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Agricultural Waste-Derived Biochar-Based Nitrogenous Fertilizer for Slow-Release Applications

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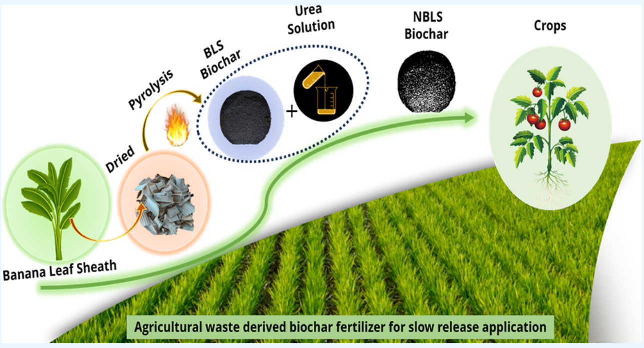

ABSTRACT: The exponential increase in population demands more food to be produced by employing modern technologies. There is a worldwide increase in the use of chemical fertilizers to rapidly enhance the crop yield. Nitrogen is a crucial plant nutrient, and nitrogenous fertilizers are the most widely used fertilizers. However, the high solubility and volatility of commonly used nitrogenous fertilizers have led to low nutrient use efficiency and alarming environmental pollution. They are lost due to the volatilization of ammonia and leaching of nitrate and release of nitrous oxide, and thus, plants only absorb approximately 20−30% of the nitrogen present in fertilizers. Slow-release fertilizers have been designed to overcome these issues and supply nutrients gradually and sustainably. Biochar, a solid material rich in carbon derived from biomass, can reduce nutrient loss in soil and extend the effectiveness of fertilizers in promoting plant uptake. In the present study, a slow-release nitrogenous fertilizer is prepared using biochar obtained by pyrolysis of a banana leaf sheath (BLS) at 500 °C for 3 h. The BLS biochar and nutrient-loaded BLS (NBLS) biochar exhibited significant water absorbance capacity, water retention capacity, swelling ratio, and equilibrium water content, which would support the maintenance of water levels in soils. The lower salt index values of the prepared fertilizer showed its potential to be used as a sustainable and clean fertilizer. The prepared BLS and NBLS biochar were also characterized by various techniques such as Fourier transform infrared (FT-IR), powder X-ray diffraction, thermogravimetric analysis, scanning electron microscopy, energy-dispersive X-ray spectroscopy, and Brunauer−Emmett−Teller (BET) methods. The FT-IR spectra of both BLS and NBLS biochar demonstrate the existence of primary, secondary, and tertiary alcohols, alkanes, alkenes, esters, and phenols. The peak at 1423 cm^{-1} in NBLS biochar corresponds to the vibration of NH^{4+} confirming nutrient loading. A minor phase change was noticed in the intensities of NBLS biochar, which may be attributed to the absorption of nutrients into the structure of biochar. TGA analysis confirmed the stability of BLS and NBLS Biochar. SEM analysis demonstrates a highly porous structure of the biochar samples due to the release of volatile matter from the biomass. The BET-specific surface area of BLS and NBLS biochar was 43.216 and 35.014 m^2/g, respectively. Nutrient release studies showed an incremental increase in the nitrogen release percentage over a period of 16 h. The gradual supply of nitrogen to the plants over an extended period demonstrated by the prepared slow-release fertilizer confirms its potential to reduce the leaching loss commonly observed in conventional chemical fertilizers.

1. INTRODUCTION

According to a recent prediction by the Food and Agriculture Organization (FAO), the global population is expected to reach 9.7 billion by 2050.[1] Agricultural productivity has to be increased to meet the rising demand for food required to feed the exponential increase in population. On the other hand, the ambiguity between the growing world population and shrinking arable land gives rise to remarkable pressures on agricultural production. Over the past decades, chemical fertilizers in agriculture have registered an additional 50% increase in crop yield.[2] Besides this intense increase in food production, the wide use of chemical fertilizers has drawn global attention due to their negative impacts on the environment. Another major reason for the overuse of fertilizers is the low fertilizer use efficiency, which fails to ensure high agricultural yields. Both excess use and suboptimal use of chemical fertilizers result in reduced fertilizer use efficiency and several environmental issues. Low fertilizer use efficiency is a major obstacle to cutting down agricultural production costs.[3] Additionally, overuse of fertilizers gives rise

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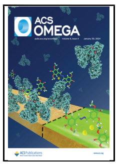

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to environmental problems viz. groundwater pollution by nitrate and algal blooms in rivers.[4] Over the years, the organic matter content of the soil decreases, resulting in topsoil depletion and soil becoming acidic, affecting crop growth and yield. To combat this problem, slow-release fertilizers (SRFs) are receiving high attention because of their potential to release nutrients at a rate that plants can absorb effectively.[5] These slow-release fertilizers can help improve the use efficiency of chemical fertilizers besides alleviating their harmful effects on the environment.[6]

Several types of slow-release fertilizers have been prepared and reported viz. polymer-based,[7] biochar-based,[8] and zeolite-based.[9] Compared to conventional fertilizers, coated fertilizers have gained momentum in the area of SRFs because the coating acts as a physical barrier hindering the nutrient transport thus reducing the diffusion rate of nutrients.[10] Generally, the release of nutrients from coated fertilizers takes place in three stages: water transport into the capsule, dissolution of fertilizers, and finally, release of the nutrients through the coating.[11] Several types of coated fertilizers have been developed to date. Renewable polyurethane derived from liquefied cotton straw was utilized for coating urea prills in developing a polyurethane-coated fertilizer.[12] The coated fertilizer was further modified by siloxane or polyether, extending slow-release longevity. A superhydrophobic biopolymer-coated fertilizer exhibiting a slower release of nutrients than that of an unmodified biopolymer-coated fertilizer was developed by Xie et al.[8]

The majority of these coated fertilizers employ polymer coatings such as polyolefin, polyvinylidene chloride, and polyurethane which are not easily degradable and can accumulate over the years.[13] Due to the tailing effect, these coated fertilizers also continue to release nutrients even in the absence of the plants.[14] Moreover, the cost involved in the production of the coated fertilizers is too high compared to the conventional fertilizers thus limiting their extensive use in agriculture.[15] Owing to these advantages biochar-based and zeolite-based slow-release fertilizers are often considered ideal as they are obtained from natural sources and are eco-friendly.[16−19]

Biochar is a carbon-rich, porous material derived from biomass commonly produced by a thermochemical process including pyrolysis, gasification, hydrothermal carbonization, and other methods. Plant and animal-derived biomass feedstocks are extensively used for the preparation of biochar. Biochar exhibits unique features like large surface area, copious surface functional groups, porous microstructure, etc., due to which it has been studied for different applications including energy storage, adsorption, catalysis, soil amendment, and carbon sequestration. Biochar displays outstanding features for the potential application, such as a large surface area, porous micromorphology, graphitic structure, and copious surface groups.[20,21] Due to its unique properties, biochar has been investigated for diverse applications, such as soil amendment,[22] adsorption,[20] waste management,[23] catalysis,[24,21] energy storage,[25] and carbon sequestration.[23] Apart from being inexpensive, renewable, and suitable for large-scale applications, biochar has been reported to enhance the soil texture and properties such as cation exchange capacity and water holding capacity.

Generally, pristine biochar is limited in nutrients, and loading nutrients onto it is crucial to improving the fertilizer. Several research studies have investigated biochar's use to develop SRFs. A phosphorus-loaded biochar-based slow-release fertilizer with high water retention capacity was prepared by integrated copyrolysis and copolymerization.[16] Chen and co-workers developed a slow release fertilizer using biochar and copolymer PVA and PVP for coating.[2] The copolymer properties, such as degradability and water resistance, were enhanced by the biochar. A potential Mg-enriched biochar-based fertilizer was prepared by pyrolysis. The prepared product demonstrated outstanding slow-release performance including lower release rates and extended release periods.[11]

Banana is an important fruit crop grown in over 120 countries, and in terms of total cultivated area, it occupies the third place. The global production of bananas is around 104 million tons.[26] India is the front-runner in the production of bananas with a total production of 29 million tons.[27] Of the total weight, the fruit bunch contributes only 30% while the leaf, leaf sheath, and pseudo stem which form the fibrous and juicy waste account for about 70% of the total biomass.[28] These wastes generated abundantly find widespread domestic and agricultural applications.[27] Their use in the production of nanofibers, bioethanol, papers, enzymes, biogas, etc. has been well explored.[29,30] Despite the availability of potential conversion processes, they are often burnt off and disposed of as waste.[27] Their high carbon content in the form of cellulose, hemicellulose, and lignin makes them suitable candidates for the preparation of carbon-based adsorbent.[31] Application of banana waste-derived adsorbents in the treatment of wastewater has been reported by several researchers.[32]

In the present study, the banana leaf sheath (BLS) was used as biomass feedstock for the preparation of biochar by pyrolysis. The prepared BLS biochar was explored for the preparation of a slow-release nitrogenous fertilizer. The biochar-based slow-release fertilizer (SRF) was developed to exploit its porous structure for nutrient impregnation. The nutrient-loaded SRF was subjected to physio-chemical characterization, and its performance was investigated by nutrient release studies. The study will help mitigate the problem of agriculture waste generated in huge amounts and ensure its conversion into a valuable product. Also, the developed eco-friendly SRF would largely reduce the use of commercial fertilizer and thus prevent environmental pollution by conserving the loss of nutrients.

2. METHODOLOGY

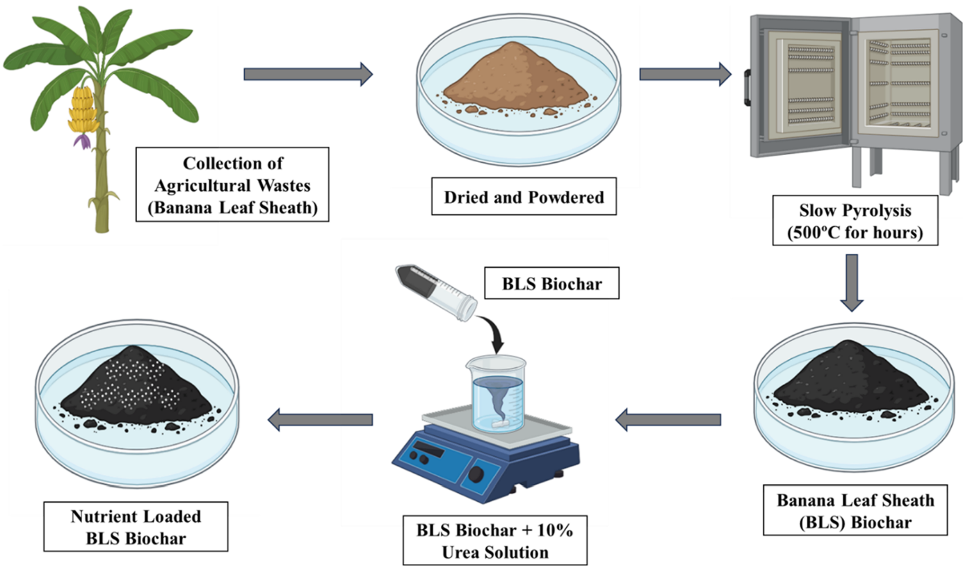
2.1. Chemicals and Raw Materials.

The raw material banana leaf sheath (BLS) used for the preparation of biochar was collected from a local agriculture farm in Vellore District, Vellore, Tamil Nadu, India. Chemicals used in this study include sodium nitrate, urea, etc. which are of laboratory grade. All of the chemicals were procured from Sigma-Aldrich.

2.2. Preparation of Banana Leaf Sheath Biochar.

Banana leaf sheath biochar was prepared by following a simple pyrolysis method. For this purpose, the collected banana leaf sheath (BLS) was washed, dried under sunlight, and pulverized to obtain fine particles. Before subjecting the particles to pyrolysis, the particles were passed through a sieve to obtain particles less than or equal to 0.65 mm. The powdered banana sheath was transferred to ceramic crucibles and placed in a tubular furnace at 500 °C for 3 h.[33] The pyrolysis process was carried out under a continuous supply of a nitrogen atmosphere at a flow rate of 20−50 mL/min. The obtained

Scheme 1. Preparation of Nutrient-Loaded Banana Leaf Sheath Biochar



banana leaf sheath (BLS) biochar was allowed to cool and stored in zipped polythene sample bags for further use.

2.3. Impregnation of BLS Biochar with Nutrient Solution. A nutrient solution was prepared by dissolving commercial urea fertilizer in deionized water. To this nutrient solution, 10 g of biochar was added, and the suspension obtained was mixed thoroughly and dried at 65 °C for 24 h. The nutrient-impregnated (NBLS) biochar was then ground to a powder and stored in airtight containers until further use. The preparation of nutrient-loaded banana leaf sheath biochar is given in Scheme 1.

2.4. Analytical Characterization of BLS Biochar and NBLS Biochar. The prepared BLS biochar and NBLS biochar were characterized by several analytical techniques which comprise Fourier-Transform Infrared Spectroscopy (Thermo Nicolet iS50 with inbuilt ATR, Shimadzu Japan) to reveal the different functional groups present in the biochar samples, X-ray powder diffraction analysis (Bruker D8 Advance) to determine the phase and crystallinity of the samples, Scanning Electron Microscopy coupled with EDAX (EVO/18 Research, Carl Zeiss) to analyze the morphology and the elemental composition of the biochar samples, TGA (SDT Q600, TA Instruments) was performed to check the thermal stability of the as-prepared biochar samples, Specific surface area, pore volume and pore size distribution of the biochar samples was confirmed using surface area analyzer (AutosorbiQ, Quantachrome USA).

2.5. Physio-Chemical Characterization. *2.5.1. Salt Index.* The salt index of the prepared BLS biochar and NBLS biochar was determined by transferring 0.25 g of each of these samples to two separate beakers, followed by adding 50 mL of distilled water. Similarly, 0.25 g of sodium nitrate was added into a separate beaker containing 50 mL of water. The contents of all three beakers were mixed well and left for 24 h. The conductivities were measured after 24 h by using a conductivity meter. The salt index of the biochar samples was calculated using the ratio of the conductivity of each solution to the conductivity of sodium nitrate.[34]

2.5.2. Swelling Ratio (SR) and Equilibrium Water Content (EWC). BLS biochar and NBLS biochar (0.50 g each) were weighed and immersed in a beaker containing 50 mL of distilled water and allowed to swell for 24 h. The biochar samples were then filtered and reweighed and the swelling ratio and water content were calculated using eqs 1 and 2,

$$\mathrm{SR} = \frac{W_s - W_d}{W_d} \tag{1}$$

$$\mathrm{ECM\%} = \frac{W_s - W_d}{W_s} \times 100 \tag{2}$$

where W_d is the dry weight and W_s of the BLS and NBLS biochar samples, respectively.

2.5.3. Water Absorbance Studies (WA). The water absorbance of a product is useful to determine the amount of water that it can absorb under specified conditions. In this procedure, 0.50 g (W_1) of the prepared BLS and NBLS biochar samples were placed separately in preweighed (W_2) Petri dishes. The Petri dishes were then placed in a desiccator containing water for 5 days to provide a moist environment. After this, the Petri dishes were weighed (W_3) and the water absorption capacity of the prepared biochar samples was determined using eq 3.

$$\mathrm{WA} = \frac{W_3 - W_2}{W_1} \times 100 \tag{3}$$

2.5.4. Water Retention Studies (WR). WR studies were carried out following the method reported by Hassan and Mahmoud 35. In this method, 50 g of sieved soil was added to a preweighed cup (W_1) which served as a control. To another preweighed cup, 50 g of soil and 0.50 g of biochar (W_2) were added. Distilled water (30 mL) was added to the cups and allowed to seep. After 24 h, the cups were reweighed (W_1 and W_2) and left in a glass box to record the weight regularly once every 24 h for the next 12 days. The water retention (WR) capacity of the sample was calculated using eq 4.

$$\mathrm{WR\%} = \frac{W_2}{W_1} \times 100 \tag{4}$$

2.6. Nutrient Release Studies in Water. Nutrient release studies were carried out to determine the leaching pattern of the nutrient from the prepared biochar-based slow-release

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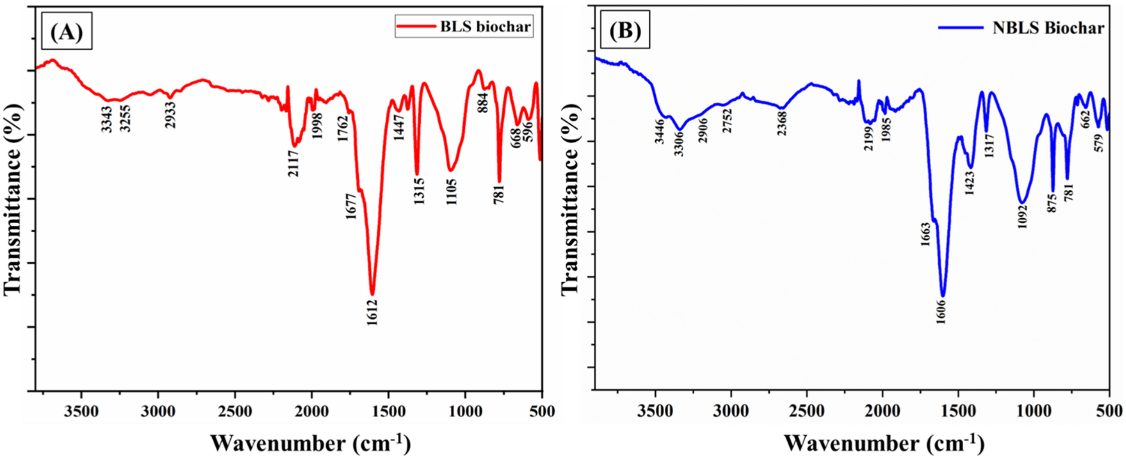

Figure 1. FTIR spectra of (A) BLS biochar and (B) NBLS biochar.

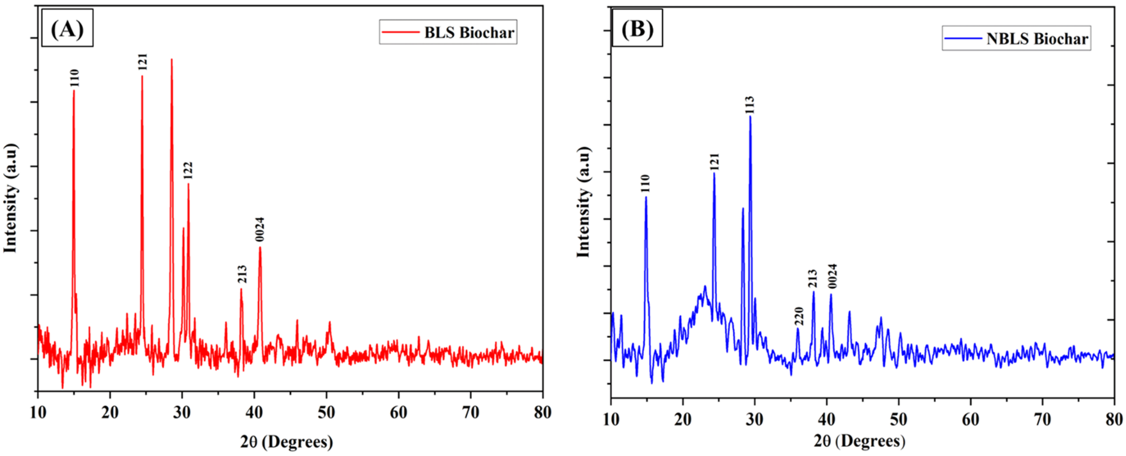

Figure 2. p-XRD diffractogram of (A) BLS biochar and (B) NBLS biochar.

fertilizer. In this experiment, 1 g of the biochar-based SRF was added to an Erlenmeyer flask containing 100 mL of water and capped with an aluminum foil to prevent evaporation loss. Two milliliters of the aliquot were withdrawn from the flask at regular time intervals, and the same volume of water was replaced in the flask to retain the volume. The concentration of urea present in the sample was determined by an Ehrlich reagent (P-methyl amino benzaldehyde). Initially, a calibration curve was constructed using UV visible spectroscopy (Analytik Jena-Specord 210 plus) reading (440 nm) for analytical grade urea, and the absorbance value and urea released were correlated. The experiment was carried out in triplicates and the mean values were represented as a percentage of total nutrients in NBLS biochar.[35]

3. RESULTS AND DISCUSSION

3.1. Characterization of BLS Biochar and NBLS Biochar.

3.1.1. Fourier-Transform Infrared Spectroscopy (FTIR). The FT-IR spectra of BLS biochar and NBLS biochar are given in Figure 1 and both show common functional groups. The O−H stretching for BLS biochar and NBLS biochar are observed at 3343 and 3446 cm^{-1} respectively, which is contributed by the moisture content present in the samples. The peaks at 2933 and 2906 are attributed to C−H stretching vibrations.[36] The peaks observed at 1612 and 1606 correspond to C═C stretching vibration showing the presence of alkenes.[37] The peaks at 1315 and 1317 cm^{-1} in BLS and NBLS biochar are linked to C−H bending, attributed to the presence of alkanes. The spectra of both BLS and NBLS biochar also demonstrate the existence of primary, secondary, and tertiary alcohols, esters, and phenols attributed to the peaks between 1300 and 950 cm^{-1}. The peak in NBLS biochar at 1423 cm^{-1} corresponds to the vibration of NH^{4+} thus confirming nutrient loading.[38]

3.1.2. Powdered X-ray Diffraction (p-XRD). Powder XRD patterns of BLS and NBLS biochar scanned in the range of $2\theta = 10-80°$ are presented in Figure 2. Both the patterns depict (2θ peaks at 14.851 and 24.357°) that the material has high carbon content with a less crystalline structure and high stability. Comparing both the XRD patterns signifies that the 28.475 and 43.375° of BLS biochar downshifted at peaks 28.375 and 43.124° in NBLS biochar, respectively. The appearance of the 40.625° peak in NBLS biochar refers to the plenary changes of the specific compound oxygen. Moreover, the minor phase change noticed in the intensities of the NBLS biochar may be attributed to the absorption of nutrients into the structure of biochar. However, the basic structure before and after nutrient loading remains the same.[9,39]

3.1.3. Thermogravimetric Analysis (TGA). TGA was performed to confirm the thermal stability of the as-prepared BLS and NBLS biochar, and the results are presented in Figure 3. Initial weight loss (10%) of the sample up to curves ranging

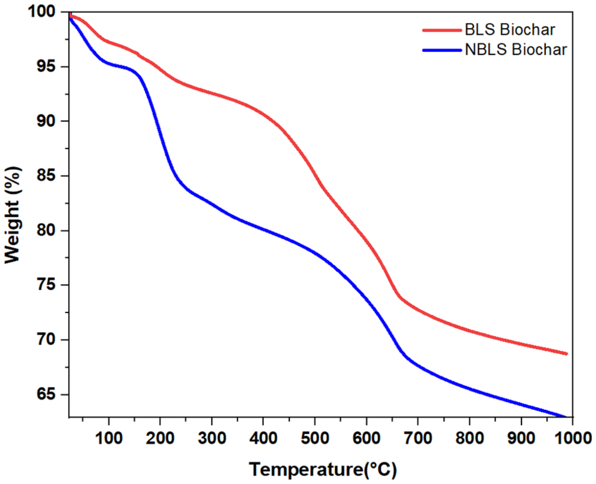

Figure 3. Thermogravimetric curves of BLS biochar (red line) and NBLS biochar (blue line).

from 100 to 150 °C shows the removal of moisture content from the samples.[39] This weight loss observed for the banana leaf sheath indicates the decomposition of volatiles, depicting its low thermal stability. In the second stage, the weight loss (30%) of the samples was observed from the peaks starting from 200 to 550 °C due to the decomposition of the organic matter of the samples. Here, hemicelluloses depreciate at a temperature of 200−300 °C, cellulose at 250−350 °C, and finally, the lignin content in the organic biomass undergoes thermal decomposition from 200 to 500 °C.[40] At the last stage (50−60%), the weight loss of the samples observed from 600 to 1000 °C is attributed to the pyrolytic decomposition, where the maximum weight difference happened because of the discharge of gases such as carbon dioxide, carbon monoxide methane, etc.[9] The minor changes in the thermogram of the NBLS biochar confirmed the loading of the nutrient onto the pores of the BLS biochar. TGA analysis confirmed the stability of NBLS biochar, which is obtained from BLS.

3.1.4. SEM and EDX Analysis. SEM analysis of the BLS biochar and NBLS biochar was carried out to gain insight into the morphology of the samples. The SEM images of the biochar samples (BLS and NBLS) demonstrate a highly porous structure due to the release of volatile matter from the biomass (Figure 4A,B). Apart from providing more sites for reaction to occur, the porous structure augments the surface area, thus favoring nutrient loading. Khan et al.[39] attributed the increased porosity to the high process temperature and liberation of volatiles from the wheat straw biomass. The elemental composition present in the BLS biochar and NBLS biochar was confirmed by using EDX analysis. Comparison of Figure 5A,B shows the impregnation of nutrients into BLS biochar.

3.1.5. Surface Area analysis (Brunauer−Emmett−Teller Method). The specific surface areas of BLS Biochar and NBLS Biochar were investigated using the Brunauer−Emmett−Teller method. The N_2 adsorption−desorption isotherms for the prepared biochar are shown in Figure 6A,B. The surface area of the BLS biochar decreased upon loading with the nutrient (urea). The pristine biochar showed a specific surface area of 43.216 m^2/g which further reduced to 35.014 m^2/g (for NBLS) upon nutrient loading. This decrease may be attributed to the crystallization of urea during the drying process. The impregnation of the nutrient leading to a reduced specific surface area can also be due to the coverage of the biochar surface and the blockage of its pores by urea. The results are in accordance with similar studies carried out with biochar-based slow-release fertilizers.[41]

3.2. Physio-Chemical Characterization of BLS and NBLS Biochar. *3.2.1. Salt Index.* Fertilizers being salts increase the salt concentration when dissolved in a soil solution. This will increase the osmotic potential of the soil solution, making it difficult for the plants to extract water from the soil. The salt index of fertilizers can indirectly affect the yield of the crops. Thus, the estimation of the salt index becomes imperative to know the likelihood of developing plant injury. The higher the value more is the damage caused to the plants leading to low productivity.[9] In this study, the salt index of the prepared biochar shows lower values (0.017 and 0.026 for BLS and NBLS biochar, respectively), demonstrating its suitability for plant growth (Table 1). The results are in accordance with other studies reporting the development of biochar from other biomass.[39] Thus, the developed fertilizer could be safe to be used for sustainable agriculture.

3.2.2. Water Absorbance (WA), Swelling Ratio (SR), and Equilibrium Water Content (EWC). Water absorbance, swelling ratio, and equilibrium water content are essential parameters to be analyzed for any slow-release fertilizer. The

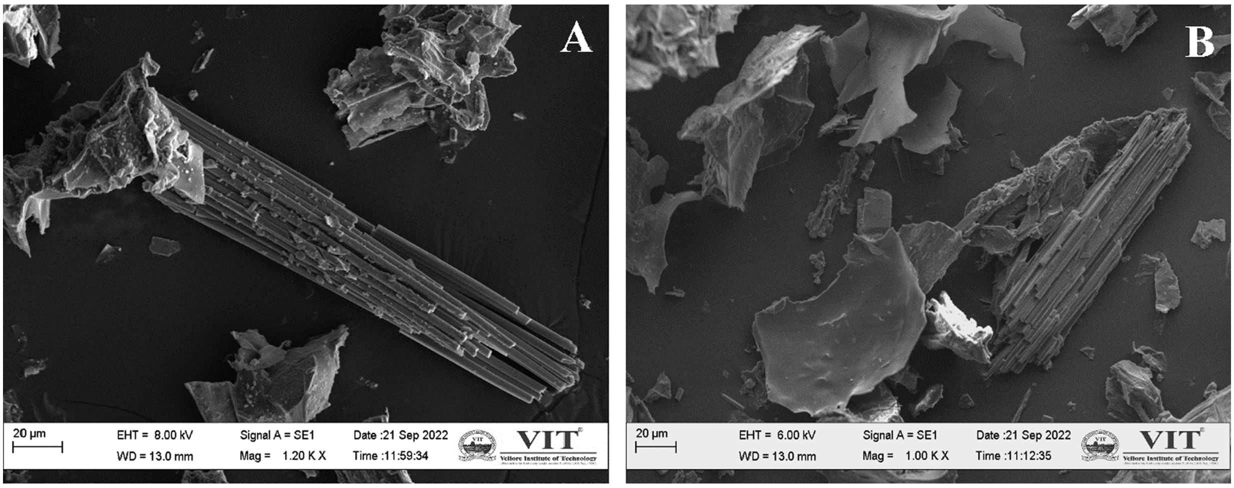

Figure 4. Scanning electron microscopy images of (A) BLS biochar and (B) NBLS biochar.

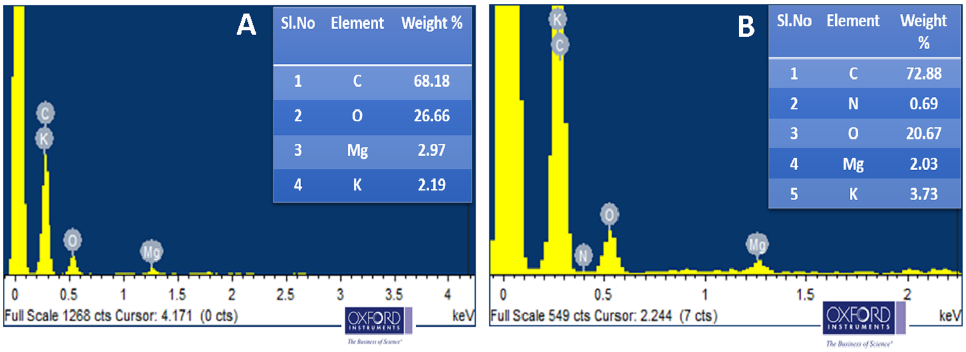

Figure 5. Elemental analysis of (A) BLS biochar and (B) NBLS biochar.

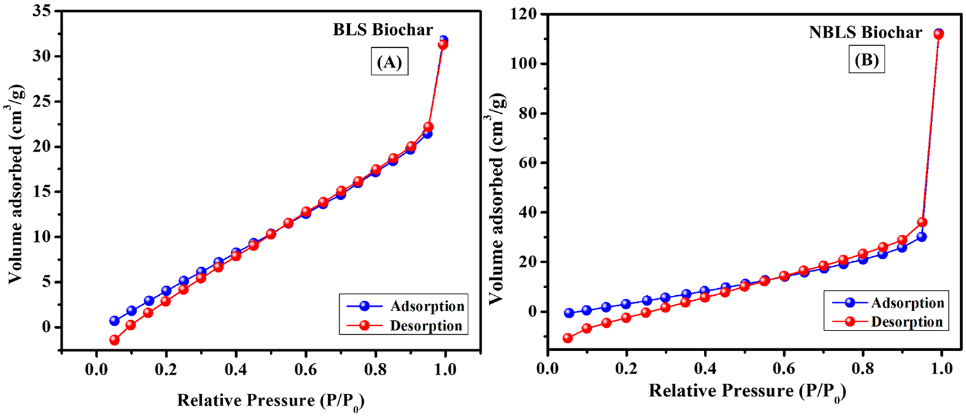

Figure 6. BET Analysis of (A) BLS biochar and (B) NBLS biochar.

Table 1. Properties of the BLS Biochar and NBLS Biochar as Slow-Release Fertilizer

		results	
s. no	physio-chemical characterization	BLS biochar	NBLS biochar
1	salt index (SI)	0.017	0.026
2	swelling ratio (SR)	1.87	2.32
3	equilibrium water content (EWC%)	51%	57%
4	water absorbance studies (WAS%)	80%	88%

results of these three parameters are given in Table 1. NBLS biochar demonstrates a slight increase in the values of water absorbance, swelling ratio, and equilibrium water content compared to the BLS biochar. The porous structure of the biochar favors the absorption of water, which would eventually be released to support plant growth. Several studies have demonstrated the potential of biochar in enhancing physical properties such as the soil structure, porosity, and water retention.[42,43]

3.2.3. Water Retention Studies (WR). The water holding capacity of a soil can be utilized to determine the maximum amount of water stored in the soil and reveal the capacity of the soil to supply water for plant growth.[11] Figure 7 depicts the water retention percentage of the soil with NBLS biochar and without biochar (control). The control soil without biochar displayed a lower percentage of water retention compared to soil with biochar. However, the WR gradually decreases with the number of days. On the fourth, eighth, and 12th day the water retention percentages of control soil were 80.04, 75.50, and 68.51 and for experimental soil were 91.84, 81.56, and 74.10 respectively. The influence of corncob biochar on the WR percentage of the soil was studied by Lateef et al.[9] and similar results have been demonstrated.

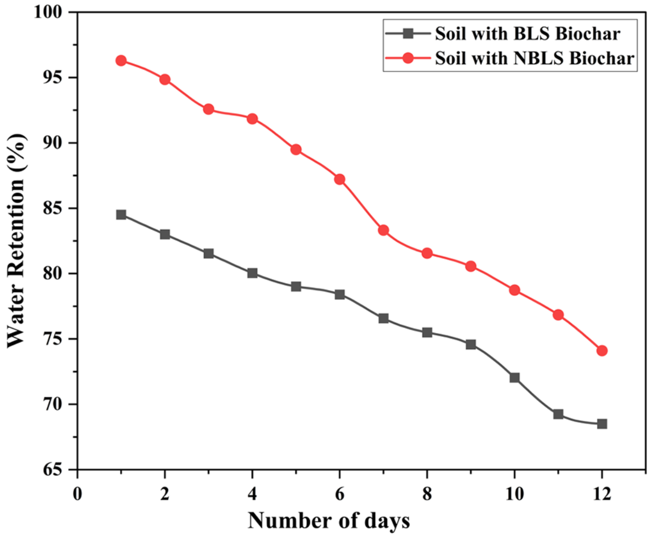

Figure 7. Water holding capacity of BLS biochar (black line) and NBLS biochar (red line).

3.2.4. Nutrient Release Studies in Water. The potential slow-release behavior of the prepared NBLS biochar was carried out in deionized water for a time span of 16 h under controlled temperature maintained at 30 ± 2 °C throughout the process. The release profile of urea from the NBLS biochar and commercial urea fertilizer is shown in Figure 8. Since urea is highly prone to leaching, commercial urea fertilizer shows nearly 100% release within 1 h, whereas only 25, 58 and 76%

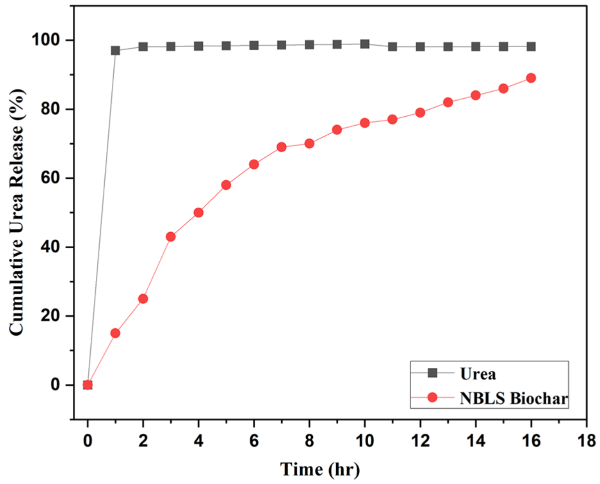

Figure 8. Nutrient release pattern of Urea and NBLS biochar in water.

of urea was released from NBLS biochar at 2, 5, and 10 h, respectively. Various factors with respect to the biochar viz. its porosity, presence of active binding sites, and adsorption of nutrients influence the release of nutrients from the fertilizers.[39] This could also be supported by the results of SEM analysis (Figure 4) showing a porous structure. The presence of surface charges on the biochar plays an important role in the adsorption and chemical interaction of soluble soil nutrients, eventually affecting the distribution of reactive groups. Consequently, the arrangement of these reactive groups on biochar is significant in determining the slow-release behavior of biochar-based slow-release fertilizers.[44] Moreover, the formation of hydrogen bonds between nutrients and reactive groups on the biochar surface is also essential for the slow-release behavior of biochar. The release of nitrogen from biochar is regulated by hydrogen bonding and electrostatic interactions involving the N−C═O and functional groups containing oxygen.[45] Thus, the release pattern shows a steady increase, which is aligned with the nutrient requirement of crops and would thus favor growth and productivity. The release pattern will also help reduce the loss of nutrients due to leaching commonly observed in conventional fertilizers.[46] A similar approach has been reported by several researchers as an acceptable method for determining the appropriateness of fertilizers for crops.[46,47] A comparison of the results of the present study with those reported in the previous research studies is provided in Table 2.

4. CONCLUSIONS

Banana leaf sheath biochar was prepared by simple pyrolysis and was loaded with nutrients by mixing with a urea solution. The nutrient-loaded biochar designated as NBLS was subjected to various analytical and physicochemical characterization. The results of XRD showed the high carbon content of the biochar with slight changes in the intensities of the peaks due to nutrient loading. FT-IR analysis revealed the presence of various functional groups in the biochar. From SEM analysis, the morphology of the biochar before and after nutrient loading displayed a porous structure that favored nutrient loading. The nutrient loading was further confirmed by elemental analysis through EDAX. The low salt index values suggested the suitability of NBLS biochar as a clean fertilizer. Also, the results of water absorbance, swelling ratio, equilibrium water content, and water retention studies demonstrated its ability to support plant growth. The nutrient release studies showed a gradual increase in the nitrogen release percentage matching the nutrient requirement of crops. This would also reduce the loss of nutrients by leaching, which is one of the limitations of conventional fertilizers.

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Author Contributions

K.R.: conceptualization, data curation, and writing-original draft. V.R.: conceptualization, visualization, review, supervision, editing.

Notes

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Table 2. Comparison of Biochar-Based Slow Release Fertilizers

fertilizers	preparation methods	nutrient	slow-release behavior	references
biochar-based controlled release nitrogen fertilizer coated with polylactic acid	impregnation, granulation and encapsulation	ammonium sulfate	70% N release in water over a period of 12 days	48
biochar as scaffolding for slow release of nitrogen fertilizer	granulation and encapsulation	urea	61−90% urea release in 4320 min	49
biochar as a coating material for biochar-coated urea	impregnation, granulation and encapsulation	urea	total nitrogen release rates below 75% on 28th day	50
biochar-based slow-release nitrogen fertilizer	impregnation	ammonium nitrate	nitrate and ammonia release of 52.9 and 77.4% after 1h	51
slow-release fertilizer encapsulated by biochar-based waterborne copolymers	encapsulation	potassium nitrate	accumulative nitrogen leaching of 65.28% after 22 days	52
biochar based slow- release nitrogenous fertilizers	impregnation	urea	cumulative urea release of 76−85% in tap water in 18 h	present study

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