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Physicochemical Characterization of Biochar Derived from Agricultural Wastes for Sustainable Agricultural and Environmental Applications

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Abstract:
Biochar derived from agricultural residues has gained increasing attention as a sustainable material for soil improvement, carbon sequestration, and environmental remediation. In this study, biochar was produced from coconut husk through slow pyrolysis at 600 °C under oxygen-limited conditions and systematically characterized using Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Brunauer–Emmett–Teller (BET) surface area analysis, and dynamic light scattering (DLS). FTIR analysis revealed the presence of oxygen-containing functional groups, including hydroxyl, carboxyl, and aromatic structures, indicating potential adsorption capability. SEM micrographs demonstrated a highly porous structure with irregular surface morphology favorable for contaminant adsorption and soil water retention. XRD patterns confirmed the presence of crystalline mineral phases such as quartz (SiO_2) and sylvite (KCl), along with amorphous carbon structures. BET analysis showed a specific surface area of 14.69 $m^2 g^{-1}$, indicating moderate porosity of the produced biochar. Dynamic light scattering analysis indicated particle sizes in the range of 2000–8000 nm, while zeta potential measurements (−17.2 mV) suggested moderate colloidal stability. These results demonstrate that coconut husk biochar possesses favorable physicochemical characteristics that make it a promising low-cost material for environmental remediation and sustainable agricultural applications.

Keywords: *Biochar, Coconut Husk, Environmental Remediation, Pyrolysis, Surface Characterization.*

I. INTRODUCTION

Biochar is a multifunctional, cost-effective carbon-rich material produced through the thermal decomposition of biomass under oxygen-limited or oxygen-free conditions, typically via slow pyrolysis [1]. This process generally occurs within a temperature range of 300°C to 600°C. In recent years, slow pyrolysis has gained considerable attention as an effective strategy for managing agricultural residues. This approach not only offers a sustainable waste management solution but also enhances the value of biomass by reducing its volume, improving grindability, simplifying storage

and handling, and lowering transportation costs compared to raw residues [2]. Biochar has attracted significant interest across various scientific and engineering disciplines due to its potential applications in carbon sequestration and as an energy-rich material. Depending on its physicochemical and energy-related properties, biochar can be utilized either as a soil amendment [3] or as a solid fuel comparable to low-grade coal [4, 5]. Numerous studies have demonstrated that biochar can enhance soil properties, including cation exchange capacity (CEC), water retention, soil aeration, and microbial activity. It also plays a role in neutralizing acidic soils and improving crop productivity [3, 6, 7]. Owing to its porous structure and surface functionality, biochar is also recognized as an economical and eco-friendly adsorbent [8]. It has shown promising potential in treating wastewater contaminated with heavy metals, acting as an efficient sorbent for pollutant removal in both soil and aquatic environments [9]. Additionally, properties such as $CaCO_3$ equivalence and the presence of basic cations have been identified as key contributors to enhancing soil fertility and plant growth in acidic conditions [10]. Biochar is further characterized by relatively low hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) atomic ratios, which contribute to its high energy density and calorific value [11]. Its strong chemical stability allows it to remain in the soil for extended periods, ranging from hundreds to thousands of years, thereby supporting long-term carbon storage and contributing to climate change mitigation [12, 13].

A wide variety of organic feedstocks can be used for biochar production, including forest residues [14], agricultural by-products [15, 16], and agro-industrial wastes [17, 18]. For example, India produces approximately 511 million tonnes of agricultural residues annually [19], with about 141 million tonnes classified as surplus [20]. Of this surplus, nearly 93 million tonnes are burned each year, contributing to environmental pollution [21]. Among these residues, pigeon pea stalks (PPS) account for about 18.53 million tonnes annually [22]. Due to their high lignin content and low digestibility, PPS are unsuitable for animal feed and are often discarded. Although a small portion is used as a low-cost fuel in rural areas, the majority remains underutilized in agricultural fields. Improper management of such residues, particularly those with low bulk density and slow decomposition rates, interferes with soil preparation and crop establishment. As a result, open-field burning is commonly practiced, leading to serious environmental concerns, including air pollution, loss of biodiversity, and adverse effects on human health [23].

To determine its suitability for various applications, biochar must be thoroughly characterized in terms of its structural, chemical, and morphological properties. Advanced analytical methods such as Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Brunauer–Emmett–Teller (BET) surface area analysis are widely employed to evaluate these physicochemical characteristics. This study focuses on the production of biochar from coconut husk using slow pyrolysis and the systematic evaluation of its physicochemical properties through multiple analytical techniques. The research aims to examine structural characteristics, functional groups, surface morphology, mineral composition, and particle size distribution. A comprehensive understanding of these properties will help determine the suitability of coconut husk-derived biochar for environmental and agricultural applications.

II. MATERIALS AND METHODS

A. Coconut Husk

Coconut is widely cultivated as a plantation crop across more than 90 countries, with an estimated global production of about 55 million tonnes per year. Large quantities of coconut residues, particularly husks and shells, are generated from oil extraction industries and other coconut-based applications. Improper disposal methods such as open burning can lead to serious environmental issues, making efficient utilization of these residues essential. Converting coconut husk through pyrolysis offers a more sustainable alternative.

The high energy content of coconut husk, approximately 18.62 MJ/kg, is mainly attributed to its significant cellulose and lignin composition. In addition to these components, coconut husk contains compounds such as pyroligneous acid, charcoal, gases, tar, tannins, and potassium. Traditionally, coconut husk is either burned directly to produce charcoal or discarded as waste. However, it has strong potential to

be developed into a value-added fuel, serving as a viable alternative to wood and other conventional energy sources. Due to its abundance and cost-effectiveness, coconut husk is also considered a promising feedstock for power generation applications.

B. Pyrolysis of Coconut Husk

The pyrolysis of coconut husk is commonly employed for producing char, particularly as a precursor for activated carbon. However, comparatively less attention has been given to the utilization of bio-oil derived from this process. Activated carbon production from coconut shell typically involves a two-stage process: initial pyrolysis at around 600°C followed by steam activation at approximately 900°C. Surface characteristics are often evaluated using the BET method, with reported surface areas reaching nearly 1000 m^2/g.

Coconut shell is widely recognized as a suitable raw material for activated carbon production due to its high volatile content, which contributes to the formation of uniform pores and a well-developed pore structure. Earlier studies have explored the influence of process parameters on pyrolysis efficiency. For instance, experiments conducted by K. Prabhakar and R. C. Maheshwari (1986) examined the effect of temperature and residence time on charcoal yield [24]. Under controlled laboratory conditions, a yield of about 70% was achieved at 300°C with a duration of 180 seconds, whereas field conditions produced significantly lower yields of approximately 27%.

Further research by E. Ganapathy Sundaram and E. Natarajan (2009) investigated slow pyrolysis of coconut shell in a fixed-bed reactor [25]. Their study focused on variables such as temperature, heating rate, particle size, and vapor residence time. Experiments were carried out within a temperature range of 400–600°C, maintaining a heating rate of 60°C/min and particle sizes between 1.18 and 1.80 mm. Optimal conditions for maximizing liquid yield were identified at 550°C using a reactor length of 200 mm. Under these conditions, product yields ranged between 22–31 wt% for char, 38–44 wt% for liquid, and 30–33 wt% for gas. The findings indicated that temperature and particle size had a more pronounced effect on product distribution than heating rate or residence time.

C. Collection of Raw Materials and Preparation of Biochar

Coconut husk is abundantly available throughout Bangladesh and was selected as the primary raw material for this study. The samples were collected from the Dhaka region after the coconuts had reached full maturity. Initially, the husks were washed with distilled water to remove adhering impurities and then oven-dried at 105°C for approximately one hour to eliminate moisture. Biochar was produced using a limited-oxygen pyrolysis process. A measured sample of 50 g of dried coconut husk was placed in a furnace (Nabertherm, West Germany). The temperature was gradually increased to 600°C at a heating rate of 5°C per minute and maintained until the pyrolysis process was complete [26].

As seen in Figure 1, the prepared biochar was weighed and prepared for further characterization. Analytical techniques such as FTIR, SEM, XRD, BET surface area analysis, and nanoparticle analysis were employed to examine its properties. It is important to note that both the raw biomass and the resulting biochar exhibit variability in their physical and chemical characteristics. To minimize heterogeneity and ensure uniformity in analysis, the produced biochar was subjected to crushing, grinding, and milling prior to characterization.

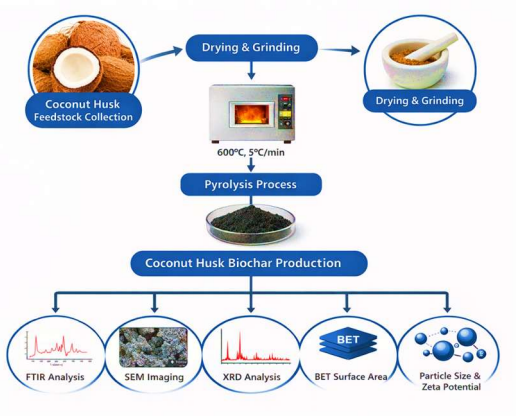

Fig. 1 Coconut husk biochar production and its structural and surface characterization

III. RESULT AND DISCUSSION

A. FTIR Analysis of Biochar

For FTIR characterization, biochar samples were prepared either by grinding and mixing with KBr (for DR-FTIR) or by analyzing them directly as powder in ATR mode. In this study, ATR-FTIR was employed, and the corresponding spectra of biochar samples are presented in Figure 2.

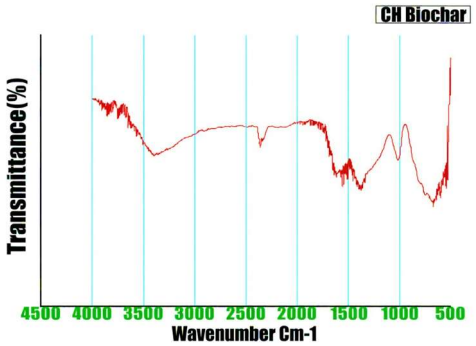

Fig. 2 FTIR Spectra of coconut husk biochar.

The FTIR spectra show broad absorption bands in the range of 3200–3600 cm^{-1}, which are attributed to O–H stretching vibrations. The relatively low intensity of these peaks indicates moisture loss due to high-temperature processing during pyrolysis [27]. Characteristic peaks associated with hemicellulose and cellulose, typically observed in the ranges of 3200–3000 cm^{-1} (O–H) and 3100–3000 cm^{-1} (C–H), are absent in the biochar samples. This confirms the thermal decomposition of these components during pyrolysis. Such degradation is expected, as hemicellulose and cellulose generally decompose within temperature ranges of 200–300°C and 300–400°C, respectively [27,28].

B. Nanoparticle Analysis of Biochar by DLS

The particle size distribution (PSD) obtained from dynamic light scattering exhibits a bimodal pattern, indicating the presence of particles with varying size Ranges.

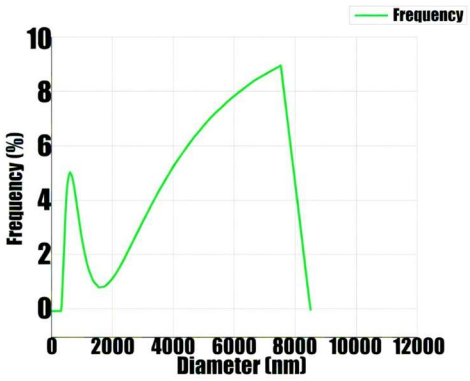

Fig. 3 Nanoparticle analysis of Coconut husk.

A minor population of submicron particles is observed around 600 nm, representing approximately 5% of the total intensity as shown in Figure 3, which may correspond to fine fragments or stable colloidal particles. In contrast, the dominant fraction shows a broader peak centered near 7.5 µm, contributing about 9% intensity.

C. Zeta Potential Analysis of Biochar

The zeta potential distribution (Figure 4) indicates that the biochar particles possess an overall negative surface charge. The highest intensity peak is observed within the range of −15 to −20 mV, with an approximate intensity of 2.4 arbitrary units. Secondary peaks are present between −25 to −30 mV and −10 to −15 mV, with lower intensities of about 0.8 and 1.1 arbitrary units, respectively.

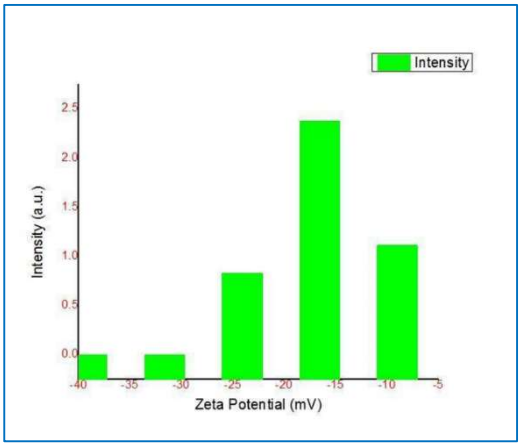

Fig. 4: Zeta potential analysis of Coconut husk biochar.

Minor populations are also detected at more negative potentials (−30 to −40 mV), although with negligible intensity. This distribution suggests moderate colloidal

stability, as the negative surface charge contributes to electrostatic repulsion between particles.

D. SEM Analysis of Biochar

Scanning Electron Microscopy (SEM) images (Figure 5) reveal that the biochar possesses a well-developed carbon-based structure with significant porosity. The formation of this porous network is attributed to the thermal decomposition of organic constituents during pyrolysis, leaving behind a carbon-rich framework.

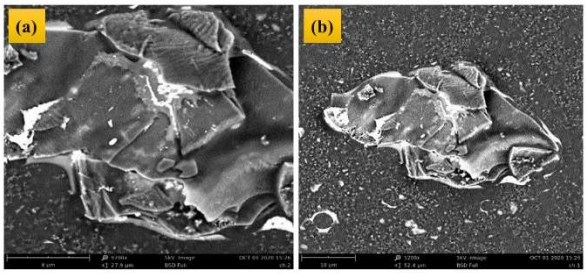

Fig. 5 SEM micrographs of Biochar at **(a)** 8 µm and **(b)** 10 µm scales.

The resulting structure exhibits a high surface area with numerous pores and cavities formed due to the release of volatile compounds. These structural features are influenced by both the pyrolysis temperature and the nature of the feedstock. The presence of interconnected pores and surface cracks enhances the material's ability to facilitate the movement of water, air, and nutrients. Such microporous and mesoporous characteristics make biochar particularly suitable for applications involving adsorption and soil amendment, as they improve interactions with surrounding chemical species and support nutrient retention.

E. XRD Analysis of Biochar

The biochar samples were finely ground using an agate mortar and pestle prior to XRD analysis. Diffraction measurements were performed using a Philips X'Pert MPD diffractometer equipped with a PW3050 goniometer and Cu Kα radiation. The instrument operated at 40 kV and 30 mA. Data were collected over a 2θ range of approximately 5° to 75°, with a step size of 0.02° and a scan speed of 0.3 seconds per step. The obtained diffraction patterns were analyzed using X'Pert Data Collector software and shown in table 1 and figure 6.

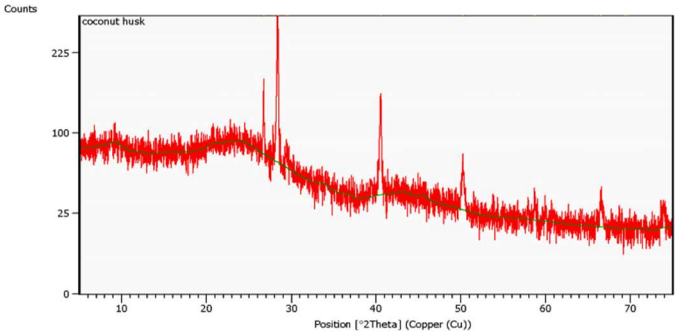

Fig. 6 XRD analysis of Coconut Husk sample

The XRD patterns (Figure 6) display a predominantly amorphous background with several distinct diffraction peaks, indicating the presence of crystalline phases within the biochar matrix. A peak at 2θ ≈ 26.7° corresponds to either graphitic carbon or quartz (SiO_2), suggesting mineral incorporation. The most intense peak at 2θ ≈ 28.4°, along with additional peaks at higher angles, is associated with potassium-containing compounds such as KCl. A broad peak around 2θ ≈ 29.5° indicates the presence of poorly crystalline phases, possibly carbonates or silicates. The calculated crystallinity index (~59%) confirms the semi-crystalline nature of the material. The average crystallite size (~104 nm) suggests well-defined mineral domains, while the low microstrain (~1.36 × 10^{-3}) indicates minimal lattice distortion. These inorganic components can significantly influence the thermal behavior and catalytic properties of biochar.

Table I: Phases identified or possibly present in the random powder diffraction pattern of coconut husk biochar samples:

2θ (°)	Height	FWHM	Left d-spacing [Å]	Rel. Int. [%]
26.7278	104.34	0.0590	3.33544	47.21
28.3721	221.03	0.0787	3.14577	100.00
29.4469	14.93	0.4723	3.03335	6.75
40.5610	109.88	0.1968	2.22418	49.72
50.2427	36.97	0.1574	1.81595	16.72
58.7062	14.41	0.2362	1.57273	6.52
66.5169	22.87	0.2362	1.40575	10.35
69.3761	3.67	0.1574	1.35464	1.66

F. BET Analysis of Biochar

(a) Cumulative Surface Area Distribution (BJH Desorption):

The BJH desorption analysis (Figure 7) shows that the contribution to surface area is minimal for pores smaller than 20 nm. As pore diameter increases, the cumulative surface area gradually rises, reaching about 3 m^2/g at ~30 nm and 6 m^2/g at ~40 nm. A sharp

increase is observed between 45 and 55 nm, where the surface area rapidly increases to approximately 75 m^2/g. This indicates that larger mesopores play a dominant role in defining the overall surface area of the biochar.

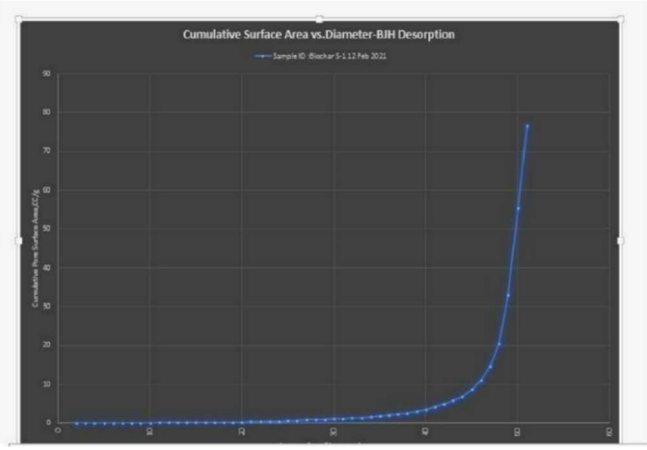

Fig. 7 Cumulative surface area (cc/g) vs diameter (angstrom) – BJH Desorption for Coconut husk BC

(b) Liquid Volume vs. Adsorption Thickness

(T-PlotAnalysis):

The T-plot results (Figure 8) indicate the presence of microporosity, as evidenced by a positive intercept when extrapolated to zero thickness. The liquid volume increases rapidly from 0.14 cc/g at 4 Å to 0.16 cc/g at 4.7 Å, followed by a gradual increase up to approximately 0.18 cc/g between 5 and 10 Å. This trend suggests effective adsorption at smaller pore sizes with a tendency toward saturation at higher thickness values.

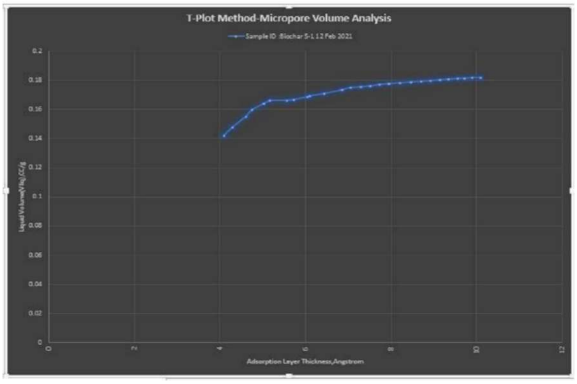

Fig. 8 Liquid volume vlq (cc/g) vs adsorption layer thickness (angstrom) for coconut shell BC

IV. CONCLUSION

In this study, biochar was successfully produced from coconut husk through slow pyrolysis at 600°C and thoroughly characterized using multiple analytical techniques. FTIR analysis confirmed the presence of oxygen-containing functional groups such as hydroxyl and carbonyl groups. SEM observations revealed a highly porous structure, which is beneficial for adsorption and nutrient retention. XRD results identified both amorphous carbon and crystalline mineral phases, including quartz and potassium compounds. BET analysis demonstrated a moderate surface area, while DLS measurements indicated particle sizes ranging from approximately 2000 to 8000 nm. Overall, the results suggest that coconut husk-derived biochar possesses desirable structural and chemical properties, making it a promising material for environmental remediation and agricultural applications. This work highlights the potential of converting agricultural waste into valuable carbon-based materials, contributing to sustainable resource management and environmental protection.

SUPPLEMENTARY DATA

Supplementary data is available on request

AUTHOR CONTRIBUTIONS

M M Hasan and M H Uddin designed the research; T Meghla , M S Rahman, and M Maola performed the experiments; S Mondal, and S C M Akash analyzed the data; M S Islam and M Maola wrote the manuscript draft; M S Islam and M H Uddin revised the manuscript. All authors approved the final version of the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest exists.

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Not applicable

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