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Exploring the Benefits of Rice Husk Waste: Synthesis and Characterization of Biochar and Nanobiochar for Agricultural and Environmental Sustainability

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Rice husk waste is a significant byproduct of rice production in developing countries, with a vast annual production. This waste material has been extensively used as an adsorbent for various substances due to its adsorption capabilities. Biochar, a carbon-rich material produced through pyrolysis of biomass, has gained attention for its diverse applications in agriculture and the environment. In this study, rice husk biochar and nanobiochar were synthesized and characterized to explore their potential benefits for agricultural and environmental sustainability. The biochar was prepared by pyrolysis of rice husk at 500°C in a low-oxygen environment, followed by grinding and sieving. Nanobiochar was obtained by ball milling the biochar particles. The physical and physicochemical properties of both biochar and nanobiochar were evaluated, including bulk density (0.41 and 0.59 Mg m^{-3}), particle density (0.49 and 0.54 Mg m^{-3}), water holding capacity (168.6 and 178.5%), pH (8.4 and 7.3), electrical conductivity (0.31 and 0.45 dS m^{-1}), cation exchange capacity (26.3 and 24.1cmol (p^{+}) kg^{-1}), volatile matter content (21.91 and 18.90%) and particle size distribution. Spectral analysis techniques such as DLS, FTIR, XRD, SEM and EDX were used to examine the size, zeta potential functional groups, crystallinity, porosity and elemental composition of the samples. The results showed that nanobiochar exhibited improved physical characteristics, such as higher porosity and water retention capacity, compared to biochar. The elemental composition and volatile matter content differed between the two materials. Nanobiochar also had significantly smaller particle size (11 nm) and a stable zeta potential. These findings suggest that rice husk nanobiochar has great potential for applications in soil fertility enhancement, adsorption of contaminants and waste management. The study contributes to the understanding of the properties and applications of rice husk waste-derived biochar and nanobiochar, promoting their utilization for sustainable agricultural and environmental practices.

Keywords: Rice husk biochar; rice husk nanobiochar; pyrolysis; ball milling; environmental sustainability.

1. INTRODUCTION

In developing countries, approximately 97% of the annual rice husk production amounts to around 80 million tonnes worldwide [1]. Rice husk has been extensively utilized as an adsorbent for the effective removal of a wide range of substances, including 10 different cations such as heavy metals, as well as 11 diverse types of dyes [2-4]. Biochar is a carbon-rich material that is formed through the thermal breakdown of lignocellulosic biomass, achieved either by subjecting it to high temperatures with limited oxygen or in the absence of oxygen altogether [5]. The production of biochar typically involves a process known as pyrolysis, where the feedstock is subjected to thermochemical decomposition. This decomposition occurs through heating the feedstock at temperatures ranging from 350-700°C, within a low oxygen environment (<1%) [6]. Biochars possess diverse physicochemical properties, including variations in pore size, surface area and functional groups. These properties are influenced by factors such as feedstock type, pyrolysis temperature, residence time, pressure and reactor type, which impact biochar yields, properties and applications [7]. The particle size of biochar can vary across a range of micrometers to centimeters, depending on the specific pyrolysis technology utilized [8]. The process of reducing the size of biochar particles to create nanoscale dimensions, referred to as nanobiochar [9,10]. The most frequently employed technique for the preparation of nanobiochar is ball-milling [11]. The surface area of nanobiochar is greater when compared to that of bulk biochar [9,11]. Reducing the size enhances the properties of biochar, making nanobiochar highly suitable for various agricultural and environmental applications. These include enhancing soil fertility, delivering nutrients, retaining nutrients, promoting soil microbial activity, adsorbing contaminants from water and soil, and sequestering carbon [12]. In light of the considerable research conducted in recent times regarding the production, characterization, and applications of nanobiochar, there is currently a valuable opportunity to compile a study that encompasses these recent advancements. The main objective of this work is to explore the potential benefits of rice husk waste by synthesizing and characterizing biochar and nanobiochar. The aim is to investigate their suitability for promoting agricultural and environmental sustainability, specifically focusing on their properties and

applications in adsorption, soil fertility enhancement and waste management.

2. MATERIALS AND METHODS

2.1 Preparation of Rice Husk Biochar

To make use of the abundant rice husk resources in India, biochar production was carried out using a modified 200 L capacity cylindrical metal drum developed by Venkatesh et al. [13] and CRIDA. The rice husk was thermochemically converted into biochar with a yield of 40-45% through pyrolysis at a temperature of 500°C for one hour in a low-oxygen environment (<1% O_2). The biochar was dried through air drying and subsequent oven drying at 60°C until a constant weight was achieved. The dried biochar was then ground and sieved through a 2 mm sieve for the preparation of nanobiochar and further analysis. Magnetic stirring was employed to reduce the particle size of the raw rice husk biochar, resulting in enhanced surface-to-volume ratios and the emergence of new surface features, both of which are advantageous for adsorption processes.

2.2 Preparation of Nanobiochar from Rice Husk Biochar

The process of preparing nanobiochar from rice husk biochar involved the utilization of ball milling, a top-down method that employs mechanical forces to reduce particle size [14]. This environmentally friendly and cost-effective process has gained significant attention, offering potential for large-scale nanopowder production [15]. The methodology described by Wang et al. [16] and Zhang et al. [17] was adopted with minor modifications for the separation of biochar nanoparticles. Initially, 100 g of rice husk biochar was weighed and sieved through a 2 mm sieve, followed by grinding in a pestle and mortar to obtain a fine powder. The powder was further sifted using a 0.5 mm sieve and ground again to a fine powder. Subsequently, another round of sieving through a 0.25 mm sieve was performed, and the resulting material was collected and finely ground using a pestle and mortar. Ultimately, 60 g of rice husk biochar was obtained from the initial 100 g. To modify the surface of the rice husk biochar, alkaline wash using sodium hexametaphosphate (SHMP) was carried out. 100 g of rice husk biochar with a sieve size of 0.25 mm was weighed into a 2 L beaker and mixed with 500 ml of distilled water. The reaction mixture was continuously stirred at 60 revolutions per minute for 10 to 20 minutes. Then, 5 g of sodium hexametaphosphate (SHMP) was added to the stirring mixture at a temperature of 50 °C and stirred for 60 to 90 minutes at 400 revolutions per minute. The resulting mixture was diluted with distilled water, stirred at room temperature for an additional 60 to 90 minutes, and allowed to settle. The settled mixture was removed from the beaker, cooled and washed with distilled water until it formed a clear suspension close to pH neutral. The suspension was centrifuged at 8000 rpm for 15 minutes, and the solid portion was collected. The solid component was dried in an oven at 60°C for 18 to 24 hours and subsequently transformed into a fine powder using a pestle and mortar. The final yield of nanobiochar obtained from 100 g of rice husk biochar ranged from 90 to 95 g. The particle size reduction achieved through this process improves surface-to-volume ratios and alters the characteristics of the particle surfaces, making nanobiochar highly suitable for adsorption and the production of nanobiochar-based fertilizers.

2.3 Characterization of Rice Husk Biochar (RB) and Rice Husk Nanobiochar (RNB)

2.3.1 Physical properties

Using the Core technique, the bulk density of rice husk biochar and rice husk nanobiochar were determined [18]. Utilizing the water pycnometer method, the particle density of RB and RNB were calculated [19]. The saturated water holding capacity of RB and RNB were measured using the Keen Rackzowski box method [20].

2.4 Physico-Chemical Properties

After continuous shaking for an hour, the pH of the biochar in the water (pHw) and the electrical conductivity (EC) in the water were measured at a 1:10 (w/v) ratio [21]. Following the method used by Yuan et al. [22] with a little modification, the cation exchange capacity (CEC) of the biochar was assessed.

2.5 Ultimate and Proximate Analysis

Ultimate or elemental analysis of biochar samples were done by carbon analyzer (Elementar) at 950ºC temperature [23]. In the case of proximate analysis, ash and volatile matter content were determined using the Mukherjee et al. [24] method.

2.6 Spectral Analysis

The size and zeta potential of the nanoparticles were assessed using Dynamic Light Scattering (DLS) in a compact scattering spectrometer after filtering the aqueous particles suspension through a 0.22 µm syringe-driven filter, providing information on hydrodynamic size and stability at low negative zeta potentials.

FTIR (Fourier Transform Infrared) spectroscopy measures the absorption of infrared radiation by a sample, providing information about the sample's functional groups and compounds. A range of 400-4000 cm^{-1} was scanned in transmittance mode after creating a homogeneous and transparent film by combining a small portion of the sample with KBr (1:200) crystal and pressing it (Tensor 27, BRUKER).

XRD analysis (Ultima IV, Rigaku, Japan) was performed to determine sample crystallinity, identify particle phases and locate Bragg's reflections. Using a Rigaku diffractometer with CuK radiation at 40 kV and 20 mA, scanning at a rate of 10° per minute, and comparing the observed XRD pattern with literature references to determine phase peaks.

To characterize the morphology, physical properties, spectral composition and chemical composition of the samples, SEM (S4800, Hitachi, Japan) analysis with a 1-2 mm palladium and gold alloy coating (20 kV beam energy) was performed. EDX analysis provided qualitative elemental composition information, including C, O, Si, Mg, Ca, S, K, Fe, Mn, Cu, and Zn, using the same 20 kV beam energy, along with gold or palladium-coated biochar samples mounted on Al stubs.

3. RESULTS AND DISCUSSION

3.1 Physical and Physico-Chemical Properties of RB and RNB

The bulk density (BD) of RB (biochar) was measured at 0.59 Mg m^{-3}, while RNB (nanobiochar) had a slightly lower BD of 0.41 Mg m^{-3}. However, RNB exhibited a lower particle density (PD) of 0.49 Mg m^{-3} compared to RB's PD of 0.54 Mg m^{-3}. This indicates that RNB had a higher porosity (56.3%) compared to RB (48.6%), allowing for increased water retention capacity, with RNB reaching a maximum water holding capacity (MWHC) of 178.5% compared to RB's MWHC of 168.6%. These findings suggest that the nanobiochar (RNB) has improved physical characteristics for water retention, making it a promising material for agricultural applications (Table 1).

The pH of RB (rice husk biochar) was measured at 8.4, while RNB (rice husk nanobiochar) had a slightly lower pH of 7.3. RB had a lower electrical conductivity (EC) of 0.31 dS/m compared to RNB's EC of 0.45 dS/m. However, RB exhibited a higher cation exchange capacity (CEC) of 26.3 cmol (p^+) kg^{-1} compared to RNB's CEC of 24.1 cmol (p^+) kg^{-1}. These results indicate that both biochars possess alkaline pH values and low electrical conductivity, suggesting their potential to influence soil pH and nutrient availability in agricultural applications (Table 2).

3.2 Ultimate and Proximate Analysis of RB and RNB

The rice husk biochar (RB) exhibited a total carbon (TC) content of 45.80% and total hydrogen (TH) content of 4.71%. The remaining portion consisted of total oxygen (TO) at 49.49%. RB had a carbon-to-nitrogen (C/N) ratio of 62.96. On the other hand, the rice husk nanobiochar (RNB) had a higher TC content of 51.35% and lower TH content of 3.58%, resulting in a TO content of 45.07%. RNB had a slightly lower C/N ratio of 60.87 compared to RB. These results indicate that both RB and RNB are carbon-rich materials with varying composition, which can have implications for their stability, nutrient cycling, and carbon sequestration potential when applied in agricultural and environmental systems (Table 3).

The rice husk biochar (RB) had a volatile matter (VM) content of 21.91%, ash content of 32.58%, and fixed carbon (FC) content of 45.51%. The rice husk nanobiochar (RNB) had a slightly lower VM content of 18.90%, higher ash content of 34.71%, and similar FC content of 46.39%. These results indicate that both RB and RNB have significant amounts of fixed carbon, suggesting their potential as stable carbonaceous materials with reduced volatile matter. The higher ash content in RNB may be attributed to the preparation process, which could have introduced additional inorganic residues during the nanobiochar production (Table 4).

3.3 Particle Size Distribution

The particle size distribution analysis revealed that the rice husk nanobiochar (RNB) had

significantly smaller particle sizes (d.nm: 11) (Fig. 1c) compared to rice husk biochar (RB) (d.nm: 2087.7) (Fig. 1a) indicating successful development of RNB. The reduction in particle size in RNB led to enhanced homogeneity of pore distribution, increased surface area, total pore volume and average pore width, which are advantageous for improved water retention capacity. These findings suggest that RNB has great potential for effective soil nutrient applications due to its smaller particle size and enhanced water retention properties [25].

3.4 Zeta Potential (ZP) Distribution

Zeta potential (ZP) is a crucial parameter that indicates the surface potential and charge of particles in suspension. It plays a significant role in determining various interactions and behaviours of particles, such as agglomeration, sedimentation and complexation with other substances. In this study, the ZP values of rice husk biochar (RB) (-47.6 mV) and rice husk nanobiochar (RNB) (-46.2 mV) were measured and depicted in Fig. 1b and d, respectively. According to general stability criteria, particles with ZP values exceeding +30 mV or below -30 mV are considered stable [26,27].

3.5 FTIR (Fourier Transform Infrared) Spectroscopy

In this work, FTIR analysis was used to classify the samples into functional groups and identify the structural analysis modifications [28] between RB and RNB, the results are displayed in Fig. 2a and b. When compared to rice husk biochar, RBN have more functional groups and several newly developing peaks. In comparison to rice husk biochar, most of the RNB sample showed the peaks of -COOH and C-H (2979 cm^{-1}, 2896 cm^{-1} and 1077 cm^{-1}) and RNB adsorption intensity was much higher than that of RB [29,30]. For the majority of RNB, the peak of the O-H stretching vibration at 3866 cm^{-1} increased significantly [31]. Additionally, the C-O peaks for RNB, increased within the range of 1071-1384 cm^{-1}. Furthermore, as the particle size decreased, the conjugation effect weakened, shifting the aromatic -C=C or/and -C=O peaks to a higher wavenumber. For example, the peak of C-N increased from 1091 cm^{-1} for rice husk biochar to 1077 cm^{-1} for RNB, These findings indicated a reduction in conjugated benzene rings in RNB [29,32]. Indicating the lowest aromaticity of RNB was the mild aromatic CH out-of-plane peaks in the fingerprint area (955 cm^{-1}, 953 cm^{-1}, 951 cm^{-1}, 797 cm^{-1}) and the strong intensity of C-H stretching of aliphatic CHx at 2979 cm^{-1}. These outcomes were consistent with the increased H/C index [29]. Plant sourced biochar with more -COOH and other C-O functional groups may be more readily to offer sorption sites for organic contaminants in environment. In comparison to rice husk biochar, RNB tended to have more functional groups and aliphatic chains, indicating their high reactivity in the environment. These functional groups provide valuable information about the chemical composition of the rice husk biochar and rice husk nanobiochar, which can have implications for its properties and potential applications such as soil amendment, water treatment and carbon sequestration. Further analysis and complementary techniques would help in a more comprehensive understanding of the biochar's composition and its various applications.

3.6 XRD (X-Ray Diffraction Analysis)

One of biochars most distinguishing qualities was its mineral content, which gave rise to a number of uses [30]. XRD was used to characterise the mineral makeup of RB and RNB **(**Fig. 3a and b). The diffuse graphite peaks in the low and high theta regions, respectively, correspond to three groups of diffraction patterns that were typically recorded over the studied 2θ range ($0\text{-}80^0$) in the majority of cases. The presence of short-range order in the carbon structure is typically characterised by diffuse and broad bands in XRD patterns, whereas highly crystalline phases with a high degree of long-range order are confirmed by sharp and narrow peaks. This is due to the loading of the graphitic basal planes in carbon materials with long-term structural order and is typically seen at a 2θ value of 25^0 [33]. The XRD analysis was used to determine how different biochar samples formed crystalline or amorphous silica. All samples (RB and RNB) crystallinity peaks were found between 20° and 33° (at 2θ), which indicates that there is a significant reduction in the amount of amorphous solids present, the removal of organic components, and appropriate material stability. The existence of quartz (SiO_2) and calcite ($CaCO_3$), respectively, can be inferred from the presence of two distinct, strong crystalline peaks at 2θ at 26.62^0 and 30.14^0 and shows that there is cellulose present, which gives crystallinity to the particles. Peaks at $2\theta = 20^0\text{-}30^0$ denote the aromatic layers stacking arrangement (graphite). Sharp, unlabeled peaks in the biochar suggest various inorganic constituents. All samples have a better crystalline structure, according to the XRD data,

which was confirmed and it is a result of SiO_2 being present in the rice husk biochar. This is a high-energy site that is employed for adsorption in a preferred manner [34]. The heterogeneous nature of the rice husk biochar surface was confirmed by the X-ray diffraction peak. In addition to quartz (SiO_2) and calcite ($CaCO_3$), the samples also contain certain related minerals, including cristobalite (SiO_2), potassium oxide (KO_2) and moganite (SiO_2).

3.7 Scanning Electron Microscopy (SEM)/energy Dispersive X-Ray Spectroscopy (EDX)

SEM images at different resolutions (500 µm, 100 µm, 20 µm, and 10 µm) were used to characterize the physical and morphological properties of rice husk biochar and rice husk nanobiochar (Fig. 4 a-h). [35,36]. The images revealed irregularly shaped particles with a rough and porous surface for both biochar samples. The higher resolutions allowed for the observation of finer details, such as cracks, gaps and a network of interconnected pores. Rice husk nanobiochar exhibited additional nanoscale features, suggesting structural modifications due to the synthesis process. The porous structures and varying pore sizes indicate potential applications in adsorption and catalytic processes. Further analysis can explore the chemical composition and specific pore properties of these materials.

EDX surface elemental analysis (C, O, N, Fe, Na, Si, P, Cl, K, and Fe) was performed in concurrently with SEM. The analysis focused on different regions, as depicted in Fig. 5 a, b and presented in the Table 5, to identify and quantify the elemental composition of the samples.

Table 1. Physical properties

Component	Bulk density (Mg m^{-3})	Particle density (Mg m^{-3})	Porosity (%)	Maximum water holding capacity (%)
RB	0.59	0.54	48.6	168.6
RNB	0.41	0.49	56.3	178.5

RB=Rice husk biochar, RNB=Riche husk nanobiochar

Table 2. Physico-chemical properties

Component	pH (1:10)	EC (1:10)	CEC (cmol (p^+) kg^{-1})
RB	8.4	0.31	26.3
RNB	7.3	0.45	24.1

RB=Rice husk biochar, RNB=Riche husk nanobiochar

Table 3.Ultimate analysis of rich husk biochar and nanobiochar

Component	TC (%)	TH (%)	TO (%)	C/N ratio
RB	45.80	4.71	49.49	62.96
RNB	51.35	3.58	45.07	60.87

RB=Rice husk biochar, RNB=Riche husk nanobiochar

Table 4. Proximate analysis

Component	VM (%)	ASH (%)	FC (%)
RB	21.91	32.58	45.51
RNB	18.90	34.71	46.39

RHB=Rice husk biochar, RHNB=Riche husk nanobiochar

Table 5. Percentage of localized carbon, oxygen and some minerals content by SEM-EDX analysis of the samples (weight percentage)

Sample	Weight (%)				
	C	O	Si	N	K
RB	19.10	37.85	27.68	0.69	4.16
RNB	33.03	35.01	24.33	0.17	1.17

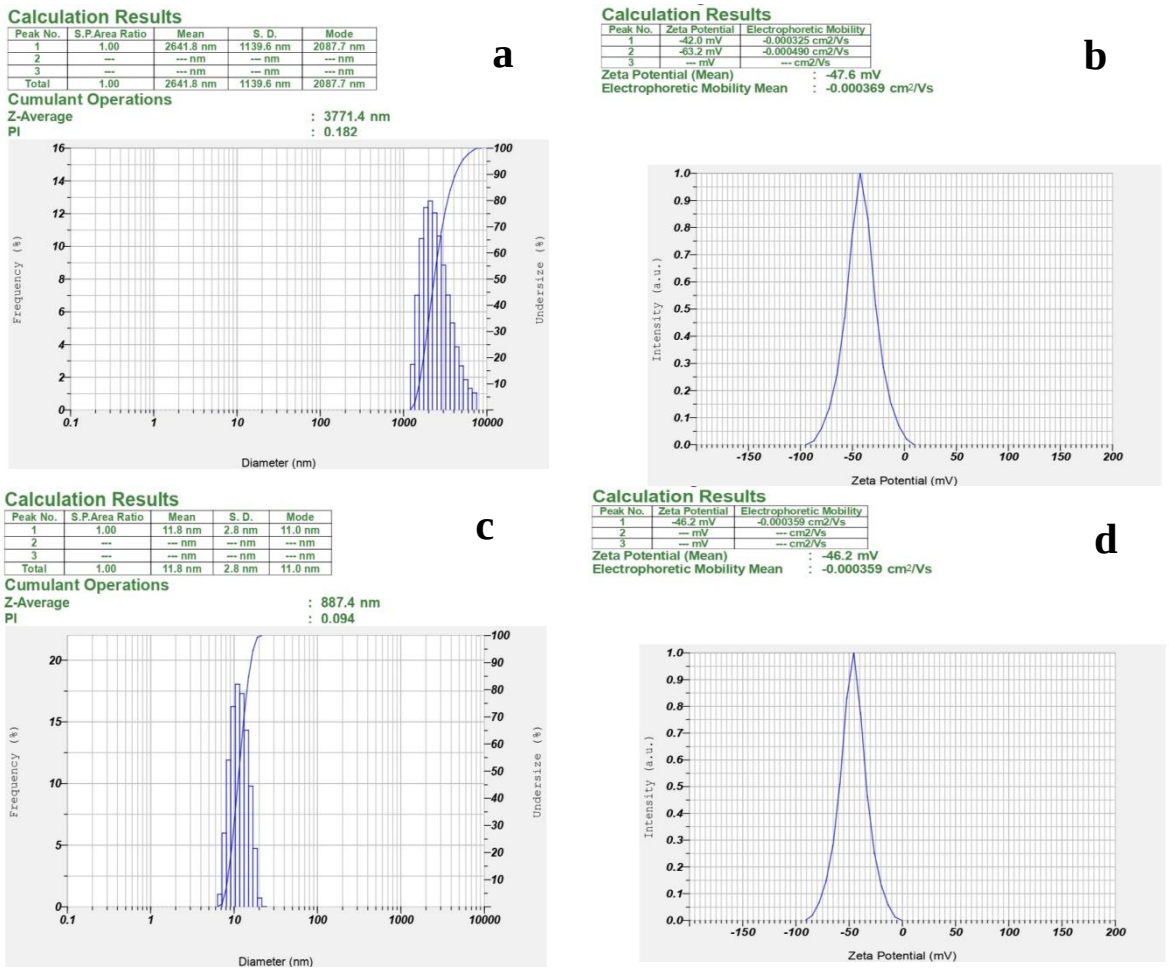

Fig. 1. (a-d) Size and zeta potential of synthesized of (a) RB - (size: 2087.7 nm), (b) RB - (zeta potential: -47.6 mV) and (c) RNB (size: 11.0 nm), (d) RNB (zeta potential: -46.2 mV)

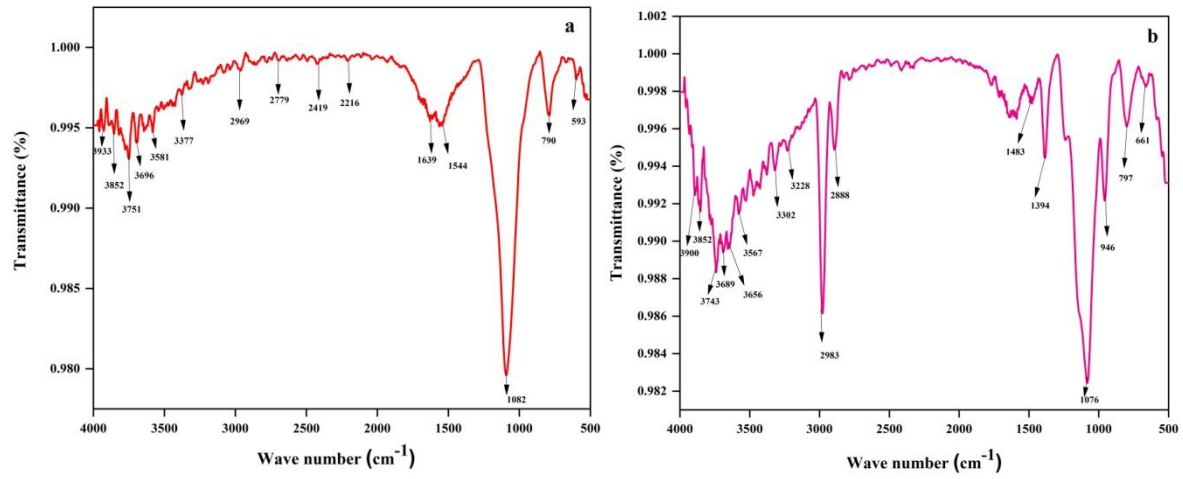

Fig. 2. (a,b) FT-IR micrograph provides evidence of distinct functional groups present on the surfaces of RB and RNB and more noticeable peaks size is observed in case of RNB (b) compare to RB (a) compare to RB (a)

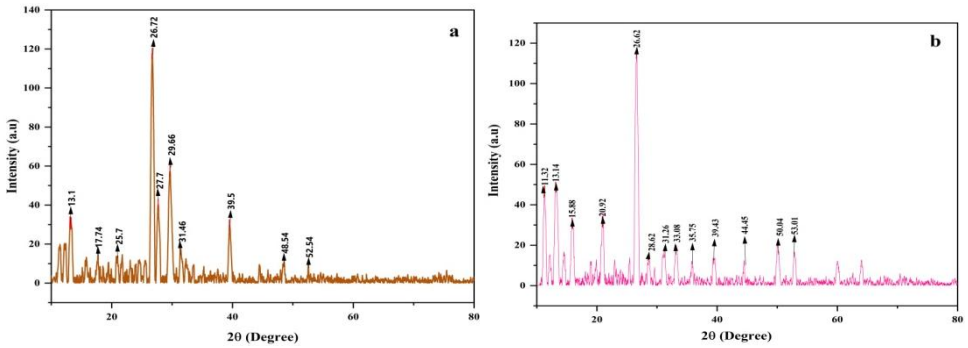

Fig. 3. (a,b) Crystal structure of the synthesized RB (Fig. 3a), RNB (Fig. 3b) were analyzed using XRD (X-ray diffraction). Distinctive diffraction peaks were observed in the crystal structure analysis of RB, specifically at 26.72, 27.7 and 29.66, while RNB exhibited n9otable peaks at 11.32, 13.14, 20.92 and 26.62

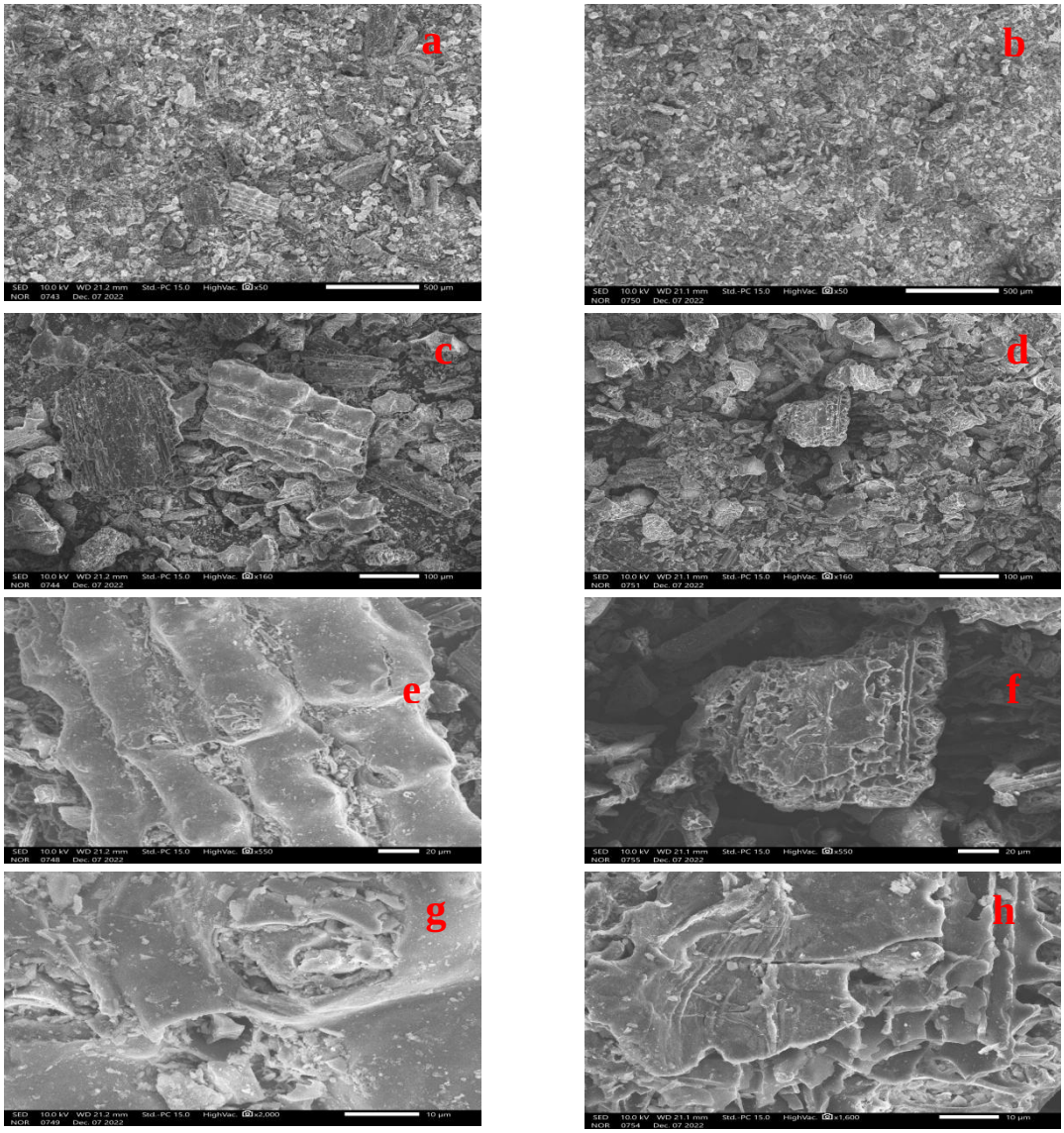

Fig. 4 (a-h). SEM images of RB N and RNB at resolutions of 500 µm (a & b), 100 µm (c & d), 20 µm (e & f) and 10 µm (g & h), respectively, showing more porous structure of rice husk nanobiochar compare to rice husk biochar

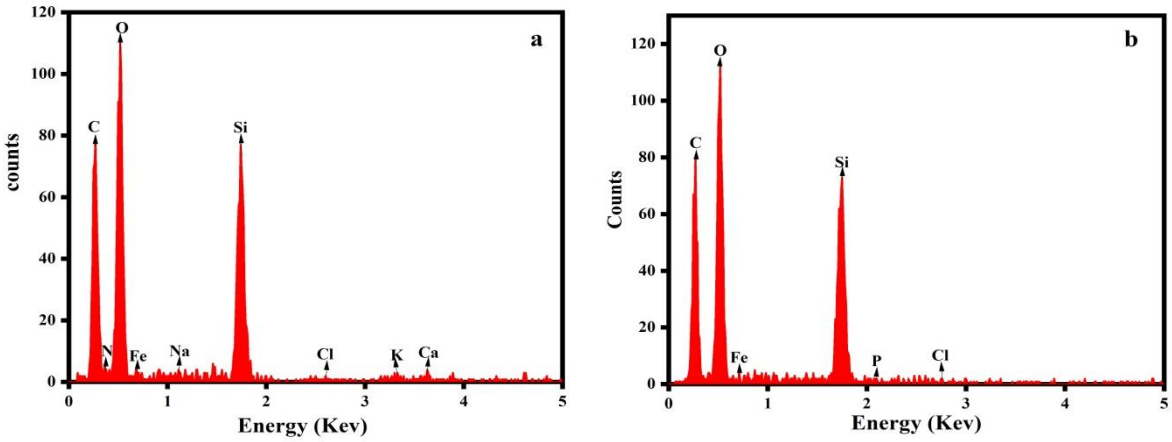

Fig. 5 (a,b). Elemental analysis (EDX) of RB (a) and RNB (b) represents the detailed composition of nutrients

The SEM-EDX analysis reveals that rice husk biochar (RB) consists of 19.10% carbon, 37.85% oxygen, 27.68% silicon, 0.69% nitrogen, and 4.16% potassium. In contrast, rice husk nanobiochar (RNB) contains 33.03% carbon, 35.01% oxygen, 24.33% silicon, 0.17% nitrogen, and 1.17% potassium. RNB exhibits lower silicon, potassium and nitrogen content compared to RB, possibly due to the nanobiochar production process. These results provide insights into the elemental composition differences between the two samples and their potential applications.

4. SUMMARY AND CONCLUSION

In this study, rice husk biochar (RB) and rice husk nanobiochar (RNB) were compared for their physical and physicochemical properties. RNB exhibited superior physical characteristics, including higher porosity, water retention capacity, and smaller particle size compared to RB. These properties make RNB a promising material for applications in agriculture, such as soil amendment and water management. RNB also showed enhanced reactivity and potential for sorption of organic contaminants. The findings contribute to promoting sustainable practices in agriculture and environmental management. Further research is recommended to explore specific applications and evaluate the environmental impact of RB and RNB.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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