
PREPARATION OF POROUS WASTE EXPANDED POLYSTYRENE/BAMBOO FIBRE NANOCOMPOSITE MATERIAL FOR CO₂ CAPTURE

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ABSTRACT

Nanoporous materials are among the most actively studied and rapidly advancing materials for carbon dioxide (CO₂) capture. This study investigated the fabrication of nanocomposites using bamboo fibre nanopowder (BFNP) and waste expanded polystyrene (WEPS) for CO₂ removal. The bamboo fibres were chemically modified with sodium hydroxide (NaOH) to eliminate lignin, pectin, and other impurities while enhancing their adhesion to the polymer matrix. The influence of NaOH treatment on the surface morphology and crystallinity of the bamboo fibres was examined using Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM/EDS), and X-ray diffraction (XRD). A Box–Behnken design (BBD) within the response surface methodology (RSM) framework was employed to construct the experimental matrix and optimize the mixing conditions. The optimized parameters were predicted to be a bamboo fibre content of 35.9wt%, a mixing time of 3.9 minutes, and a mixing temperature of 27.5°C. The nanocomposites were fabricated using the lay-up technique, and their properties were characterized by FTIR, XRD, SEM, and Brunauer–Emmett–Teller (BET) analysis. The nanocomposites exhibited a BET surface area of 847.6 m²/g and an average pore diameter of 1.85nm confirming their microporous nature, a CO₂ adsorption capacity of 2.034 mmol/g at 110°C under 1 bar pressure confirming their suitability for CO₂ adsorption.

Keywords: Carbon capture; bamboo fibre; waste expanded polystyrene; nanocomposites; CO₂ adsorption

1. INTRODUCTION

Carbon capture is an essential technology for reducing carbon dioxide (CO₂) emissions, particularly because fossil fuels continue to provide a substantial proportion of the world's energy. It is expected to play a central role in achieving net-zero emissions by 2050 and beyond. Existing carbon-capture technologies are primarily designed for heavy industries but require further refinement because they often involve hazardous chemicals and substantial energy consumption. Consequently, these systems are costly and complex to construct. Captured carbon can either be stored or reused, potentially creating an additional revenue stream (Nikita *et al.*, 2025).

The development of adsorbents with high adsorption capacities is fundamental to achieving effective adsorption performance. Various materials have been investigated for CO₂ adsorption, including zeolites, metal oxides, mesoporous silica, and activated charcoal (Gowthaman *et al.*, 2021). Solid sorbents, such as porous organic polymers, activated carbon, zeolites, and metal–organic frameworks, have gained increasing attention because of their high adsorption efficiency, durability, and operational simplicity (Ting *et al.*, 2020).

Plastic pollution remains a persistent global problem, as the large-scale production of disposable plastics exceeds the capacity of existing waste-management systems. Waste plastics can be engineered for pollutant removal and carbon capture, providing a practical and sustainable pathway for managing plastic waste while contributing to efforts to mitigate global warming associated with carbon emissions. This approach supports the development of a cleaner and more sustainable future (Jiacheng & Qian, 2024). Such materials address plastic-waste challenges while offering cost-effective and efficient solutions for environmental remediation, in some cases outperforming commercial adsorbents (Pritesh *et al.*, 2024).

Bamboo fibre, a renewable and biodegradable material, can be combined with waste expanded polystyrene, a common packaging-related pollutant, to reduce landfill demand and plastic contamination (Peng *et al.*, 2022). This strategy supports a circular economy by reducing reliance on virgin polymers and lowering the carbon footprint through the use of environmentally friendly reinforcement. Nanocomposites produced from these materials may demonstrate improved mechanical properties, including greater tensile strength, as a result of bamboo's high cellulose content and strong fibre–matrix bonding. They may also offer low density, good thermal stability, and reduced water absorption compared with conventional plastics (Chin-Hao & Teng-Chun, 2020).

This study is strongly motivated by the need for sustainable, environmentally friendly, and cost-effective materials capable of addressing both agricultural-waste management and plastic pollution. Integrating bamboo fibre with waste expanded polystyrene can produce a high-performance, lightweight composite while transforming waste materials into valuable industrial resources (Chen *et al.*, 2016). Both raw materials are widely available; however, WEPS is a significant contributor to landfill pollution because of its high volume-to-mass ratio (Farid & Ahad, 2022).

2. MATERIALS AND METHODS

The primary materials used in this investigation were waste expanded polystyrene (WEPS) (Fig. 1), collected from electronics shops along Ahmadu Bello Way in Kaduna State, Nigeria, and bamboo (*Bambusa vulgaris*) fibres (BF), sourced from Basawa Market in the Zaria district of Kaduna State, Nigeria.

2.1 Preparation of Bamboo Fibre Nanopowder

Fresh bamboo culms were collected and washed thoroughly to eliminate soil, debris, and other contaminants from their surfaces. The cleaned culms were then reduced to chips approximately 2.0–5.0 cm in length (Fig. 1b) with a manually operated mechanical cutter, this preliminary size reduction increased the surface area exposed during chemical treatment. The chips were immersed in a 10wt% sodium hydroxide (NaOH) solution for 2–4 hours (Fig. 1a). The alkaline treatment was used to remove hemicellulose, lignin, and pectin, thereby loosening the fibre bundles and promoting cellulose separation. A bamboo-chip-to-NaOH-solution ratio of 1:10 (w/v) was maintained to ensure sufficient alkali penetration. The fibres were oven-dried for 8 hours at 80°C until a constant weight was obtained. The dried bamboo fibres were ground using a ball until they were reduced to fine powder sized particles of 75 nm (Fig. 1c).



Figure 1: (a) Bamboo Fibres Soaked in NaOH solution (b) Dried Bamboo Fibres (c) Bamboo Fibre Powder

Dynamic light scattering (DLS) was employed to establish the particle-size distribution of the bamboo fibre nanopowder. In this analysis, a laser beam was passed through the dispersed sample, and the scattering generated by particle–beam interactions was evaluated with a DLS instrument.

2.2 Characterization of Bamboo Fibre Nanopowder (BFNP)

The bamboo fibre nanopowder was characterized through physical, chemical, and thermal analyses. The assessment covered its proximate composition, morphology, crystalline structure, surface characteristics, and mechanical and thermal properties.

2.2.1 Fourier transform infrared spectroscopy (FTIR)

The functional groups in the bamboo fibre samples were identified with a Fourier transform infrared spectrometer (FT/ IR-4700, JASCO International Co., Ltd., Pfungstadt, Germany). Samples were analyzed both before and after NaOH treatment to identify the existing functional groups and determine the changes induced by alkalization. Particular emphasis was placed on hydroxyl (OH) groups because of their role in moisture uptake by cellulosic fibres. Approximately 2 mg of each sample was blended with KBr and compressed into pellets. Spectra were collected between 4000 and 500 cm^{-1} at a resolution of 4 cm^{-1} .

2.2.2 Scanning electron microscopy (SEM)

Scanning electron microscopy was performed in accordance with ASTM E766 to investigate the surface morphology and microstructure of the untreated and treated fibres. The raw bamboo nanopowder was examined with a scanning electron microscope (Phillips XL 30 ESEM, FEI Company, Hillsboro, OR, USA) fitted with a large-field detector. Micrographs were acquired at an accelerating voltage of 15 kV and magnifications of 100 $\times$ and 500 $\times$. For examination, 10 μL of sample was placed on a copper grid and dried under light for 15 minutes. SEM analysis yielded information about fibre roughness, surface imperfections, and the likelihood of interfacial adhesion, which are significant factors in composite-material applications (Hobtemariam *et al.*, 2025).

2.2.3 X-ray diffraction (XRD)

The bamboo fibre was analyzed by X-ray diffraction using a PANalytical Empyrean diffractometer equipped with a cobalt target, rotating sample stage, and goniometer operating in the 2 θ configuration. The cobalt source produced radiation with a wavelength of 0.179 nm. The generator settings were 40 kV and 45 mA. Diffraction intensities were measured across a 2 θ range of 5°–110°, with a step interval of 0.0167° and a scan rate of 0.015°/s. The crystallinity index was determined using the Segal equation (Equation 1), which estimates the relative amounts of crystalline and amorphous phases that influence fibre strength and thermal stability (Szaosky *et al.*, 2024):

$$\text{CrI (\%)} = [(I_{002} - I_{\text{am}})/I_{002}] \times 100 \quad (1)$$

In this equation, I_{002} is the maximum intensity of the 002 lattice reflection, representing the primary peak of native cellulose at 2 θ = 22.5°, whereas I_{am} is the diffraction intensity associated with the amorphous region (Yang *et al.*, 2023).

2.3 Design of Experiments (DoE)

Response surface methodology (RSM) using the Box–Behnken design (BBD) implemented in Design-Expert software was used to analyze the experimental data, generate the design matrix, and determine the optimum mixing conditions. The experimental design incorporated three factors at three levels. Numerical optimization was conducted with fibre loading (wt%), mixing time (min), and mixing temperature (°C) as the independent variables, while tensile strength (TS) served as the response variable.

2.4 Preparation of BFNP/WEPS Nanocomposite

The bamboo fibre nanopowder/waste expanded polystyrene (BFNP/WEPS) nanocomposite was fabricated through solution casting followed by compression molding. A schematic of the preparation process is provided in Fig. 2.

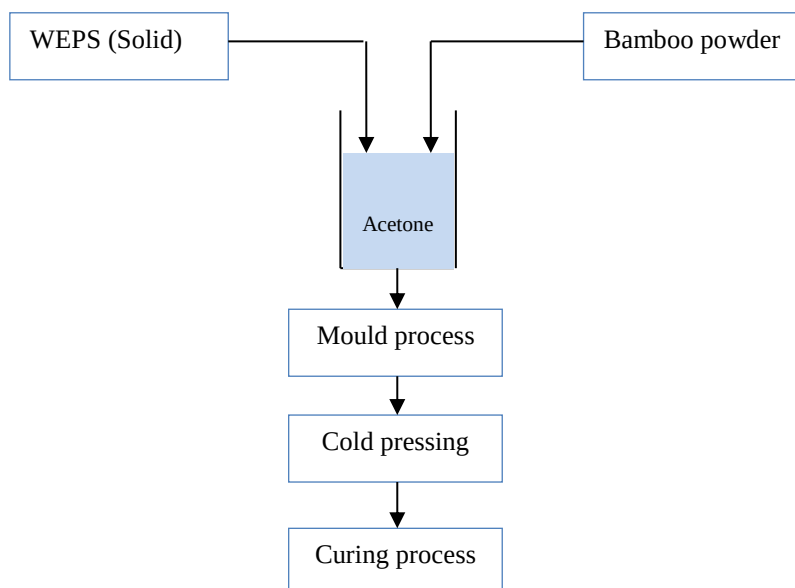


Figure 2: Block Flow Diagram for Preparation of BFNP/WEPS Nanocomposite

A 1.5 kg quantity of solid WEPS waste was dissolved in 1 L of acetone and stirred until a consistent solution formed. The bamboo fibre powder was then combined with the dissolved WEPS in a container and thoroughly blended with a mechanical mixer. The mixture contained 35wt% bamboo fibre powder, corresponding to the optimum loading identified through BBD optimization, and 65wt% dissolved WEPS paste. Mixing was continued until a uniform blend was obtained. The blend was poured into a wooden mold coated with petroleum jelly to minimise adhesion and manually compacted using a 150kN compression-molding machine (Hemel Hempstead, Hertfordshire, England). The molded BFNP/WEPS nanocomposite was cured and dried for 21 days before being removed from the mold and subjected to further analysis.

2.5 Characterization of BFNP/WEPS Nanocomposites

The prepared BFNP/WEPS nanocomposites were examined through physical, mechanical, and chemical analyses to assess their properties and performance.

2.5.1 Brunauer–Emmett–Teller (BET) analysis

BET analysis involved exposing the porous solid to nitrogen molecules at the boiling point of the inert gas. The procedure was conducted in accordance with ASTM B922-10. Approximately 0.5 g of sample was placed in a sample cell and degassed to eliminate moisture, volatile substances, and other impurities. The degassed material was subsequently installed in a BET analyzer (Quantachrome Nova Instruments, version 11.03) and exposed to nitrogen across a range of relative pressures. The equilibrium volume of adsorbed gas was measured to produce a Type IV adsorption isotherm.

2.6 CO₂ Adsorption Experiment

As shown in Fig. 3, a fixed-bed reactor was assembled to measure the CO₂ adsorption capacity of the adsorbent and evaluate the effects of important operating variables through a

gravimetric technique. This method is especially appropriate at low pressures because almost the entire measured gas dose is adsorbed.

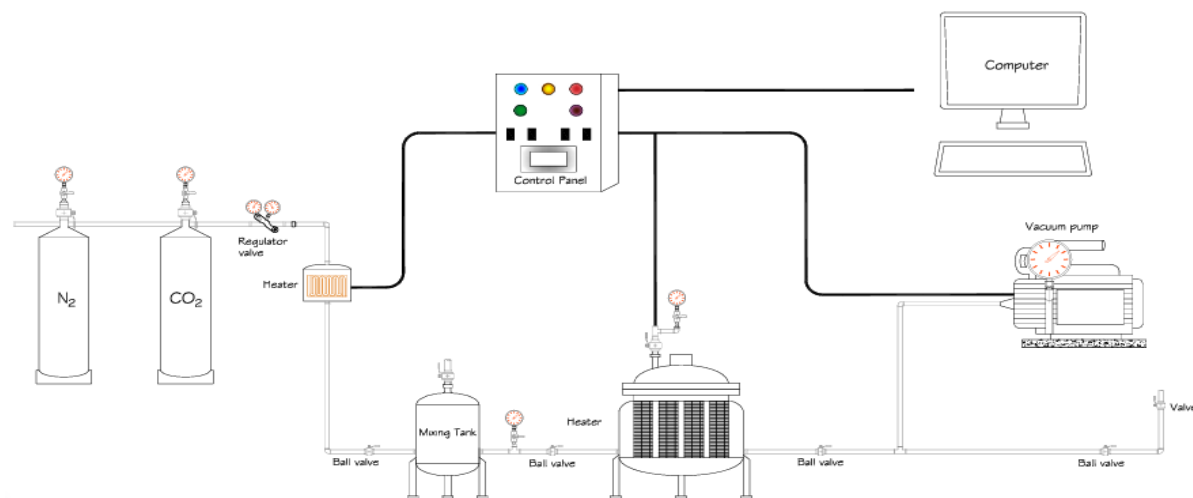


Figure 3: The Experimental Setup for Measuring CO₂ Adsorption

The reactor was cylindrical, with an internal volume of 100 cm³. For each run, 1.5 g of solid adsorbent was placed in an internal reactor compartment. Prior to every experiment, the adsorbent was heated under a pure N₂ stream for 30 minutes at 110°C and subsequently evacuated for 30 minutes to remove previously adsorbed CO₂ and moisture. High-purity CO₂ from the cylinder was adjusted to the desired pressure with a pressure regulator and gauge before being introduced into the mixing tank. Stable gas was delivered to the adsorbent reactor and the mass of adsorbent after adsorption was measured using a digital weighing balance. The CO₂ uptake was calculated using equation 3.

$$q = \Delta m / M \quad (3)$$

Where, q is the CO₂ uptake, $\Delta m = m_1 - m_0$ (m_0 is the mass of adsorbent before adsorption, m_1 is mass of adsorbent after adsorption) and M is the molar mass of CO₂ (44.01 g/mol).

3. RESULTS AND DISCUSSION

This section presents and analyzes the results obtained from the experimental investigations. It is divided into two principal parts. The first addresses the characterization of bamboo fibres, whereas the second presents the characterization results for the nanocomposite produced from bamboo fibres and waste expanded polystyrene (WEPS).

3.1 Characterization of Bamboo Fibres

The experimental design (BBD/RSM optimization of mixing parameters) and multi-technique characterization (FTIR, SEM/EDS, XRD, and BET) show methodological rigor and critically analyze the bamboo fibre material.

3.1.1 FTIR analysis of raw bamboo fibre

Fourier transform infrared (FTIR) analysis was used to identify the absorption peaks and their corresponding wavenumbers, thereby determining the functional groups present and evaluating the chemical changes associated with the alkaline treatment of the bamboo fibres. The spectra obtained for the raw bamboo fibres are shown in Figure 4.

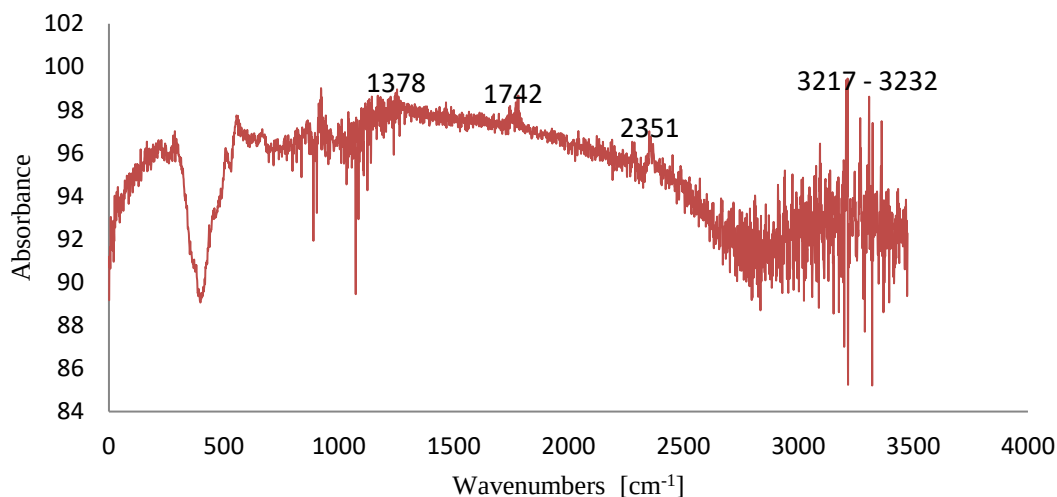


Figure 4: FTIR Spectrum of Raw Bamboo Fibre

The spectrum indicates the presence of several undesirable constituents, including hydroxyl (OH) groups, pectin, wax, hemicellulose, and lignin. The principal absorption peaks are clearly identified in the spectrum. The absorption band near 3200 cm⁻¹ is associated with fatty acids and is attributed to O=H stretching vibrations. A weak absorption band also appears at 1378 cm⁻¹, indicating the presence of lignin and corresponding to C=C stretching vibrations. In addition, the peak observed at 1742 cm⁻¹ indicates the presence of waxes and fatty-acid esters and is attributed to C=O vibrations.

3.1.2 XRD analysis of bamboo fibre

The X-ray diffraction (XRD) patterns presented in Fig. 5 compare the raw and chemically treated bamboo fibres. The patterns show a broad diffraction feature near $2\theta = 22^\circ$, confirming the crystalline nature of the fibre. Three principal diffraction peaks occur at $2\theta = 15.4^\circ$, 17.4° , and 22.5° , corresponding to the 1-10, 110, and 200 planes, respectively. The sharp peak near $2\theta = 22^\circ$ is characteristic of cellulose. Specifically, the diffraction peak at 22.0° corresponds to the 002 crystallographic plane of the cellulose I lattice. These three characteristic reflections are commonly associated with cellulose I β in natural fibres, in which the cellulose chains are arranged in parallel and connected by hydrogen bonding. Although cellulose occurs naturally in both the I α and I β forms, cellulose I β is the form predominantly found in higher plants and was therefore considered in this analysis.

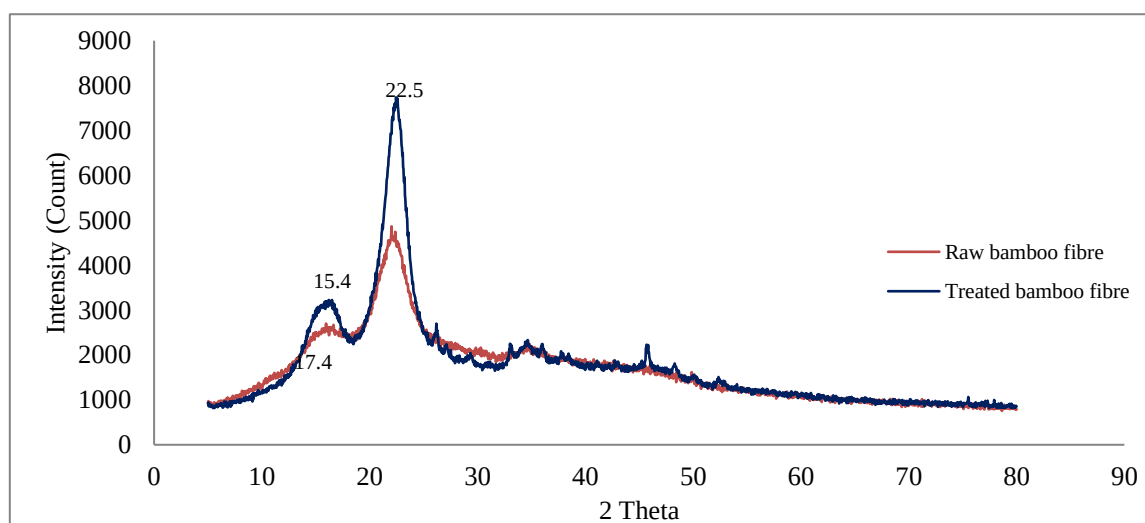


Figure 5: XRD Spectrum of Raw and Treated Bamboo Fibres

The crystallinity index (CrI) was determined using the empirical Segal method. The crystallinity indices calculated for the raw and treated bamboo fibres are presented in Table 1.

Table 1: Crystallinity Index of Bamboo Fibres

Bamboo Fibre	I (002)	I_{am}	CrI (%)
Raw	4778	2515	47
Treated	7596	3045	60

The treated bamboo fibre shows higher crystallinity than the raw bamboo fibre and lower than those of most of natural fibres like jack tree fibre with crystallinity index of 86% (Shahin *et al.*, 2025) and hemp with crystallinity index of 88% (Gedik *et al.*, 2021). High crystallinity means excellent strength of the fibre and they can provide better reinforcement for composite production, the crystallinity index also has effect on water absorption as amorphous region can absorb more water.

3.2 Optimization of Mixing Parameters Using BBD

The mixing parameters for the BFNP/WEPS Nanocomposite were optimized using the Box–Behnken design (BBD) module of response surface methodology. The responses obtained for the selected mixing conditions used to prepare the nanocomposite are presented in Table 2.

Table 2: Responses of the Mixing Parameters for the BFNP/WEPS Nanocomposite

Std	Run	Factor 1 A: Fibre Loading (wt %)	Factor 2 B: Mixing Time (min)	Factor 3 C: Mixing Temp (C)	Response Tensile Strength (MPa)
17	1	15	3	27.5	43.6
3	2	50	5	27.5	31.1
16	3	35	1	27.5	42.9
12	4	50	5	50	44.1
7	5	50	3	50	24.2
4	6	35	1	27.5	39.6
11	7	35	5	50	41.5
14	8	50	5	27.5	42.7
15	9	35	1	27.5	43.3
2	10	15	3	27.5	37.3
1	11	15	3	27.5	26.6
6	12	50	3	35	21.2
13	13	50	5	27.5	42.9
9	14	35	5	35	26.7
8	15	35	1	50	44.2
10	16	50	5	35	31.9
5	17	50	3	35	20.2

A second-order polynomial regression model was developed to establish the relationship between the processing factors and the tensile strength response. The resulting equation, expressed in terms of coded factors, is given as follows:

$$TS = +43.08 + 5.03A + 1.83B + 6.75C + 0.55AB + 4.75AC - 0.65BC - 9.02A^2 - 0.42B^2 - 6.61C^2 \quad (2)$$

Desirability converts each response variable into a dimensionless scale ranging from 0, representing an undesirable result, to 1, representing an ideal result. The individual desirability values are then combined to produce an overall desirability score, D, as shown in Table 3. This procedure facilitates the simultaneous evaluation of multiple responses by providing a single optimization metric and thereby supporting more efficient decision-making. The score reflects the preferred range established for each response.

Table 3: Response Optimization and Desirability of the Mixing Parameters

Number	Fibre Loading.	Mixing Time	Mixing Temp	Tensile Strength	Desirability
1	<u>35.112</u>	<u>3.291</u>	<u>25.788</u>	<u>44.271</u>	1
2	35.654	3.915	25.014	45.429	1
3	35.618	3.738	25.752	45.228	1
4	35.239	3.394	25.714	44.552	1
5	35.827	3.226	25.775	45.538	1
6	35.859	3.957	25.946	45.551	1
7	<u>35.963</u>	<u>3.963</u>	<u>25.763</u>	<u>45.716</u>	<u>1</u>
8	35.147	3.908	25.951	44.311	1
9	35.891	3.619	25.987	45.581	1
10	35.369	3.572	25.747	44.798	1

To provide additional validation of the model, two conditions, corresponding to the first and seventh experimental runs, were selected. The predicted values were calculated from the centre points between the high, intermediate, and low factor levels. Confirmatory experiments were subsequently conducted to assess the reliability of the model. The percentage error for tensile strength was calculated by comparing the predicted values with the experimentally measured values. The validation results are presented in Table 4.

Table 4: Confirmatory Experiments

Fibre Loading (g)	Mixing Time (min)	Mixing Temp (°C)		TS (MPa)
35.112	3.291	25.788	Actual	42.21
			Predicted	44.27
			Error%	3.06
35.963	3.963	25.763	Actual	43.78
			Predicted	45.716
			Error%	1.936

The absolute relative errors between the predicted and experimental values were 3.06% and 1.96%, respectively. Because both values are below 5%, the developed prediction models for the tensile strength (TS) of the BFNP/WEPS nanocomposite can be considered accurate and reliable.

3.3 Characterization of BFNP/WEPS Nanocomposites

To obtain a comprehensive understanding of the behavior of the BFNP/WEPS nanocomposites, a series of mechanical, physical, and thermal tests were conducted on the prepared materials.

3.3.1 FTIR analysis of the BFNP/WEPS nanocomposite

The FTIR spectra of the BFNP/WEPS nanocomposite presented in Fig. 6 contain distinct absorption bands associated with cellulose and hemicellulose, confirming the characteristic lignocellulosic composition of the bamboo fibres. The broad band centered at 3480 cm⁻¹ is assigned to the O–H stretching vibrations of hydroxyl groups. This band indicates the presence of absorbed water, free phenols, and primary and secondary aliphatic alcohols occurring in cellulose and hemicellulose.

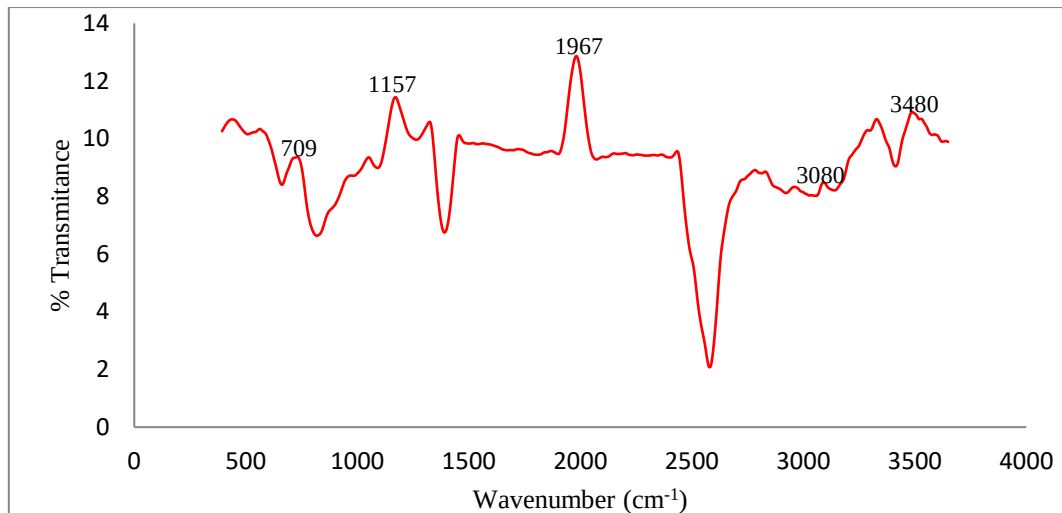


Figure 6: FTIR Spectrum for BFNP/WEPS Nanocomposites

The band at 1967 cm^{-1} is related to the stretching vibrations of aliphatic C–H groups, particularly CH_2 , and further confirms the presence of cellulose and hemicellulose. The absorption band at 1157 cm^{-1} corresponds to C=O stretching vibrations associated with carbonyl groups, which are attributable to the acetyl groups commonly found in hemicellulose. In spectra containing WEPS, the bands observed between 3000 and 2800 cm^{-1} are assigned to C–H stretching vibrations associated with hydrocarbons in the WEPS. The band at 709 cm^{-1} is related to phenyl-ring substitution. Its presence alongside the cellulose-related signals confirms the incorporation of bamboo natural fibres.

3.3.2 SEM analysis of BFNP/WEPS nanocomposites

SEM analysis was conducted to examine the morphology of the produced nanocomposite. The micrograph in Fig. 7 shows that the bamboo fibres were distributed uniformly throughout the polymer matrix. This homogeneous dispersion is responsible for the strong interfacial adhesion between the fibres and the polymer matrix (Mohan *et al.*, 2020). In addition, the expansion of gas bubbles within the freshly dissolved expanded polystyrene paste, caused by acetone evaporation under reduced pressure, forced the thin layer of the paste into contact with the particle surfaces. This process may have influenced the compounding behaviour and mechanical interlocking between the bamboo fibres and the WEPS matrix. The SEM examination also revealed microstructural damage mechanisms, including fibre–matrix debonding, fibre swelling, and matrix cracking. These features are broadly comparable to those reported for date-palm-leaf-fibre-reinforced composites (Hobtemariam *et al.*, 2025). The polymer matrix was observed to wet the fibres effectively, thereby promoting strong interfacial bonding.

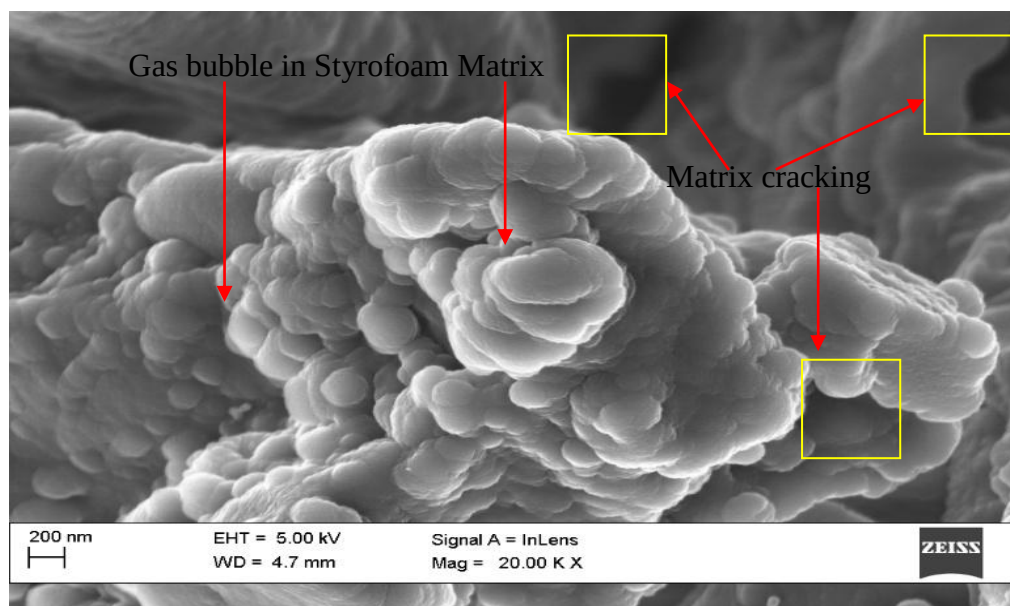


Figure 7: SEM Spectrum of BFNP/WEPS Nanocomposite

3.3.3 BET analysis of BFNP/WEPS nanocomposite

The BET analysis demonstrated that the BFNP/WEPS nanocomposite is highly porous. As shown in Table 5, the material exhibited a Brunauer–Emmett–Teller surface area of 847.6 m²/g and an average pore diameter of 1.85 nm, indicating a predominantly microporous structure. According to the International Union of Pure and Applied Chemistry (IUPAC), microporous materials have pore diameters not exceeding 2nm. Based on the 1972 recommendations for physisorption, pores are classified as micropores when their diameters are below 2nm, mesopores when they range from 2 to 50nm and macropores when they exceed 50nm.

Table 5: Porosity Properties

Parameter	BFNP/WEPS nanocomposites
BET Surface area	181.9 m ² /g
BJH pore volume	0.16 cm ³ /g
BJH pore diameter	1.85 nm
Langmuir surface area	847.6 m ² /g
DR micropore volume	0.164 cm ³ /g

Under the IUPAC classification, materials with a high proportion of micropores and a uniform micropore size distribution below 2nm possess important characteristics for effective and selective CO₂ adsorption. The measured micropore volume of 0.16cm³/g and average micropore diameter of 1.85nm can readily accommodate the relatively small CO₂ molecule, which has a kinetic diameter of approximately 0.33 nm. Micropores therefore provide favourable structural conditions for CO₂ adsorption in porous adsorbents (Telmo *et al.*, 2025). The narrow pore structure corresponds well with the kinetic diameter of CO₂, enhancing adsorbate–adsorbent interactions and selectivity relative to N₂ (Lei *et al.*, 2025). Similarly, metal–organic frameworks (MOFs) and zeolites benefit from narrow pores, typically measuring approximately 3.5–8 Å, to achieve high CO₂ uptake.

4. CONCLUSION

Waste expanded polystyrene and bamboo fibres were converted into a nanocomposite through a simple and cost-effective process, producing a material with potential application as an adsorbent for CO₂ capture. FTIR, SEM, XRD, and BET analyses were conducted to investigate the structure and

morphology of the nanocomposite. The material exhibited a specific surface area of 847.6m²/g and an average pore diameter of 1.85nm, confirming its microporous nature. The adsorbent material demonstrates a CO₂ uptake capacity of 2.034mmol/g at 110°C and 2 bars. Because micropores are particularly favourable for the adsorption of small molecules, confirming their suitability for CO₂ adsorption the uniform porous structure of the BFNP/WEPS nanocomposite indicates its potential as an effective, low-cost precursor for the production of adsorbents for CO₂ capture.

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