

Development and Characterization of Sugarcane Bagasse Cellulose (SBC) and Recycled Polystyrene (RPS) for Filtration of Water

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Abstract

The increasing generation of agricultural residues and plastic wastes creates an opportunity for developing low-cost materials for water treatment. This study developed and characterized a sugarcane-bagasse-cellulose/recycled-polystyrene (SBC-rPS) granular composite and compared a non-templated composite (S1) with a calcium-carbonate-templated porous composite (S2). Sugarcane bagasse was subjected to alkaline delignification and bleaching to obtain cellulose, while post-consumer expanded polystyrene (EPS) was cleaned and dissolved in toluene to produce recycled polystyrene resin. Sodium dodecyl sulfate (SDS) was used as a compatibilizing agent. S2 additionally contained CaCO_3 as a sacrificial pore-forming agent followed by acid leaching with 1 M HNO_3 . The composites were characterized using FTIR, XRD, SEM-EDS and BET nitrogen adsorption. Filtration performance was evaluated using synthetic kaolin turbid water at initial turbidity levels of 10, 5 and 1 NTU and flow rates of 1.11, 3.23 and 7.26 mL/s. FTIR confirmed retention of characteristic polystyrene bands in both composites, while the O-H absorption was less prominent in S2. The dominant XRD reflection occurred at 22.23° for S1 and 29.47° for S2. SEM showed a comparatively compact S1 morphology and a more open, irregular S2 structure. BET surface area increased from $254.612 \text{ m}^2/\text{g}$ for S1 to $275.762 \text{ m}^2/\text{g}$ for S2, while BJH pore volume increased from 0.130 to $0.135 \text{ cm}^3/\text{g}$. S2 consistently outperformed S1 in turbidity removal. At 1.11 mL/s, S2 achieved 63%, 88% and 92% removal at 10, 5 and 1 NTU, respectively. The maximum observed removal was 92% at 1 NTU. The results demonstrate the potential of the waste-derived SBC-rPS composite as a granular filtration medium, particularly for low-turbidity polishing applications.

Keywords: sugarcane bagasse cellulose; recycled polystyrene; porous composite; SDS; CaCO_3 ; turbidity removal; granular filtration; waste valorization

Introduction

The demand for sustainable water-treatment materials is increasing alongside concerns about water security, plastic pollution and the environmental burden of conventional filtration media. Sugarcane bagasse is an abundant lignocellulosic residue containing substantial cellulose, while expanded polystyrene is a persistent plastic waste that is difficult to recycle because of its low density and collection challenges. Converting both wastes into a functional filtration material offers a circular-economy route for waste valorization (Geissdoerfer et al., 2017; Pang et al., 2018; Lopez et al., 2017). Cellulose is attractive for water-treatment materials because of its

hydroxyl-rich structure and potential for surface interactions. However, cellulose is hydrophilic whereas polystyrene is hydrophobic, creating an interfacial compatibility challenge. Surfactant-mediated compatibilization can improve dispersion and interfacial interaction between the phases. In this work, sodium dodecyl sulfate (SDS) was used to assist composite formation (Hassan et al., 2022; Liu et al., 2020). A second design strategy was the introduction of calcium carbonate as a sacrificial porogen. CaCO_3 can be incorporated into a polymeric matrix and subsequently leached with acid to generate additional voids and surface accessibility (Sergeeva et al., 2015; Wu et al., 2024). The present study therefore investigated whether a porous SBC-rPS composite could provide improved turbidity removal compared with a non-templated control. The specific objective was to develop the two SBC-rPS formulations, characterize their chemical, structural, morphological and textural properties, and compare their turbidity-removal performance under different influent turbidity levels and flow rates.

Materials and Methods

Materials

Sugarcane bagasse was obtained from Savannah Sugar Company Limited, Numan, Adamawa State, Nigeria. Post-consumer EPS was collected from waste sources in Yola, Adamawa State. Analytical-grade sodium hydroxide, sodium hypochlorite, toluene, SDS, calcium carbonate and nitric acid were used. A calibrated HACH 2100N turbidimeter was used for turbidity measurement.

Preparation of Sugarcane Bagasse Cellulose

Approximately 604 g of dried and pulverized sugarcane bagasse was subjected to alkaline delignification followed by bleaching. The delignified pulp was bleached using 500 mL of 5% (w/v) sodium hypochlorite at 70 °C for 90 min with continuous stirring. The pulp was filtered, repeatedly washed to neutral pH, oven-dried at 60 °C for 24 h, ground and stored in airtight containers. The procedure was adapted from reported cellulose-extraction approaches (Aigbodion et al., 2019; Adewuyi & Pereira, 2021; Pang et al., 2018).

Recycling and Dissolution of Polystyrene

The collected EPS was sorted, washed with dilute detergent, rinsed and air-dried for 24–48 h. Dried EPS was cut into small pieces and 100 g was added to 420 mL of analytical-grade toluene. The mixture was stirred at 60 °C for 4–6 h until a homogeneous viscous resin was obtained. The solution was filtered while warm through a Whatman GF/A glass microfiber filter under vacuum and stored in airtight glass containers (Lopez et al., 2017; Ramos et al., 2020).

Fabrication of S1 and S2 Composites

Composite	Cellulose (g)	rPS resin (mL)	SDS (g)	CaCO_3 (g)
S1 (non-templated)	30	250	25	0
S2 (porous)	30	250	25	30

For both formulations, 250 mL of rPS resin was mixed with 25 g SDS for 30 min at room temperature. Thirty grams of prepared cellulose was then added gradually and the mixture was heated to 50 °C for 1–2 h to obtain homogeneous slurry. For S1, the slurry was cast to approximately 5 mm thickness, air-dried for 24 h and cured at 80 °C for 6 h before crushing and sieving. For S2, 30 g of 5–10 μm CaCO_3 was first dispersed in the slurry, followed by casting,

drying, curing, crushing and sieving. S2 granules were immersed in 1 M HNO₃ for 24 h, washed to neutral pH and dried at 60 °C for 24 h to generate the porous structure.

Characterization S1 and S2 Composites

FTIR spectra were acquired over the infrared region using an Agilent FTIR instrument at 4 cm⁻¹ resolution with 32 scans. SEM–EDS were used to examine surface morphology and localized elemental composition. XRD was performed using Cu-K α radiation ($\lambda = 1.5406 \text{ \AA}$), with patterns recorded over approximately 5–80° 2 θ at 2°/min. BET nitrogen adsorption–desorption was conducted after degassing samples at 120 °C for 12 h; BET surface area and BJH pore parameters were determined. These procedures follow the methodology reported in the thesis and associated literature (Thakur & Thakur, 2018; Thommes et al., 2015).

Turbidity Filtration Test

The composites were evaluated in a laboratory column system using synthetic kaolin turbid water. Initial turbidity levels were 10, 5 and 1 NTU, and flow rates were 1.11, 3.23 and 7.26 mL/s. Influent and effluent turbidity were measured using a HACH 2100N turbidimeter. Experiments were conducted in triplicate. Removal efficiency was calculated as:

$$\text{Turbidity removal (\%)} = [T_i - T_f / T_i] \times 100$$

Where T_i is influent turbidity and T_f is effluent turbidity (APHA, AWWA, & WEF, 2017).

Results and Discussion



Figure 1. Pictorial representation of the prepared SBC–rPS composites: S1 (non-porous control) and S2 (porous composite)

FTIR Analysis

The S1 spectrum contained a broad O–H band at approximately 3468.9 cm⁻¹, together with bands near 3026.6, 2922.5 and 2852.5 cm⁻¹ associated with aromatic and aliphatic C–H stretching. Peaks around 1602.8, 1498.4 and 1453.5 cm⁻¹ were consistent with aromatic-ring vibrations of the polystyrene phase, while bands around 1172.2 and 1023.6 cm⁻¹ were associated with cellulose fingerprint-region vibrations.

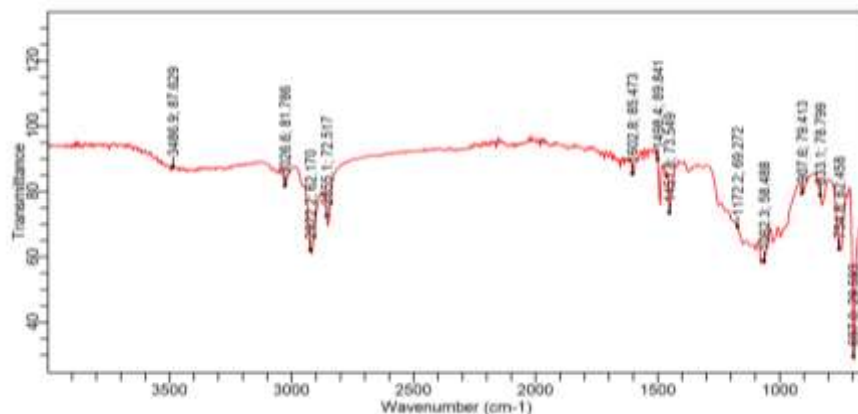


Figure 1. FTIR spectrum of S1 (non-porous SBC-rPS composite)

S2 retained the main polystyrene-related bands, including approximately 3026.6, 2920.8, 2852.8, 1599.0, 1495.5 and 1455.7 cm^{-1} . The broad O-H envelope was less prominent in S2. This difference may reflect changes in hydrogen bonding, surface moisture, hydroxyl accessibility or relative phase exposure. Importantly, the FTIR data support retention of the principal aromatic polymer framework after the CaCO_3 -templating/leaching treatment but do not independently prove porosity or complete cellulose removal.

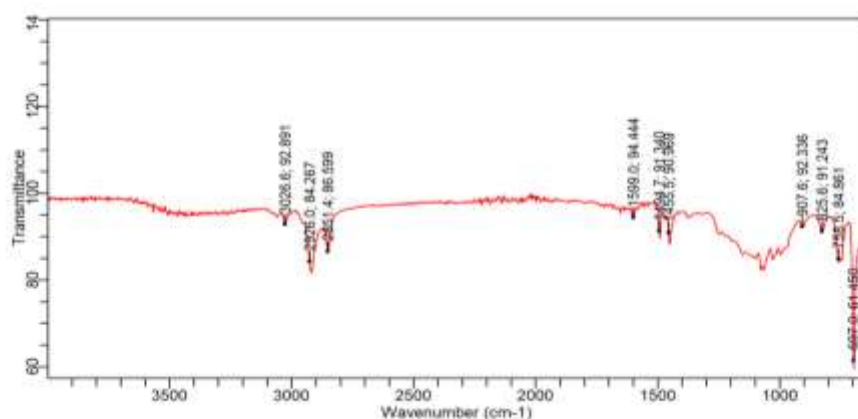


Figure 2. FTIR spectrum of S2 (porous SBC-rPS composite)

XRD Analysis

The strongest S1 reflection occurred at $2\theta = 22.23^\circ$, with an intensity of 248.61 cps, d-spacing of 3.996 Å and FWHM of 2.218° . S2 exhibited a different distribution of reflections, with the strongest peak at 29.47° (184.94 cps; d-spacing 3.029 Å; FWHM 0.717°). The change in dominant reflection indicates a change in the relative contribution of ordered structural domains. Several S2 reflections, including those around 29.47° , 36.41° , 43.39° , 47.37° and 48.55° , overlap reported calcite positions. Together with the higher localized calcium signal in S2, this suggests residual calcium-containing material, although complete phase identification or complete CaCO_3 removal cannot be established from the available data alone.

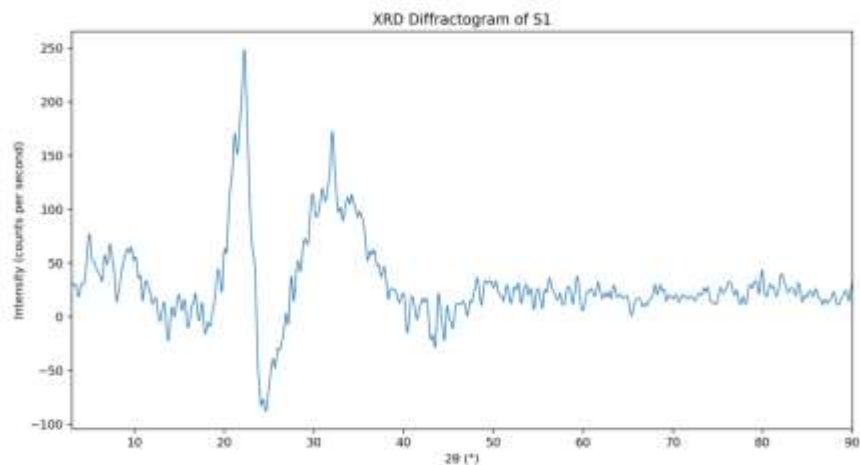


Figure 3. XRD diffractogram of S1 (non-porous SBC-rPS composite)

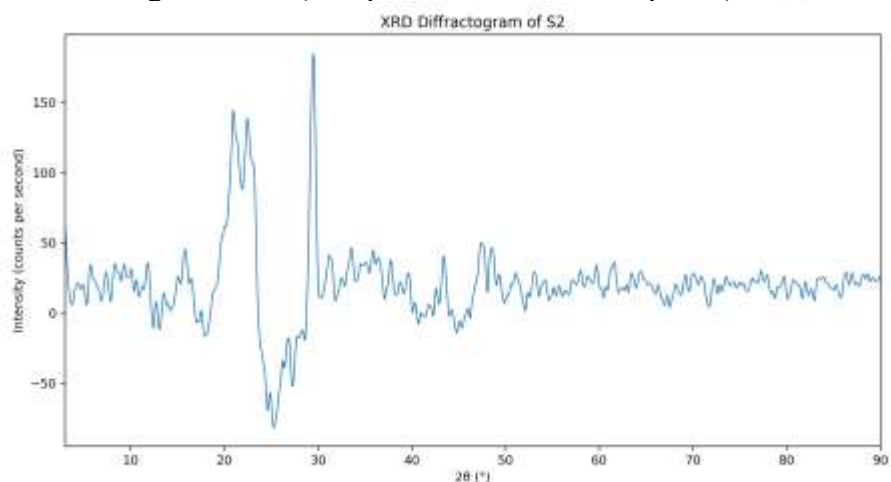


Figure 4. XRD diffractogram of S2 (porous SBC-rPS composite)

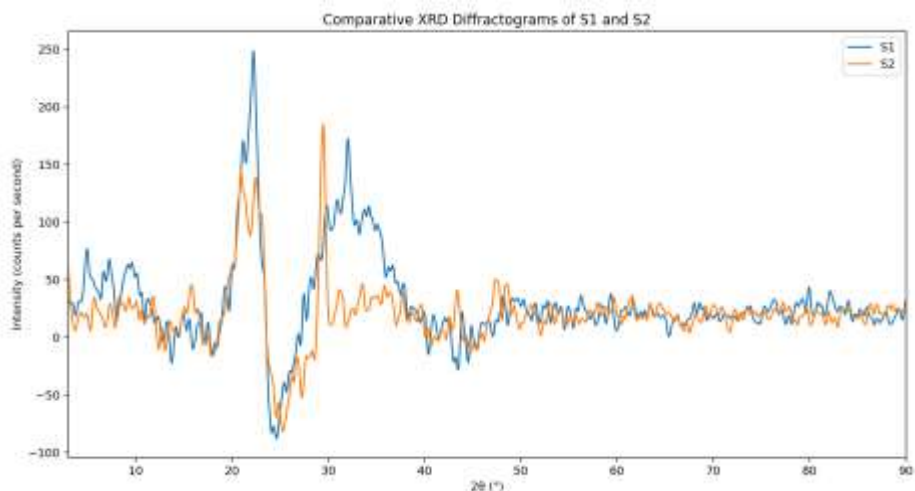


Figure 5. Comparative XRD diffractograms of S1 and S2

SEM–EDS Analysis

SEM showed that S1 had a comparatively compact, heterogeneous and continuous morphology with few obvious large voids. In contrast, S2 displayed a more open and irregular surface with prominent dark void-like regions and channels, consistent with structural modification associated with the sacrificial-template approach. The S2 image was acquired at a different magnification and field of view from S1, so the images provide qualitative rather than direct numerical pore-size comparison.

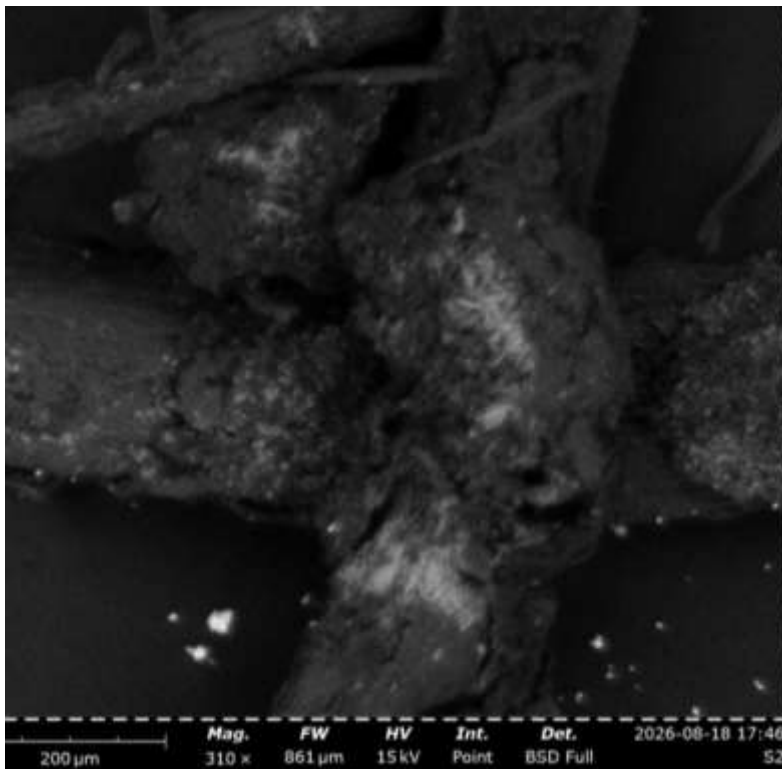


Figure 6. SEM micrograph of S2 showing the surface morphology of the porous SBC–rPS composite

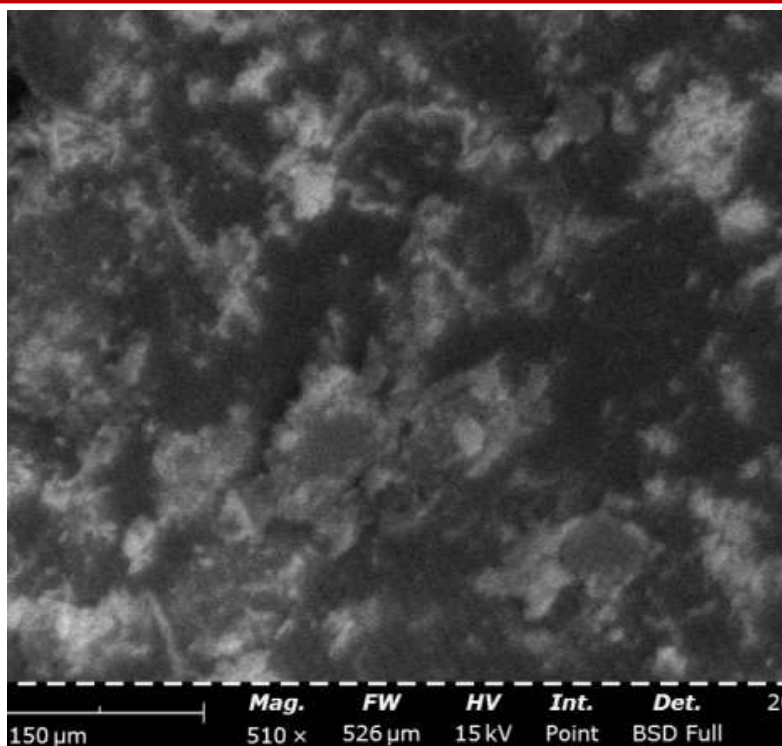


Figure 7. SEM micrograph of S1 showing the surface morphology of the non-porous SBC-rPS composite

Element	S1 atomic (%)	S2 atomic (%)	Difference
C	43.77	43.02	-0.75
O	26.10	32.00	+5.90
S	9.13	5.06	-4.07
Na	12.42	0.00	-12.42
Ca	3.05	11.68	+8.63
Zn	1.61	3.89	+2.28

Carbon remained the dominant detected element in both analysed regions. The localized calcium signal increased from 3.05 at.% in S1 to 11.68 at.% in S2. Because EDS measurements are localized and influenced by surface roughness and the selected analysis region, these values should not be interpreted as definitive bulk composition. The higher Ca signal nevertheless supports the XRD indication that calcium-containing material remained detectable in S2.

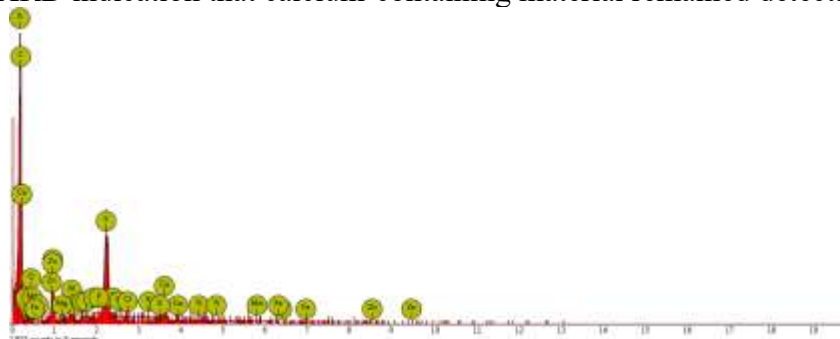


Figure 8. EDS spectrum of S1 showing elemental signals detected in the analysed region

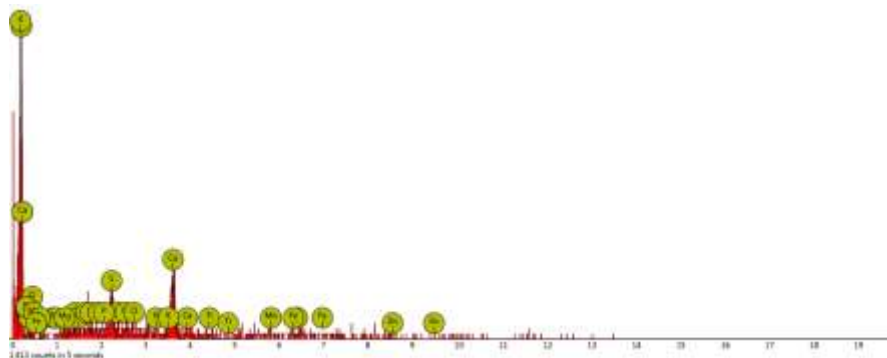


Figure 9. EDS spectrum of S2 showing elemental signals detected in the analysed region

BET Surface Area and Pore Structure

Parameter	S1	S2	Change
BET surface area (m ² /g)	254.612	275.762	+8.31%
BJH surface area (m ² /g)	263.564	278.755	+5.76%
BJH pore volume (cm ³ /g)	0.130	0.135	+3.85%
BJH pore diameter (nm)	2.113	2.108	-0.24%

S2 had a higher BET surface area than S1, increasing from 254.612 to 275.762 m²/g, while BJH pore volume increased from 0.130 to 0.135 cm³/g. The characteristic BJH pore diameter was essentially unchanged (2.113 versus 2.108 nm). Thus, the available data support an increase in accessible surface and pore volume rather than a major enlargement of the characteristic adsorption-derived pore diameter. This interpretation agrees with the more open S2 SEM morphology. The DFT and other model-dependent descriptors in the thesis showed larger differences, but because pore models depend on assumptions and no replicate sorption uncertainty was reported, those values are not used here as primary evidence.

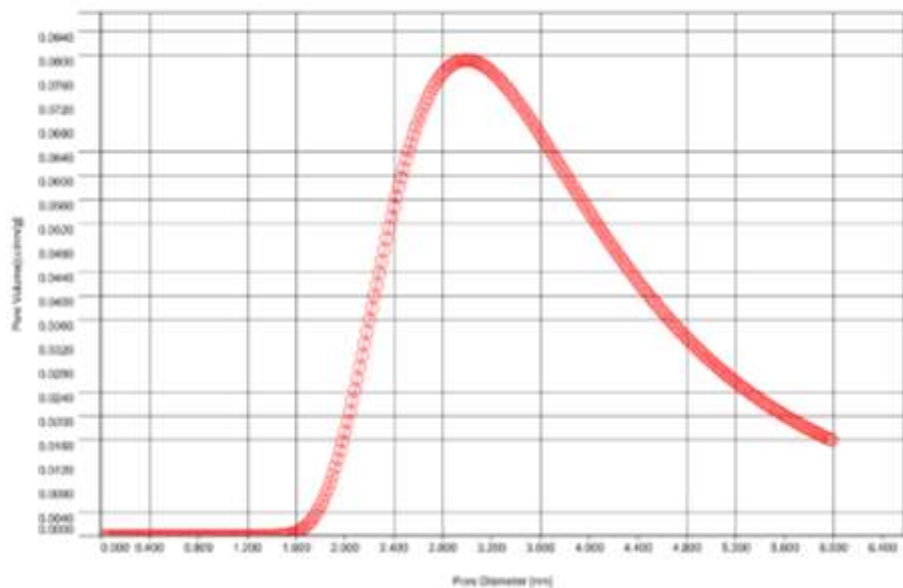


Figure 10. DA micropore pore-size distribution for S1

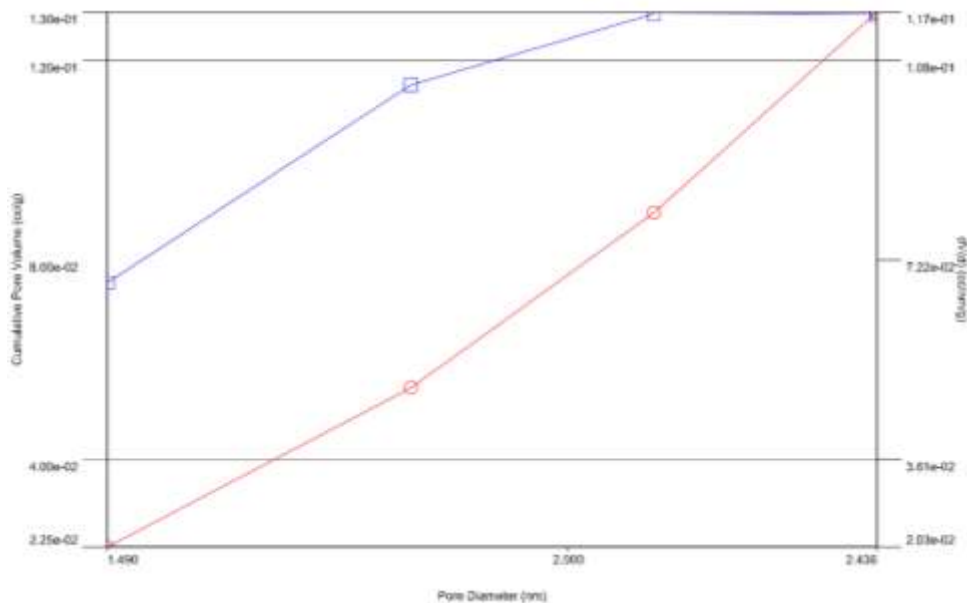


Figure 11. BJH adsorption pore-volume distribution for S1

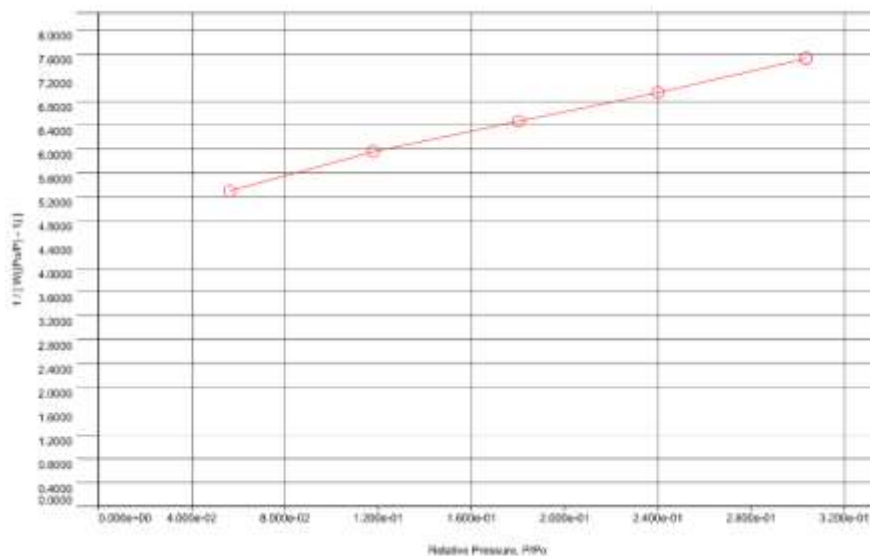


Figure 12. Multi-point BET plot for S1

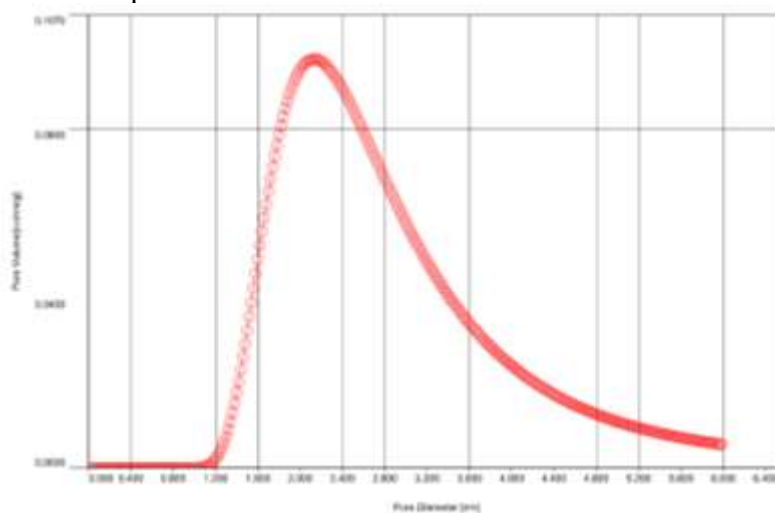


Figure 13. DA micropore pore-size distribution for S2

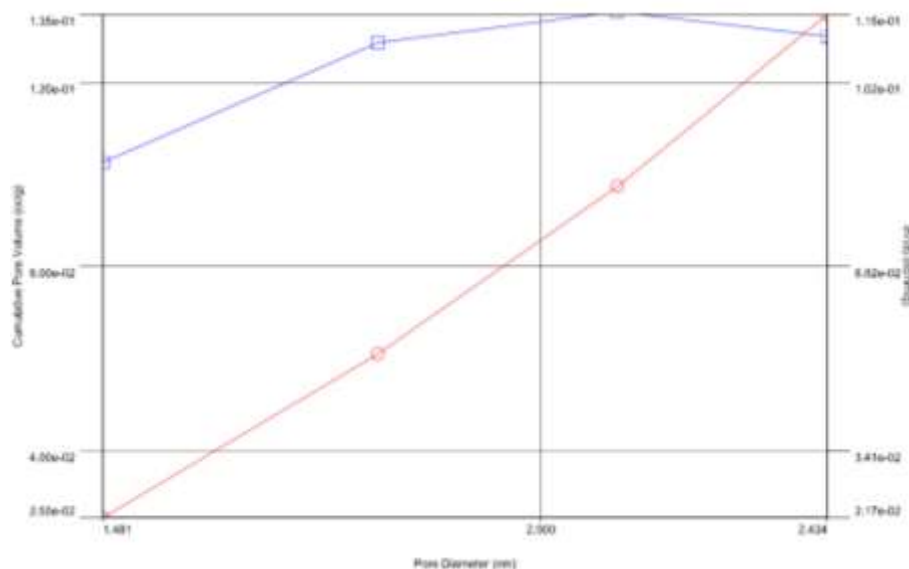


Figure 14. BJH adsorption pore-volume distribution for S2

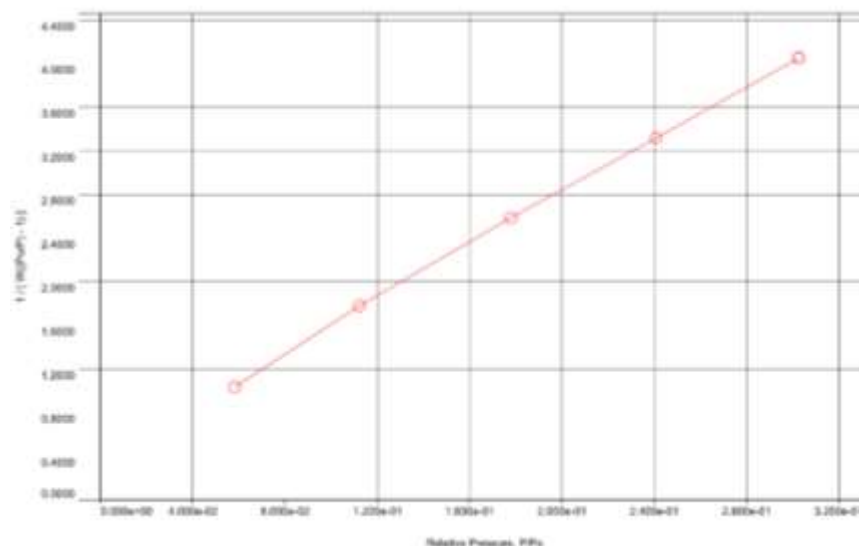


Figure 15. Multi-point BET plot for S2

Turbidity Removal Performance

Initial NTU	Sample	1.11 mL/s	3.23 mL/s	7.26 mL/s	Best removal
10	S1	44.0%	31.0%	19.5%	44.0%
10	S2	63.0%	51.0%	28.0%	63.0%
5	S1	75.0%	63.5%	42.8%	75.0%
5	S2	88.0%	71.0%	52.0%	88.0%
1	S1	85.0%	74.0%	51.0%	85.0%
1	S2	92.0%	83.0%	70.0%	92.0%

Turbidity removal depended on initial turbidity, composite type and flow rate. S2 consistently outperformed S1 at all three turbidity levels. At 10 NTU, S2 achieved 63.0% removal at the lowest flow rate, compared with 44.0% for S1. At 5 NTU, S2 achieved 88.0% compared with

75.0% for S1. At 1 NTU, S2 achieved the maximum observed removal of 92.0%, reducing turbidity from 1.00 to 0.08 NTU.

For both composites, removal efficiency generally decreased as flow rate increased. This pattern is consistent with the role of hydraulic residence/contact time in depth filtration: lower flow allows more opportunity for suspended particles to interact with and be retained by the filter bed. Similar dependence of filtration performance on flow conditions has been reported in water-treatment studies (Chua et al., 2020; Han et al., 2022).

Comparative Mean Performance

Initial turbidity (NTU)	S1 mean removal (%)	S2 mean removal (%)
10	31.5	47.3
5	60.4	70.3
1	70.0	81.7

The mean results reinforce the superiority of S2 under the tested conditions. S2 exceeded S1 by 15.8 percentage points at 10 NTU, 9.9 points at 5 NTU and 11.7 points at 1 NTU. The improvement is plausibly related to the more open surface and slightly higher accessible BET area of S2, although filtration performance is controlled by multiple factors including pore accessibility, wetting, particle size, flow rate and surface chemistry.

Conclusion

All major characterization outputs available in the supplied M.Sc. thesis—FTIR, XRD, SEM–EDS and BET plots—have been retained in this revised journal manuscript. The original figure content is reproduced without changing the measured values or spectra.

A granular filtration composite was successfully developed from sugarcane bagasse cellulose and recycled polystyrene. The non-templated S1 and CaCO₃-templated S2 formulations retained the characteristic aromatic polystyrene framework, while S2 exhibited a more open morphology and higher BET surface area. BET area increased by 8.31% and BJH pore volume by 3.85% from S1 to S2. Under the tested column conditions, S2 consistently produced higher turbidity removal than S1, with a maximum observed removal efficiency of 92% at 1 NTU and 1.11 mL/s. The composite therefore shows promise as a waste-derived granular medium for turbidity polishing. However, the present results do not establish drinking-water safety, dissolved-contaminant selectivity, long-term hydraulic durability or complete removal of the CaCO₃ template.

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