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Sugarcane bagasse-derived multi-nutrient-enriched biochar as a soil amendment for laterite soils

Aida Treesa Sojan[1], Smitha John Kundukulam[1]*, T. Geetha[2], Shanthi Prabha Viswanathan[3], V. Thulasi[4], V. I. Beena[1], C. Santhosh[1], S. Anitha[5], P. S. Muhammed Abdullah[1]

[1]Department of Soil Science and Agricultural Chemistry, College of Agriculture, Kerala Agricultural University, Thrissur, Kerala, India.
[2]Department of Chemistry, Vimala College (Autonomous), Thrissur, Kerala, India.
[3]Biochar Today, Reddick, Florida, USA.
[4]Department of Soil Science and Agricultural Chemistry, Regional Agricultural Research Station, Palakkad, Kerala, India.
[5]Department of Agronomy, College of Agriculture, Kerala Agricultural University, Thrissur, Kerala, India.

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ABSTRACT

Sugarcane bagasse, a major agro-industrial byproduct generated during sugar extraction, poses serious disposal challenges, particularly in India, where more than 91 million tons of SB are produced each year. Sugarcane bagasse has traditionally been used for combustion-based energy recovery; however, the environmental downsides of bagasse burning – such as air pollution and soil degradation – necessitate sustainable alternatives. The present work explores the valorization of sugarcane bagasse through, pyrolysis to produce biochar, followed by its conversion into a multi-nutrient-enriched fertilizer (sugarcane biochar-based multi-nutrient fertiliser [SBMNF]). Sugarcane bagasse was pyrolyzed at 330°C and subsequently impregnated with a stabilized multi-nutrient mixture containing Nitrogen, Potassium, Zinc, Boron, Copper, Iron, Manganese, and Molybdenum. The resulting SBMNF was characterized for its physicochemical properties (pH, electrical conductivity, ash, porosity), structural features (scanning electron microscopy, Fourier-transform infrared, X-ray diffraction), and thermal stability (thermogravimetric analysis-derivative thermogravimetry). Compared with raw sugarcane bagasse, SBMNF exhibited improved porosity (71.15%), water absorption (56.5%), swelling ratio (5.96 g/g), and equilibrium water content (95.8%). It also improved the water retention capacity of SBMNF-amended laterite soils. These results highlight SBMNF's dual role in waste valorization and soil fertility enhancement. The study presents a scalable and eco-friendly strategy to recycle sugarcane residues into value-added, climate-resilient agro-inputs for sustainable farming systems.

1. INTRODUCTION

Sugarcane (*Saccharum officinarum* L.), known for its high sugar content, is a primary feedstock in the sugar industry and industrial ethanol production [1]. Sugar extraction generates a large amount of waste, approximately 279 million metric tons of sugarcane bagasse globally, which is composed of 40–50% cellulose, 19–25% hemicellulose, 17–25% lignin, and 2–4% ash [2]. Disposing this residue in an environmentally sustainable manner remains a challenge for the sugar industry. Although some sugar mills utilize bagasse for the cogeneration of steam and electricity to meet their internal energy needs, a significant proportion of this byproduct remains underutilized. While a part of the bagasse is used in landfills or the paper industry, most of it is still discarded inappropriately through incineration [3-5]. Burning of sugarcane bagasse has severe environmental consequences, including degraded air quality and the release of harmful pollutants, such as volatile organic compounds and carbon monoxide (CO). It also leads to environmental contamination and reduces soil microbial diversity due to the generation of fly ash [6].

Sugarcane bagasse, an agro- waste, can be used directly as a soil amendment. Upon incorporation into the soil as an amendment, it acts as a natural organic fertilizer, improving hydro-physico-chemical properties of soil, such as water-holding capacity, cation exchange capacity, and organic matter. In addition, soil health is improved by boosting water absorption and greater availability of key macronutrients, such as Nitrogen (N), Phosphorus (P), and Potassium (K). Moreover, the addition of sugarcane bagasse enhances soil drainage, aeration, and structural stability. Consequently, the application of sugarcane bagasse to soil reduces the dependence on irrigation and chemical fertilizers, thereby lowering environmental pollution [7]. Despite these benefits, the bulky and voluminous nature of sugarcane bagasse makes its direct

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**Corresponding Author:*
Smitha John Kundukulam,
Department of Soil Science and Agricultural Chemistry, College of Agriculture, Kerala Agricultural University, Thrissur - 680656, Kerala, India.
E-mail: smithajohn.k @ kau.in

field application impractical, as the process is labor-intensive and time-consuming. The volume of sugarcane bagasse can be reduced through composting or by converting it into biochar. Composting sugarcane bagasse generates nutrient-rich organic manure loaded with helpful microbes that can be used as an organic fertilizer [8]. Nevertheless, composting is a labor- and time-intensive process. In contrast, the conversion of sugarcane bagasse into biochar is relatively rapid and results in a substantial reduction in material volume.

Biochar is a porous carbon-rich material produced by pyrolysis under an oxygen-limited atmosphere. The conversion of agricultural biomass into biochar represents an environmentally sustainable disposal strategy, as it involves relatively low greenhouse gas emissions during production [9-11]. With its application as a soil amendment, biochar improves soil structure, enhances water retention, and promotes nutrient uptake; moreover, it contributes to climate change mitigation by serving as a persistent carbon sink [12,13]. Most studies have reported that the addition of biochar to soil improved soil quality significantly in acidic and neutral pH soils. The alkaline nature of biochar can directly neutralize acidic soils and the functional groups on its surface may adsorb hydrogen ions, reducing soil acidity. It also improves water holding capacity and nutrient availability of coarse or medium textured soils [14-18]. However, improvement in nutrient content depends upon the nutrient content of biochar, which in turn depends on the feedstock and pyrolysis temperature. Furthermore, a substantial amount of biochar is typically required to achieve a high crop yield [19,20]. This problem can be overcome if the biochar is enriched with nutrients before being applied to soil.

Attempts have been made to improve the quality of biochar by combining it with organic fertilizers. Soaking biochar in anaerobic digestate enriches it with ammoniacal N, K and phosphate ions. However, this method was not widely adopted due to the difficulty of transporting digestate from commercial biogas plants to biochar production units [20]. Mixing biochar with organic fertilizer, such as solid digestate and vermicompost, is another method of preparing biochar-based fertilizer, but the fertilizer so prepared contained only around 15–30% biochar [14,15]. A more effective approach toward augmenting the quality of biochar is by loading it with inorganic fertilizers. Loading inorganic fertilizer onto biochar offers a pathway that limits nutrient loss from the field by leaching and enhances crop yields by 20–30% [21,22]. Previous studies have reported the synthesis of biochar enriched with primary macronutrients, such as N (urea), P (phosphate), and N-P-K, secondary macronutrients, such as Calcium (Ca) and Magnesium (Mg), and micronutrients, such as Zinc (Zn) and Iron (Fe) [23-26]. However, no attempt has been made to enrich biochar through multi-element adsorption encompassing primary macronutrients, such as N and K, along with micronutrients, such as Zn, Boron (B), Copper (Cu), Fe, Manganese (Mn), and Molybdenum (Mo). This study details the conversion of sugarcane bagasse into multi-nutrient-enriched biochar-based fertilizers by intercalating essential nutrients into its porous structure.

Unlike earlier studies that mainly focused on macronutrients, such as N, P, and K [23,27], the present study emphasizes multi-element adsorption to maximize overall soil benefits, improve soil health, and enhance productivity, particularly in laterite soils. The objectives of the study are to: (1) Thermochemically convert sugarcane bagasse into sugarcane biochar and (2) intercalate multi-nutrients into the biochar matrix. This dual-purpose approach addresses both waste management and nutrient leaching challenges, thereby promoting sustainable agricultural practices.

2. MATERIALS AND METHODS

2.1. Preparation of sugarcane-biochar (SB)

Sugarcane biochar was prepared by pyrolyzing sugarcane bagasse collected locally from sugarcane juice vendors in Thrissur District, Kerala, India. The raw material was air-dried for 2–3 days, chopped into small pieces, and placed in a local kiln of 90 cm^3 chamber size with a strong metallic lid [Figure 1(a-c)]. The flow of air into the kiln was restricted by mud plastering. The temperature of 330°C was maintained with a mean residence time of 24 h. The biochar was then collected, cooled, crushed, and sieved through a 2 mm sieve to obtain a fine, homogeneous powder [Figure 1(d)].

2.2. Preparation of Multi-nutrient Mixture (MNM) and Stability Analysis

The MNM was prepared by the combination of urea ($CO(NH_2)_2$), potassium sulfate (K_2SO_4), zinc sulfate ($ZnSO_4.\ H_2O$), boric acid (H_3BO_3), copper sulfate ($CuSO_4.5H_2O$), ferrous sulfate ($FeSO_4.7H_2O$), Mn sulfate ($MnSO_4.7H_2O$) and molybdenum trioxide (MoO_3) to achieve a composition of 7.5% N, 10% K, 6% Zn, 4% B, 0.02% Cu, 0.02% Fe, 0.25% Mn, and 0.01% Mo. The stability and storage quality of the prepared MNM were analyzed by observing color change, solubility, and tendency to cake at regular intervals over 6 months.

2.3. Intercalation of MNM to SB to Obtain Sugarcane Biochar-Based Multi-Nutrient Fertilizer (SBMNF)

The SBMNF was prepared by intercalating multi-nutrients onto the biochar. To 100 mL of distilled water, 10 g of biochar and 0.5 g of nutrient mixture were added and agitated for 3 h on a rotary shaker at ambient temperature. The suspension was then filtered, The substrate was oven-dried at 105°C for 24 h, and stored in plastic containers for further analysis and use.

2.4. Characterization of SB and SBMNF

2.4.1. Physical and chemical properties

The moisture content, ash percentage, pH, and electrical conductivity (EC) of SB and SBMNF were determined in duplicate using standard procedures, and the mean values were reported [28,29]. Bulk density, particle density, and porosity were determined using the Keen–Raczkowski box method [30].

2.4.2. Analytical characterization

Understanding the morphology, structure, and chemical composition of biochar is crucial for determining its potential applications in various areas, such as restoration of the environment, soil improvement, and carbon sequestration. The morphology of SB and SBMNF was analyzed using scanning electron microscopy (SEM) (Joel 6390LA/OXFORD XMX N SEM-EDAX), and functional groups were identified via Fourier-transform infrared (FT-IR) Spectroscopy (Perkin Elmer Spectrum). X-ray diffraction (XRD) (Aeris XRD, Malvern Panalytical) was used for determining the phase and assessing the crystallinity. Thermal stability was examined using a Thermogravimetric analyzer (TGA) (Perkin Elmer STA6000).

2.4.3. Water Absorption, Swelling Ratio (SR), and Saturation Moisture Content (SMC)

Water absorption was determined by immersing a biochar sample (initial weight W_1) in deionized water for 5 days and then reweighing the wet sample after immersion (W_2) and calculating water absorption using equation (1) [31].

$$Water\ Absorption\ (\%) = \frac{(W_2 - W_1)}{W_1} \times 100 \quad (1)$$

SR and SMC were measured by soaking one g of biochar in 200 mL of water for 24 h. The SR and SMC were calculated using equation (2) and (3) [32].

$$SR(g/g) = \frac{(W_S - W_d)}{W_d} \quad (2)$$

$$SMC\ (\%) = \frac{(W_S - W_d)}{W_S} \times 100 \quad (3)$$

where, W_d represents the dry weight and W_s represents the wet weight of the biochar.

2.4.4. Water retention studies

Laterite soil used for this experiment was initially characterized and its pH, texture and EC were determined. A pre-weighted cup was taken, into which 50 g of laterite soil was added, followed by 30 mL of deionized water (W_{D0}). This cup was then placed inside a closed glass container, and its weight was measured every day over 10 days (W_{Dn}). Water retention was determined using equation (4). The experiment was done in duplicate.

$$WR\ (\%) = \frac{W_{Dn}}{W_{D0}} \times 100 \quad (4)$$

The procedure was repeated with 50 g of soil mixed with 2 g of SBMNF to determine the water retention of SBMNF- amended soil.

3. RESULTS AND DISCUSSION

3.1. Synthesis of MNM

The nutrient mixture was formulated using various Analytical Reagent grade chemicals and monitored at regular intervals over 6 months. No color change or caking was observed throughout the study. It also dissolved readily in deionized water. Thus, the nutrient mixture is stable and can potentially be stored for at least 6 months.

3.2. Characterization of SB and SBMNF

3.2.1. Physical and electrochemical properties

The physical and electrochemical properties of the biochar (SB) and the developed SBMNF are presented in Table 1. A notable reduction in pH occurred in SBMNF (8.58) compared with SB (9.76), which indicates a shift toward neutrality upon nutrient incorporation. The EC decreased from 1.73 dS/m in SB to 1.14 dS/m in SBMNF, suggesting a lower soluble salt content in the modified material. The ash content significantly declined from 33.07% in SB to 6.49% in SBMNF, an 80% decrease, while the moisture content increased by 9.3%, from 9.6% to 18.90%, likely due to nutrient impregnation and enhanced water retention. A slight increase in bulk density (6.25%) was observed in SBMNF compared to SB, while the particle density decreased by 18.42%. The porosity improved marginally in SBMNF (71.15%) compared to SB (67.87%), a 4.8% increase, indicating better aeration and potentially enhanced nutrient-holding capacity in the formulated fertilizer. Since SBMNF was prepared by vigorously shaking the biochar in a nutrient solution to impregnate nutrients, it is possible that fine ash particles were lost from the sugarcane biochar during the process [33]. This loss of ash particles may account for the higher porosity, the lower pH, EC, and ash content of SBMNF compared to SB. In addition, the nutrient impregnation process, by depositing nutrients into the biochar's pores, likely contributed to an increase in the bulk density of SBMNF. The final nutrient content in SBMNF was found to be 0.56% N, 1.23% P, and 1.027% K, along with micronutrient concentrations of Fe at 1927 mg/kg, Zn at 902 mg/kg, Mn at 386 mg/kg, B at 117.14 mg/kg, and Cu at 76 mg/kg.

Table 1: Physical and electrochemical properties of SB and SBMNF.

S. No.	Parameters	SB	SBMNF
1	pH	9.76	8.58
2	EC (dS/m)	1.73	1.14
3	Ash (%)	33.07	6.49
4	Moisture (%)	9.6	18.90
5	Bulk density (mg m^{-3})	0.16	0.17
6	Particle density (Mg m^{-3})	1.14	0.93
7	Porosity (%)	67.87	71.15

SBMNF: Sugarcane biochar-based multi-nutrient fertilizer.

3.2.2. FT-IR spectroscopy

The functional groups on the surface of both SB and SBMNF were identified by FT-IR spectroscopy [Figure 2a and b]. Both SB and SBMNF show common functional groups [Table 2]. A broad peak appearing between 3650 cm^{-1} and 3000 cm^{-1} can be attributed to OH-stretching vibrations, possibly originating from either water molecule adsorbed on the biochar or residual hydroxyl groups remaining after partial degradation of cellulose or hemicellulose. The peaks at 1567 cm^{-1} in SB and at 1561 cm^{-1} in SBMNF are characteristic of carbon carbon double bond (C=C) stretching of the aromatic ring. The one at 1374 and 1371 cm^{-1} indicated C-H deformation, possibly originating from residual hemicellulose and cellulose fragments in the biochar [34]. The absorption peak at 1035 cm^{-1} may correspond to aromatic C-H [35] or to the Si-O-Si bond of SiO_2 [36]. Furthermore, the peak at 874 cm^{-1} could be attributed to C-H stretching, and the

Figure 1: Process of biochar preparation: (a) Kiln used for biochar preparation, (b) Kiln filled with sugarcane bagasse, (c) Closed kiln during pyrolysis process, (d) Sugarcane biochar.

peaks at 754 and 750 cm^{-1} were probably due to out-of-plane ring deformation or weak vibrational –CH_2 rocking [37]. The peaks observed in the region between 500 and 800 cm^{-1} in SB and SBMNF could be assigned to metal oxides, such as FeO and ZnO [38].

3.2.3. Powdered XRD (p-XRD)

The p-XRD pattern of SB and SBMNF in the scan range of 0–80° are presented in Figure 3. The diffuse broad band, centered at 2θ value 22°, indexed as C (002), indicates the amorphous nature of the biochar. The short, narrow, intense peak at 2θ value 31° suggests the presence of a highly crystalline inorganic fraction, which may be attributed to SiO_2. In the XRD spectra of SBMNF [Figure 3b], the broad peak centered around 2θ value 23° was more pronounced than in SB. Moreover, the peaks attributed to inorganic moieties at 2θ values of 30° and 31.3° decreased in intensity. Of these peaks, the one at 30° might be attributed to SiO_2, while the one at 31° is assigned to calcium oxide. These minor changes in the intensities of SBMNF may be attributed to the adsorption of nutrients on the surface of the biochar, without altering its basic carbon structure.

Table 2: Functional groups of SB and SBMNF according to FT-IR spectrum.

S. No.	SB (cm^{-1})	SBMNF (cm^{-1})	Functional group
1	3000–3650	3000–3650	OH-stretching vibrations
2	1567	1561	C=C stretching of the aromatic ring
3	1374	1371	C-H deformation
4	1035	1035	aromatic C-H or Si-O-Si bond of SiO_2
5	874	874	C-H stretching
6	754	750	–CH_2 rocking or out-of-plane ring deformation
7	-	521	M-O bonds

SBMNF: Sugarcane biochar-based multi-nutrient fertilizer,
FT-IR: Fourier-transform infrared.

3.2.4. Thermogravimetric analysis (TGA)

The TGA profile of SB [Figure 4a] exhibited an initial weight loss of approximately 10–12% within the 100–120°C range, primarily due to the evaporation of moisture and the volatilization of thermally unstable compounds on the biochar surface [39-41]. Further weight reduction between 100°C and 400°C was attributed to the thermal breakdown of cellulose. A prominent peak observed at around 411°C, marked by overlapping weight loss, was associated with the degradation of more stable organic components, such as lignin. This phase likely involves both the formation of aromatic structures and the evolution of gases, such as CO_2, CO, and CH_4. A sharp mass loss occurred during this stage, leading to a residual yield of 20–30% [42].

In contrast, the TGA and derivative thermogravimetry (DTG) curves of SBMNF [Figure 4b] showed distinct thermal behavior. The initial peak between 30°C and 100°C, corresponded to a 5–10% weight loss, which was attributed to the evaporation of physically bound moisture. The mass remained comparatively stable up to about 350°C, indicating a limited presence of loosely bound volatiles or free water. A major weight loss, exceeding 50–60%, was recorded between 300°C and 550°C, likely due to the decomposition of nutrient-loaded organic matter. Beyond this stage, from 550°C to 750°C, the mass stabilized,

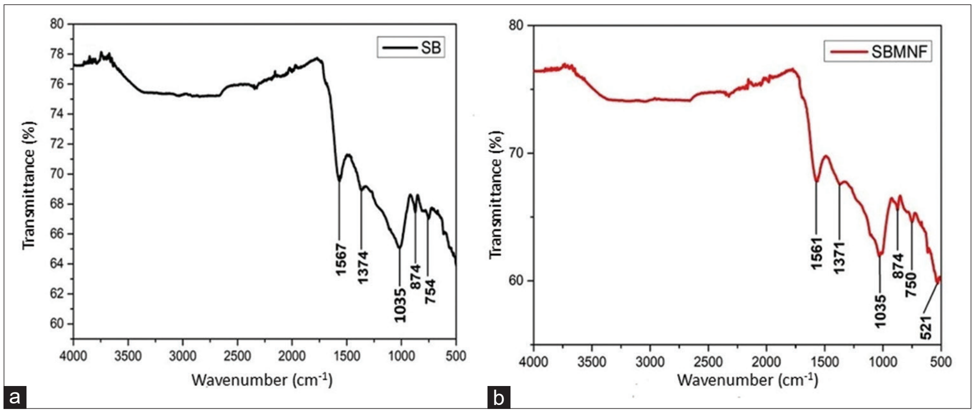

Figure 2: Fourier-transform infrared spectroscopy of (a) SB and (b) sugarcane biochar-based multi-nutrient fertiliser.

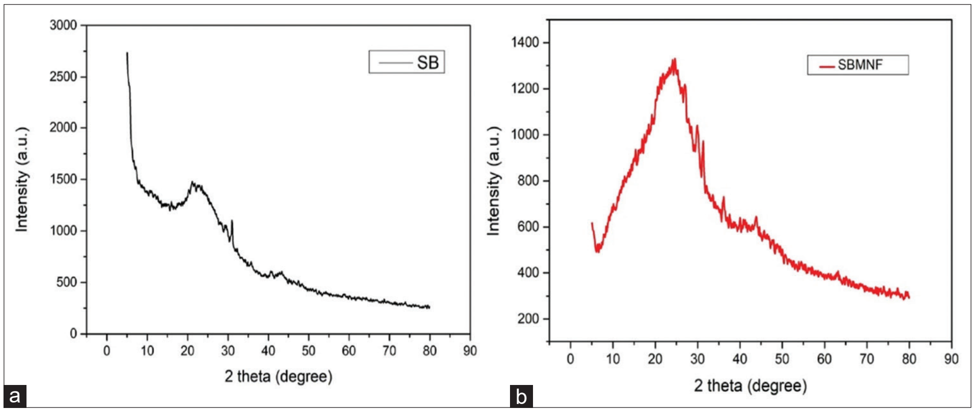

Figure 3: X-ray diffraction analysis of (a) SB and (b) sugarcane biochar-based multi-nutrient fertiliser.

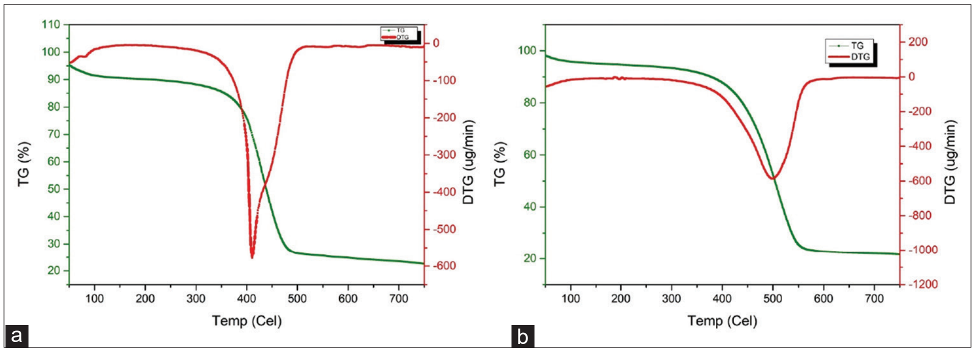

Figure 4: Thermogravimetric analysis (green line) and derivative thermogravimetry (blue line) thermograms of (a) SB and (b) sugarcane biochar-based multi-nutrient fertiliser.

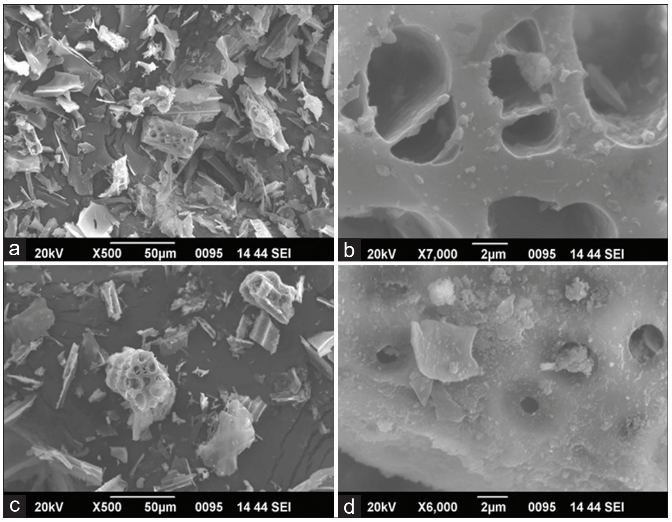

Figure 5: Scanning electron microscopy micrographs of SB (a and b) and sugarcane biochar-based multi-nutrient fertilizer (c and d), to 50 µm and 2 µm, respectively.

leaving behind inert ash residues. Notably, the DTG peak of SBMNF shifted to a higher temperature range (411°C–498.5°C), implying improved thermal stability. This peak shifts further validate the successful incorporation of nutrients into the biochar matrix.

3.2.5. SEM

The biochar exhibited a sieve-like appearance with well-developed pores in the SEM images at 50 µm and 2 µm magnification [Figure 5a and b]. Pore formation may be due to the rapid volatilization of organic components present in feedstock materials during the pyrolysis [43,44]. The porous structure of the biochar and the diversity of pore sizes may aid in binding multiple metal ions [9]. An unevenly thick surface texture is observed in the SEM micrographs of SBMNF at 50 µm and 2 µm magnification [Figure 5c and d], indicating the successful loading of nutrients onto the sample. SBMNF exhibited a smaller average pore size compared to SB, likely due to the deposition of nutrients on the inner walls of the pores [24,45].

3.2.6. Water absorption, SR and SMC

The water absorption (WA), SR, and SMC of SB and SBMNF are presented in Table 3.

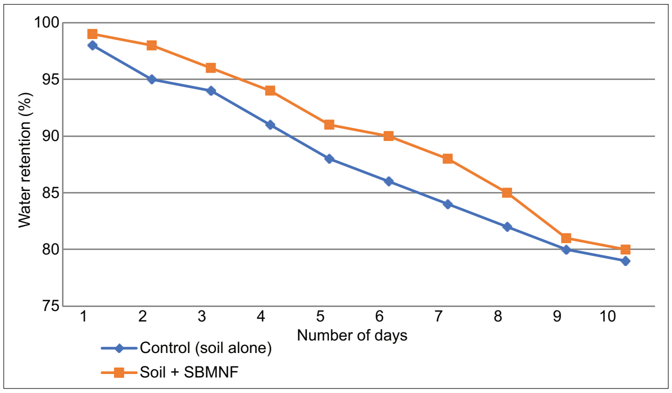

Figure 6: Water retention capacity of soil + sugarcane biochar-based multi-nutrient fertiliser and soil alone.

Table 3: Physicochemical properties of SB and SBMNF.

S. No.	Properties	SB	SBMNF
1	Water absorbance (%)	51.50	56.50
2	Swelling ratio (g/g)	4.48	5.96
3	Saturation moisture content (%)	81.75	95.80

SBMNF: Sugarcane biochar-based multi-nutrient fertilizer.

Previous studies have reported that the addition of biochar to laterite soil improves its water-holding capacity due to the presence of abundant micropores in biochar that helps retain water. It is also known to improve soil aggregation [46,47]. In this study, the ability of SBMNF to absorb and retain water was greater than that of SB. The WA, SMC, and SR of SBMNF were higher than SB, indicating that SBMNF is a superior soil amendment, especially under dry climatic conditions. These improved properties can also expand the range of plant-available water by lowering the permanent wilting point and increasing field capacity, thereby enhancing water availability for plants. Soil amended with SBMNF can delay the onset of water stress in crops. It can retain more water from precipitation, potentially boosting crop yields in non-irrigated regions and improving irrigation efficiency in areas reliant on irrigation [20]. The enhanced water absorption and retention capabilities of biochar-based fertilizers have been reported previously. It has been suggested that the deposition of nutrients as aggregates on an asymmetrical plane and the resulting changes in porosity may explain the higher WA, SMC, and SR observed in SBMNF [25,26,48].

3.2.7. Water retention studies

The water retention capacity of soil reflects its ability to provide moisture essential for plant growth. The laterite soil used in this experiment was classified as sandy clay loam in texture. The soil pH was 5.2, and the EC was 0.02 dS/m. Figure 6 presents the percentage of water retained by both the control soil and SBMNF-amended soils over a period of 10 days. The graph clearly shows a gradual decline in water retention percentage over time. Soils treated with SBMNF consistently retained more water than the control throughout the observation period. This improved retention can be attributed to the high internal microporosity of biochar and the capacity of fine biochar particles to occupy the gaps between soil particles [49]. This interaction reduces the average pore size, thereby increasing soil micropores and enabling water to be retained for extended durations [50].

4. CONCLUSION

This study successfully demonstrates the valorization of sugarcane bagasse, an abundant agro-industrial waste, into a SBMNF, addressing the dual challenges of agricultural waste management and inefficient nutrient delivery. By enriching sugarcane bagasse biochar (SB) with both macro- and micronutrients, we developed a material that exhibits improved physicochemical properties, including higher porosity, greater water retention, and enhanced thermal stability. The addition of biochar to laterite soil improves its water retention capacity. The characterization techniques (SEM, FTIR, XRD, and TGA) confirmed successful nutrient loading without altering the core structure of the biochar. Thus, SBMNF emerges as a promising alternative to conventional fertilizers. Its ability to release nutrients gradually makes it particularly suitable for lateritic and moisture-deficient soils, offering a sustainable, climate-smart solution for improving soil fertility and crop productivity. By converting agricultural residues into high-value inputs, the adoption of SBMNF supports the principles of a circular bioeconomy, reinforcing the potential of biochar-based fertilizers in advancing sustainable agriculture.

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6. AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

7. CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper. Shanthi Prabha Viswanathan is affiliated with Biochar Today, Reddick, Florida; however, this affiliation did not influence the study design, data collection, analysis, interpretation of results, manuscript preparation, or the decision to publish. The author acted entirely in an independent capacity.

8. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

9. DATA AVAILABILITY

All the data is available with the first author and corresponding author and shall be provided upon request.

10. PUBLISHER'S NOTE

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11. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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