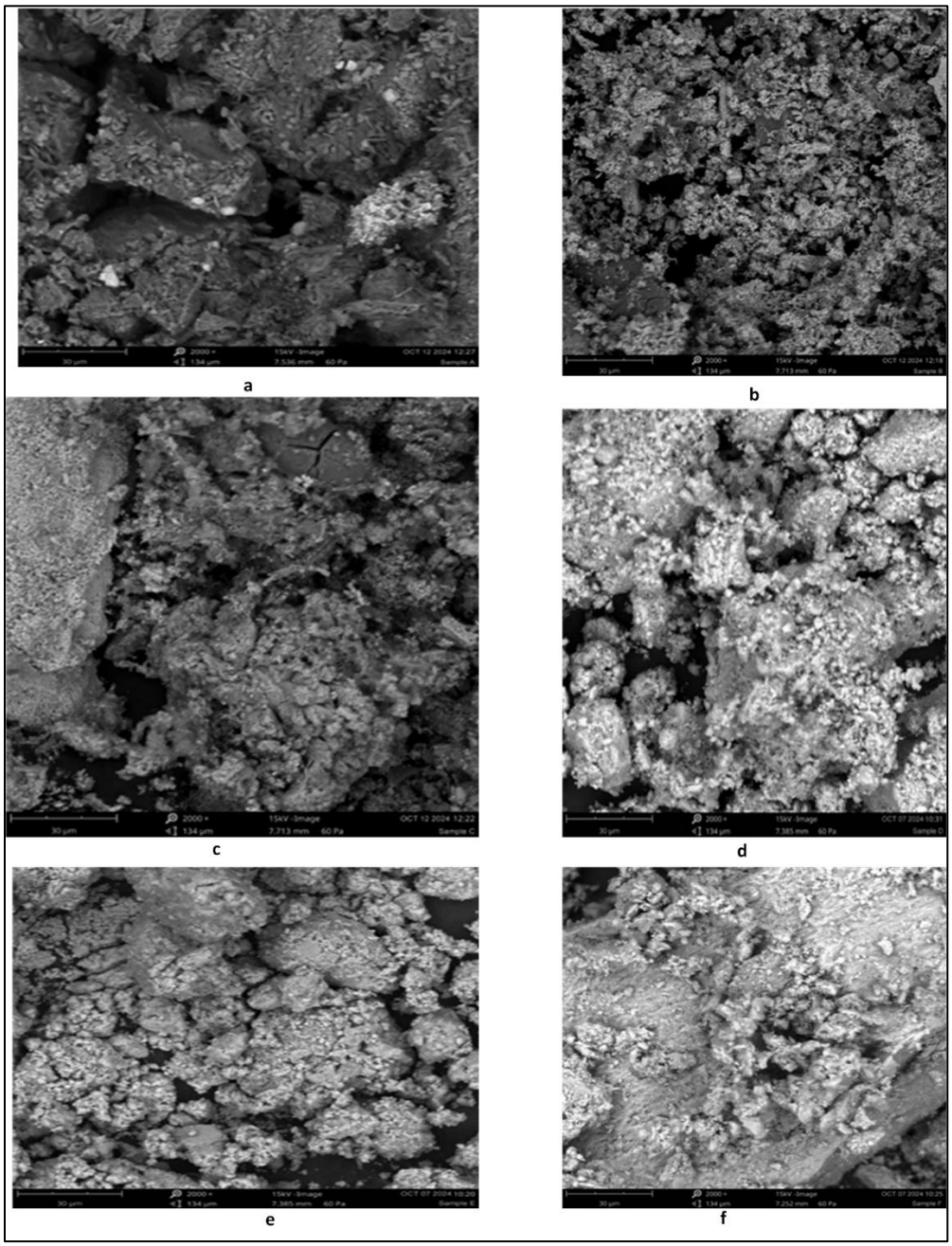

Figure 3 SEM analysis of samples *A* (*a*), *B* (*b*), *C* (*c*), *D* (*d*), *E* (*e*), *F* (*f*) x 2000

3.5. Effect of pyrolysis conditions on plant growth

The results of the effect of the two samples with the best biochar quality, samples *A* and *C*, on enhancing plant growth are presented in Table 3. The results showed that sample *A* performed better in enhancing plant growth than sample *C* at the end of 3 weeks. There were more leaves on the stem of the plant with sample *A* than sample *C*. Also, the leaves of the plant with sample *C* started drying off after the nineteenth day. This might be due to the presence of compounds with hydrogen bonds in sample *A* which is not present in sample *C*. Results of the FTIR analysis show sample *A* contains many hydrate groups including ammonium/amino groups which act as a precursor for protein biosynthesis, which is necessary for plant growth and plant tissue formation. The results are in line with the work of Hammer, Forstreuter [12] who studied the combined effect of biochar, fungi and salinity on plant growth and reported that plants depend on microorganisms to exploit the benefit of biochar for plant growth and that biochar may be advantageous in saline soils.

Table 3 Rate of plant growth for 3 weeks

Day	**1**		**2**		**3**		**4**		**5**	
Sample	**Height (cm)**	**leaves**	**Height (cm)**	**leaves**	**Height (cm)**	**leaves**	**Height (cm)**	**No of leaves**	**Height (cm)**	**leaves**
A			0.0		2.5	sprout	4.5	2.0	5.8	2.0
C			0.3		3.0	sprout	4.0	2.0	6.6	
Day	6		7		8		9		10	
A	6.5	2.0	8.5	2+*	10.0	5	12.0	5	13.5	5+*
C	7.5	2.0	8.5	2+*	11.0	5	11.5	5+*	12.5	5+*
Day	11		12		13		14		15	
A	15.8	8	16.3	8	17.0	8	18.0	8+*	20.0	8+*
C	14.2	8	14.8	8	15.5	8	16.5	8	17.0	8+*
Day	16		17		18		19		20	
A	22.0	11	25.5	11	26.0	11	28.0	11+*	29.4	11+*
C	17.0	8	17.5	8	18.7	8+*	19.2	8+*	19.5	--
Day	21									
A	31.0	12								
C	19.8	--								

*leaves plus sprout

4. Conclusion

The present study has contributed significantly to the understanding of how pyrolysis conditions affect biochar quality and act as an enhancer for plant growth. Beans shaft, an abundant agricultural residue, possesses a favourable chemical composition that makes it an excellent candidate for conversion into biochar. By rigorously examining the influence of temperature, and residence time on the physicochemical properties of biochar derived from beans shaft, this research provides a robust framework for optimizing biochar production. The optimized biochar sample *A* produced at 350 °C and 40 min, is the best condition that preserves reactive functional groups and stands out as a viable and effective tool for enhancing plant growth. This study provides clear evidence that biochar quality is highly sensitive to pyrolysis conditions.

Compliance with ethical standards

Disclosure of conflict of interest

There are no conflicts of interest to disclose by Aramide Adenike Adesina, Motunrayo Fatimah Yusuf, Moyosore Dorcas Abbey, Oreoluwa Ruth Agbaje, Sarah Ibukunoluwa Shorinolu, and Julius Gbenga Akinbomi in publishing this manuscript.

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