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Preparation and Pore Structure Characterization of Balsa Wood

(*Ochroma pyramidale*)/GO Composites

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Abstract: In the current investigation, balsa wood (*Ochroma pyramidale*) was employed as the matrix material, and graphene oxide (GO) was introduced to fabricate a composite material, with the aim of systematically elucidating the regulatory mechanism of GO on the multiscale pore structure of wood. The balsa wood was first pretreated with Na₂SO₃/NaOH mixed solutions at varying concentrations to achieve pore enlargement via delignification. The results revealed that under optimal conditions (concentrations of Na₂SO₃ and NaOH of 50 g/L, treatment temperature of 70 °C and duration of 2 h), the pretreated balsa wood had the largest average pore size and best pore connectivity. Subsequently, GO solutions at different concentrations were introduced into the pretreated wood through vacuum impregnation. Characterization results confirmed that GO successfully penetrated the interior of the wood and established a stable interfacial bond with the wood matrix via hydrogen bonding, while the crystalline structure of the wood cellulose remained well preserved. The incorporation of GO significantly facilitated the charring process at high temperatures, thereby enhancing the thermal stability of the resulting composite. Pore structure analysis revealed that at a GO concentration of 3%, the composite displayed a hierarchical pore size distribution (spanning 3-10 nm, 500-2000 nm, and 5200-15200 nm), while retaining satisfactory pore connectivity. Notably, excessively high or low GO concentrations were found to be detrimental to the formation of a hierarchical pore architecture and to compromise pore connectivity.

Keywords: Balsa wood, Graphene oxide, Pore structure, macropores, micropores

1. Introduction

Fast-growing wood constitutes an important resource in forestry production. Owing to its low density and poor mechanical strength, it is not suitable for direct application as solid wood for load-bearing furniture, and is mainly utilized as raw material for paper manufacturing, wood-based panels and other commodities. To broaden the practical application scenarios and raise the added value of fast-growing wood, two strategies can be adopted: one is reinforcement modification to improve its physical and mechanical properties (Zhang 2024; Wanju Li 2020; Yang 2019) and the other is functional modification to endow it with specific functionalities (Lai 2023; Zheng 2022; Cheng 2022). Notably, both reinforcement modification and functional modification rely on the abundant pore structure inherent to fast-growing wood.

In practical applications, pore structure regulation is generally required to endow modified fast-growing wood with favorable mechanical properties or functionalities. Studies have demonstrated that partial hemicellulose and lignin in wood can be removed via chemical methods, which elevates porosity and improves the connectivity of wood pores (Ren 2023; Darajat 2025; Kumar 2021). For instance, Zhang

et al.(2023) adopted $\text{NaClO}_2/\text{CH}_3\text{COOH}$ mixed solution to adjust the pore structure of poplar (*Populus L.*). The results revealed that the specific surface area of treated wood increased by approximately 3.7 times (from $15 \text{ m}^2/\text{g}$ to $71 \text{ m}^2/\text{g}$), and the total pore volume rose around 2.5 times (from $0.027 \text{ cm}^3/\text{g}$ to $0.095 \text{ cm}^3/\text{g}$), in comparison with untreated wood. Jang et al.(Jang and Kang 2021) performed delignification on Korean Toona (*Toona sinensis*) using $\text{NaOH}/\text{Na}_2\text{SO}_3$ mixed solution. It was found that a large number of closed pores in wood transformed into open pores, and the overall connectivity of the pore system was significantly enhanced. Modification strategies relying on chemical removal of lignin and hemicellulose are mainly applied to expand original wood pores and optimize pore connectivity. By contrast, carbonization combined with activation treatment enables the construction of hierarchical porous structures containing micropores, mesopores and macropores within wood(Jiao 2020; Grima-Olmedo 2023; Yao 2023). Shao et al. (Shao 2020) treated poplar via carbonization coupled with KOH chemical activation. After modification, the specific surface area of wood increased from $511 \text{ m}^2/\text{g}$ to $2153 \text{ m}^2/\text{g}$, the total pore volume grew from $0.17 \text{ cm}^3/\text{g}$ to $1.13 \text{ cm}^3/\text{g}$, and the proportion of micropores exceeded 70%. Moreover, the combination of porous materials (e.g., metal-organic frameworks) with fast-growing wood is another strategy to tailor wood pore structures and introduce extra micropores. The as-fabricated composites exhibit outstanding adsorption capacity and can be utilized for the adsorption of gases (Li 2026) and dye wastewater(Cui 2023). The abundant pore structure of fast-growing wood provides physical space for modification and functionalization, while abundant active groups including phenolic hydroxyl groups, alcoholic hydroxyl groups, aromatic groups, carbonyl groups, carboxyl groups, conjugated double bonds and methoxy groups offer natural chemical modification sites(Jiang 2018; Zhu 2016). The synergistic effect of the above two factors opens up an effective route for wood modification.

Graphene oxide (GO) is a typical two-dimensional layered carbon nanomaterial. Its surface is rich in numerous oxygen-containing functional groups including hydroxyl ($-\text{OH}$), carboxyl ($-\text{COOH}$) and epoxy ($\text{C}-\text{O}-\text{C}$) groups(Lerf 1998), endowing GO with a high specific surface area, favorable dispersibility and superior chemical activity(Liu 2022). The abundant surface functional groups of GO can form stable composite systems with other matrices via hydrogen bonding, electrostatic interactions and $\pi-\pi$ conjugation effects(Khine 2022). Therefore, GO exhibits promising application prospects in the functional modification of wood, such as conductive wood(Wang 2022; Fu 2022) and wood-based energy storage materials(Huang 2020). At present, existing studies mainly focus on optimizing the functional properties of GO-modified wood, whereas systematic investigations concerning the reconstruction and regulation mechanism of wood pore structure by GO are still insufficient. In view of the above, balsa wood was selected as the matrix in this work, and composites were fabricated via the introduction of GO. The interfacial interaction mechanism between GO and wood was systematically explored, and the regulation mechanism of GO on the hierarchical pore structure of wood was clarified. This study can provide theoretical basis and technical support for the modification and subsequent processing of fast-growing wood.

2. Materials and methods

2.1 Materials

Balsa wood (*Ochroma pyramidale*) with a tree age of 4 years was harvested in Xishuangbanna, Yunnan Province. Sapwood specimens were cut from the xylem at a height of 1.5 m above the ground, with dimensions of 20 mm (length) $\times$ 20 mm (width) $\times$ 1 mm (thickness). The air-dried density was $0.15 \text{ g}/\text{cm}^3$ and the moisture content was 11%.

Sodium hydroxide (NaOH, purity $\geq 98\%$) and sodium sulfite (Na_2SO_3 , purity $\geq 98\%$) were purchased from Titan Technology Co., Ltd. (Shanghai, China). Graphene oxide aqueous dispersion with a solid content of 7 % was supplied by Guangdong Zhuguangxi New Energy Technology Co., Ltd. Distilled water was self-prepared in the laboratory.

2.2 Material preparation

Firstly, NaOH solutions and Na_2SO_3 solutions with various concentrations were prepared for further use. The cut wood slices with a fixed mass were immersed in a beaker containing 100 mL Na_2SO_3 /NaOH mixed solution (volume ratio=1:1, in the text, they are designated as $\text{Na}_2\text{SO}_3\text{x/NaOH}_y$, where x and y represent the concentration values of the two components, respectively). Subsequently, the beaker was placed in an oil bath pot (LC-DF-101S, Lichen Scientific Instrument (Zhejiang) Co., Ltd.) for heating and stirring. In this work, nine sets of treatment parameters were designed (Table 1). After treatment, the samples were repeatedly soaked and rinsed with distilled water until the pH value of the eluate reached 7-8. Afterwards, the specimens were freeze-dried (Scientz-10N, Ningbo Scientz Biotechnology Co., Ltd., $-64\text{ }^\circ\text{C}$, 50 Pa, 24 h) to obtain pretreated wood. The pore structures of the nine groups of pretreated wood samples were characterized, and the group with the maximum average pore diameter was selected for subsequent modification.

Table 1 Process conditions for treating balsa wood with NaOH/ Na_2SO_3 mixed solution

Groups	Na_2SO_3 concentration (g/L)	NaOH concentration (g/L)	Temperature ($^\circ\text{C}$)	Reaction time (h)
1	10	20	70	1
2	30	20	80	2
3	50	20	90	4
4	10	50	80	4
5	30	50	90	1
6	50	50	70	2
7	10	80	90	2
8	30	80	70	4
9	50	80	80	1

GO dispersions with mass fractions of 1 %, 2 %, 3 %, 4 % and 5 % were prepared for use. The optimized pretreated wood slices were immersed in GO dispersions of different concentrations, followed by vacuum impregnation (LC-DZF-6020A, Lichen Scientific Instrument (Zhejiang) Co., Ltd.) at 0.08 MPa for 1 h. Thereafter, the samples were kept at ambient temperature and atmospheric pressure for 12 h. Finally, the specimens were taken out, and residual solution on the surface was removed. Balsa wood/GO composites (It is designated as Balsa wood/GO_z, where z represents the concentration value of GO, namely 1, 2, 3, 4, and 5, respectively) were obtained after freeze-drying ($-64\text{ }^\circ\text{C}$, 50 Pa, 24 h). The fabrication procedure of the composites is illustrated in Figure 1.

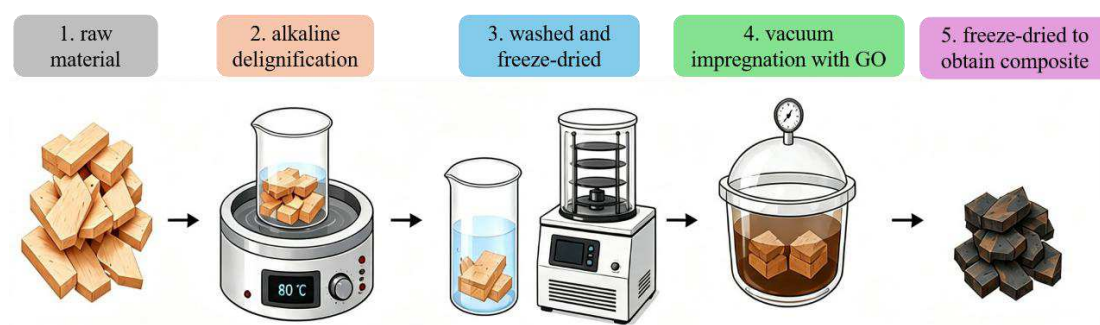


Fig. 1 Flow chart of the preparation of balsa wood/GO composites

2.3 Characterization

The pore-scale micromorphology of pristine wood and balsa wood/GO composites was observed via a scanning electron microscope (SEM, TESCAN MAIA 3 LMH, TESCAN, Czech Republic) under an accelerating voltage of 20 kV and a working distance of 6 mm. An energy-dispersive X-ray spectrometer (EDS, X-ACT, Oxford Instruments, United Kingdom) was adopted to characterize the elemental composition and spatial distribution of elements within balsa wood/GO composites.

Macropore structures of wood specimens were measured using an automated mercury porosimeter (MIP, AutoPore V 9620, Micromeritics Instrument Corporation, USA). Specimens were cut into square wood chips (10 mm×10 mm). Prior to testing, the samples were degassed under vacuum (1 Pa) at 120 °C for 8 h, and the measurement temperature was maintained at 25 °C.

A specific surface area analyzer (Quantachrome Nova 4000e, Quantachrome Instruments, USA) was employed to acquire mesopore and micropore information of the balsa wood/GO composites, with nitrogen adsorption-desorption isotherms collected at -196 °C. Before characterization, the samples were chopped into 1 mm × 1 mm particles and subjected to vacuum degassing (1 Pa) at 120 °C for 8 h.

Fourier-transform infrared spectroscopy (FTIR, Nicolet Summit X, Thermo Fisher Scientific, USA) was utilized to identify variations in functional groups of wood before and after GO modification. A small quantity of sample was homogeneously blended with potassium bromide at a mass ratio of approximately 1:200. The ground mixture was compressed into pellets for infrared detection over the wavenumber range of 400-4000 cm⁻¹.

An X-ray diffractometer (XRD, SmartLab SE, Rigaku Corporation, Japan) was used to investigate the crystalline structure of the as-prepared materials. The aqueous GO suspension was freeze-dried to yield homogeneous GO powder prior to XRD testing. A copper target served as the anode, the operating voltage and current were set to 30 kV and 10 mA, respectively. The scanning 2θ range covered 5°-40° at a scan rate of 5 °/min.

Thermal stability measurements were carried out on a simultaneous thermal analyzer (STA, STA 449, Netzsch, Germany). Samples were heated from room temperature to 800 °C at a heating rate of 10 °C/min.

3. Results and discussion

3.1 The morphology and structure of balsa wood/GO composites

Figure 2 (A, C and E) displays the macroscopic morphologies of untreated balsa wood, pure GO and balsa-wood/GO composite, while Figure 2 (B, D and F) presents the corresponding microscopic morphologies of the three materials. Figure 2 (G, H) show the EDS elemental-distribution maps of the balsa-wood/GO composite. As can be observed from the images, the colour of balsa wood darkened after

GO modification, which indicates the attachment of GO onto the wood surface.

The inner walls of vessel lumens in untreated balsa wood (Figure 2(B)) are smooth and free of obvious deposits, retaining the regular porous architecture of natural wood. After GO impregnation (Figure 2(F)), abundant folded sheet-like substances are anchored on the inner surfaces of wood vessels. Their morphology resembles the two-dimensional layered structure of pristine GO (Figure 2(D)). Furthermore, EDS results reveal that these sheet-shaped deposits are mainly composed of carbon and oxygen (Figure 2(G, H)), and the elemental distribution matches well with the sheet-like substances in Figure 2(F). The above-mentioned findings demonstrate that GO has successfully infiltrated into the wood interior and formed stable composite structures on the inner walls of wood vessels.

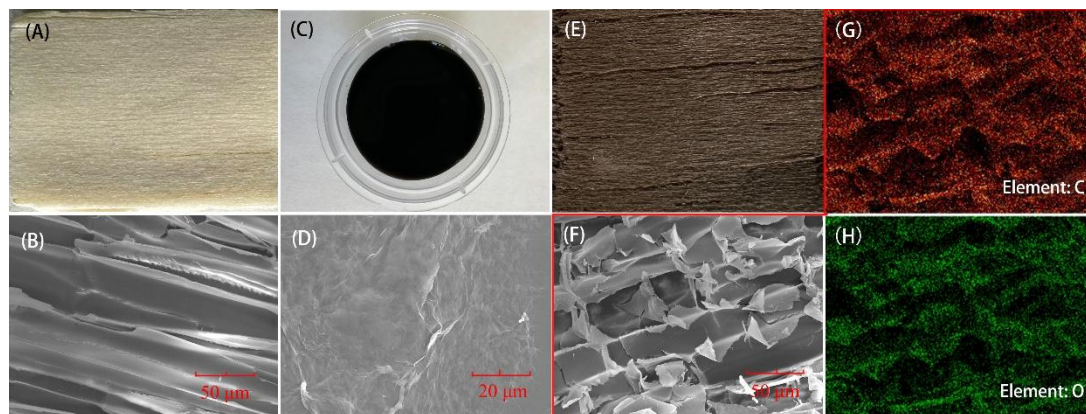


Fig. 2 Macro- and micromorphology of balsa wood, GO, and balsa wood/GO composites, and EDS elemental mapping of balsa wood/GO

Figure 3 shows the XRD patterns of pristine balsa wood, graphene oxide (GO) and balsa-wood/GO composite. Two diffraction peaks of balsa-wood appear at $2\theta=15.9^\circ$ and $2\theta=22.5^\circ$, which correspond to the (101) and (002) crystal planes of cellulose inside wood, respectively. These peaks represent the typical crystalline characteristics of natural wood. The diffraction peak of GO located at $2\theta=11.9^\circ$ is assigned to the (001) crystal plane of its layered architecture. This characteristic peak arises from the enlarged interlayer spacing induced by abundant oxygen-containing functional groups intercalated between GO nanosheets, and it serves as the signature diffraction peak for GO (Cutroneo 2022). Both characteristic diffraction peaks originating from cellulose and GO can be detected in the XRD profile of the balsa wood/GO composite. The peak position and full-width-at-half-maximum (FWHM) of cellulose barely undergo variation, whereas the diffraction-peak intensity of GO decreases markedly. This phenomenon verifies the effective exfoliation of GO nanosheets within the wood matrix, and the original regularly-stacked layered structure of GO is disassembled (Gu 2025). Meanwhile, the composite retains all characteristic diffraction peaks of native cellulose from balsa wood without crystal-form transformation. It is demonstrated that the crystalline structure of cellulose in balsa wood is well-preserved during composite fabrication, and stable interfacial bonding is achieved between balsa-wood substrate and GO.

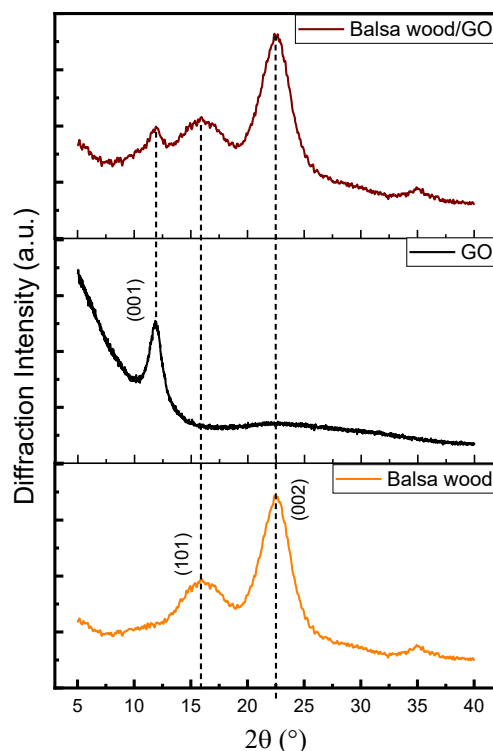


Fig. 3 XRD patterns of balsa wood, GO, and balsa wood/GO composite

Figure 4 presents the FTIR spectra of pristine balsa wood, GO and the balsa wood/GO composite. For the spectrum of balsa wood, the absorption band at 1508 cm^{-1} originates from the C=C stretching vibration of aromatic rings in the phenylpropane structural units of lignin (Xu 2013; Zhang 2016). The characteristic peak at 1739 cm^{-1} is attributed to the C=O stretching vibration of acetyl or ester groups in hemicellulose (Tu 2020). This peak intensity declines obviously in the spectrum of the balsa wood/GO composite, which is primarily ascribed to the dissolution of hemicellulose when the wood sample is treated with mixed NaOH/Na₂SO₃ aqueous solution. In addition, the absorption band located at 1267 cm^{-1} in the GO spectrum corresponds to the asymmetric stretching vibration of epoxy groups (C-O-C) (Dreyer 2010; Marcano 2010). As one of the most representative characteristic peaks of GO, this signal proves the generation of epoxy moieties after the oxidation of the graphene skeleton. The identical peak can also be observed for the balsa wood/GO composite. This finding suggests that after GO penetrates into the wood matrix, stable interfacial adhesion is established via hydrogen bonding interactions between oxygen-containing functional groups (hydroxyl, carboxyl and epoxy groups) on GO and wood chemical constituents.

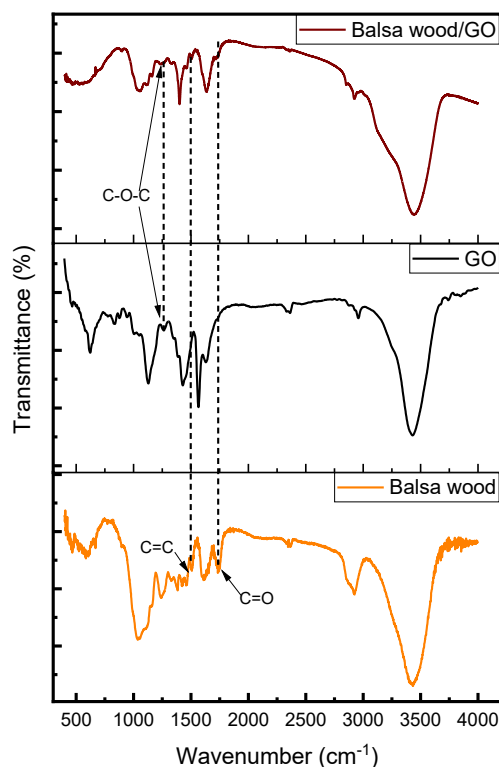


Fig. 4 FTIR spectra of balsa wood, GO, and balsa wood/GO composite

Figure 5 displays the TGA curves of balsa wood and balsa wood/GO composite. The thermogravimetric process of both samples can be divided into three stages: low-temperature moisture removal, rapid thermal pyrolysis and high-temperature carbonization. The thermal decomposition of pure balsa wood proceeds in three phases. Volatilization of bound water takes place from room temperature to 150 °C; the temperature range of 150-350 °C corresponds to the thermal degradation of cellulose, hemicellulose and lignin; slow carbonization occurs above 350 °C. As for the balsa wood/GO composite, desorption of bound water is also observed within room temperature to 150 °C. Weight loss proceeds more rapidly than that of pristine balsa wood between 150 °C and 250 °C. Large quantities of oxygen-containing functional groups are distributed on the GO surface. These groups become thermally unstable near 200 °C and decompose preferentially with the release of small molecule gases including CO₂ and H₂O (McAllister 2007; Becerril 2008). Nevertheless, the two curves intersect at 288 °C. Afterwards, the weight-loss rate of the composite slows down considerably. At 500 °C, the char residue yield of pristine balsa wood reaches approximately 25%-26%, while that of the balsa wood/GO composite is about 26%-27%, slightly higher than the blank sample. The above results demonstrate that incorporated GO effectively facilitates char-forming reactions under high-temperature conditions and generates a more stable char layer, thereby improving the thermal stability of the composite.

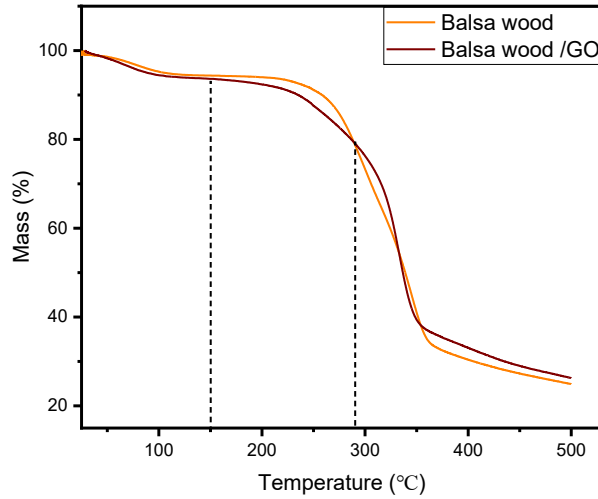


Fig. 5 TGA curves of balsa wood and balsa wood/GO composite

3.2 The pore structure of balsa wood/GO Composites

Figure 6 illustrates the macropore distribution of untreated balsa wood and balsa wood samples treated with mixed NaOH/Na₂SO₃ solutions of different concentrations. It can be seen that the pore size range of untreated balsa wood is 360-1066 nm, with an average pore diameter of approximately 869.8 nm. An increasing trend in pore size is observed for all balsa wood specimens after the mixed solution treatment. The most significant pore structure variation is obtained under the treatment conditions of 50 g/L NaOH and 50 g/L Na₂SO₃, reaction temperature of 70 °C and reaction duration of 2 h. The pore size distribution is substantially broadened, and the average pore diameter rises to 2649.79 nm (Table 2).

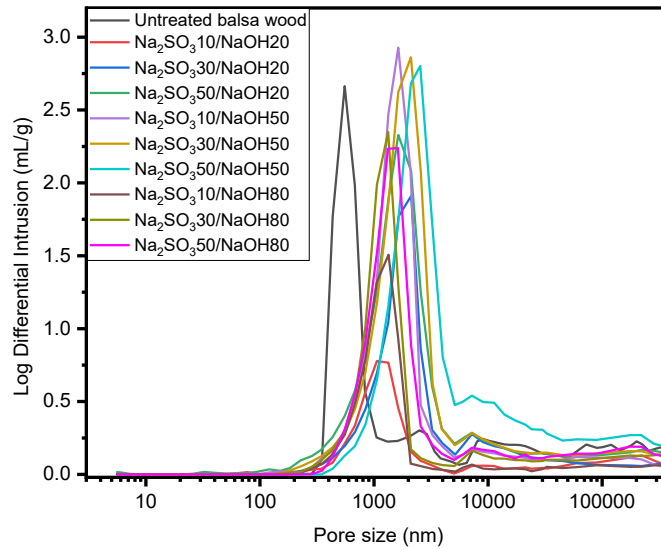


Fig. 6 Macropore distribution of balsa wood treated with NaOH/Na₂SO₃ mixed solutions

Figure 7 shows the cumulative mercury intrusion curves of balsa wood treated with NaOH/Na₂SO₃ mixed solutions at various concentrations. The critical pore size of untreated balsa wood is approximately 735 nm. After treatment with a mixed solution of 50 g/L Na₂SO₃ and 50 g/L NaOH, the critical pore size increased to approximately 10,000 nm, and the cumulative mercury intrusion volume increased from

0.43 mL/g to 1.79 mL/g, indicating that the bottlenecks originally restricting the flow were opened up, and the overall connectivity of the wood was greatly improved. In addition, as demonstrated by Figure 6, Figure 7 and Table 2, the average pore diameter of wood generally increases first and then decreases with the rising NaOH concentration. With increasing Na_2SO_3 concentration, the cumulative mercury intrusion volume of the balsa wood modified by the mixed solution exhibited an overall increasing trend. This is mainly attributed to the combined effect of NaOH and Na_2SO_3 in the pore-expansion process of wood. NaOH selectively removes lignin and hemicellulose during the pore-expansion process, while Na_2SO_3 introduces sulfonic acid groups ($-\text{SO}_3\text{Na}$) onto the lignin molecules through sulfonation under alkaline conditions, thereby increasing the water solubility of lignin and accelerating its removal (Song 2017). Under their synergistic effect, a suitable pH range is required, excessively low pH hinders the removal of lignin and hemicellulose, while overly high pH suppresses lignin sulfonation (Singh 2003). In the present work, balsa wood exhibited best pore-expansion effect after being heated and stirred in a 50 g/L NaOH/50 g/L Na_2SO_3 mixed solution at 70 °C for 2 h.

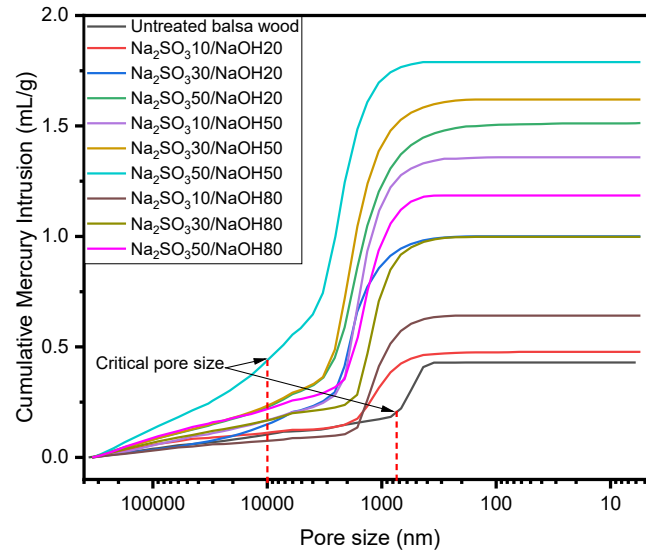


Fig. 7 The cumulative mercury intrusion curves of balsa wood treated with various concentrations of NaOH/ Na_2SO_3 mixed solutions

Table 2 Macropore structure of wood after treatment with NaOH/ Na_2SO_3 mixed solutions

Groups	Pore volume (mL/g)	Total pore area (m ² /g)	Average pore diameter (nm)
Untreated Balsa wood	3.50	12.83	869.80
Na_2SO_3 10/NaOH20	0.48	1.62	1180.48
Na_2SO_3 30/NaOH20	1.00	2.37	1685.93
Na_2SO_3 50/NaOH20	1.51	5.90	1025.60
Na_2SO_3 10/NaOH50	1.36	3.76	1444.65
Na_2SO_3 30/NaOH50	1.62	3.94	1645.23
Na_2SO_3 50/NaOH50	1.79	2.70	2649.79
Na_2SO_3 10/NaOH80	0.64	2.25	1139.68
Na_2SO_3 30/NaOH80	0.99	3.14	1271.38
Na_2SO_3 50/NaOH80	1.18	3.08	1540.30

Figure 8 shows the macropore size distribution of the composite formed by combining balsa wood treated with the optimal pretreatment process and different concentrations of GO. Combined with the pore structure parameters in Table 3, it can be seen that with increasing GO doping concentration, the average pore size of the composite materials exhibits an overall downward trend, while the pore size distribution characteristics of each group of specimens differ significantly. When the GO concentration is 1‰-2‰, the pore range of 1000-5200 nm in the wood changes to a relatively small extent, whereas the proportion of pores in the 5200-15200 nm range decreases. When the GO concentration increases to 4‰-5‰, the original pores of 1000-5200 nm shrink to the 400-2000 nm range, and the pores in the 5200-15200 nm range essentially disappear. At a GO concentration of 3‰, the vast majority of pores in the 1000-5200 nm range contract to 500-2700 nm, while the large-sized pores of 5200-15200 nm are still retained. The above pore evolution pattern stems from the regulatory effect of GO on the interconnected pore structure of balsa wood. When GO enters the porous material, it first deposits on the pore wall surfaces to form a coating, and gradually fills the pore cavities as the concentration increases (Vladimirovich and Melnikov 2018; Jahandideh 2022). Under low-concentration conditions, GO particles preferentially adsorb at the throats of macropores, forming a barrier layer at the pore interconnection channels (Gad-Allah 2017), thereby weakening the connectivity between pore channels (Gao 2022) and requiring higher pressure for mercury to break through (throat narrowing). According to the Washburn equation (Washburn 1921), throat narrowing causes more pores to be classified into smaller pore size categories, which may be the main reason for the marked decrease in the proportion of 5200-15200 nm macropores observed in the present study for the samples with low GO concentrations (1‰-2‰). When the GO solution concentration is high (4‰-5‰), not only is there sufficient GO to fill and shrink the 1000-5200 nm pores to approximately 400-2000 nm, but the excess GO continues to enter the 5200-15200 nm macropore region, depositing extensively on the inner walls of the macropores, occupying the internal space of the macropores, and substantially reducing pore connectivity, making it very difficult to detect pores in the 5200-15200 nm range. At a GO concentration of 3‰, sufficient GO can stack layer by layer, overlap, and densely fill these pores, causing the original 1000-5200 nm pores to be filled and shrunk by a large number of GO nanosheets to approximately 500-2000 nm. In contrast, the macropores of 5200-15200 nm are larger in size and are not completely filled by GO, and are therefore preserved.

The above analysis is corroborated by the cumulative mercury intrusion curves (Fig. 9). As shown in the figure, the critical pore size of Balsa wood/GO3 is approximately 6500 nm, which is smaller than the 10000 nm of the pretreated balsa wood, yet it still exhibits a significant advantage compared with the other four composite material groups, indicating that the pretreated balsa wood combined with 3‰ GO still maintains relatively good pore connectivity.

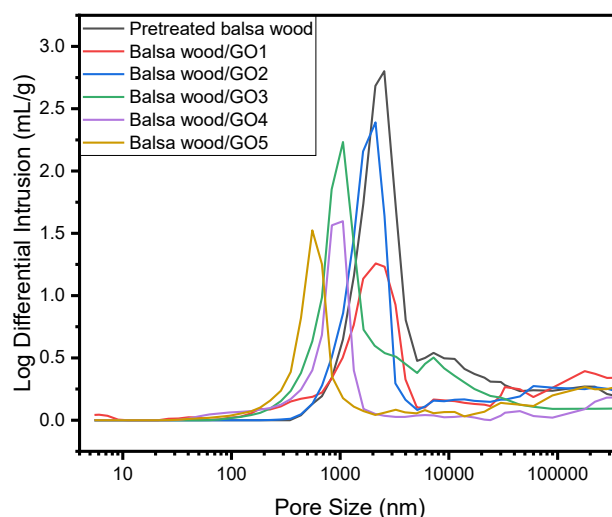


Fig. 8 Macropore size distribution of balsa wood/GO composites

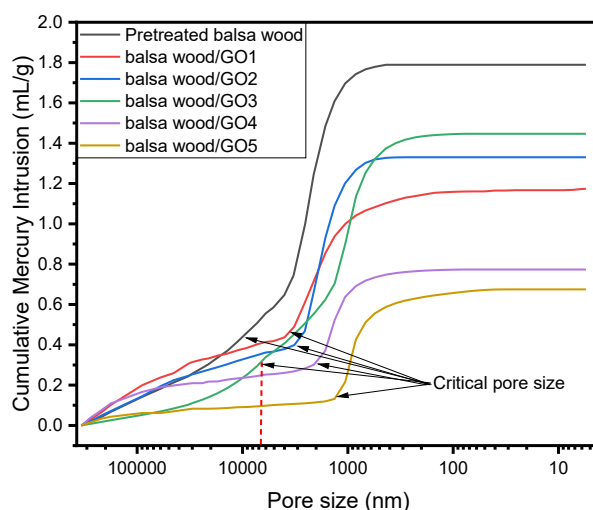


Fig. 9 Pore size-cumulative mercury intrusion curves of balsa wood/GO composites

Table 3 Macropore structure of balsa wood/GO composites

Groups	Pore volume (mL/g)	Total pore area (m ² /g)	Average pore diameter (nm)
Balsa wood/GO1	1.17	2.69	2122
Balsa wood/GO2	1.33	2.56	2078
Balsa wood/GO3	1.44	4.98	1161
Balsa wood/GO4	0.67	4.54	593
Balsa wood/GO5	0.77	5.06	554

Figure 10 shows the N₂ adsorption/desorption isotherms of the composite materials obtained after doping balsa wood with different concentrations of GO. As can be seen from the figure, the five sets of adsorption/desorption isotherms all belong to the Type III isotherm, indicating that the interaction between the adsorbate molecules (N₂) and the adsorbent (balsa wood/GO composite) surface is relatively weak, while the interaction among the adsorbate molecules themselves is relatively strong. Therefore,

the initial adsorption capacity is very low. As the pressure increases, a small number of molecules adsorb onto the surface, which subsequently promotes the aggregation of more molecules. In addition, when the GO concentration is 1%-4%, the N₂ adsorption/desorption curves of the composite materials exhibit similar trends, and the micropore-mesopore size distributions are also essentially the same (Fig. 11). When the GO concentration is 2%-3%, the composite materials possess relatively large micropore volumes and micropore specific surface areas (Table 4). When the GO concentration increases to 5%, the micropore volume and micropore specific surface area of the composite material decrease significantly. This is mainly because the excessive GO leads to lamellar stacking, covering, and filling effects, which block or destroy the original micropore structure of the wood (Rekos 2019; Neshat 2024), resulting in a reduction in micropore volume and specific surface area.

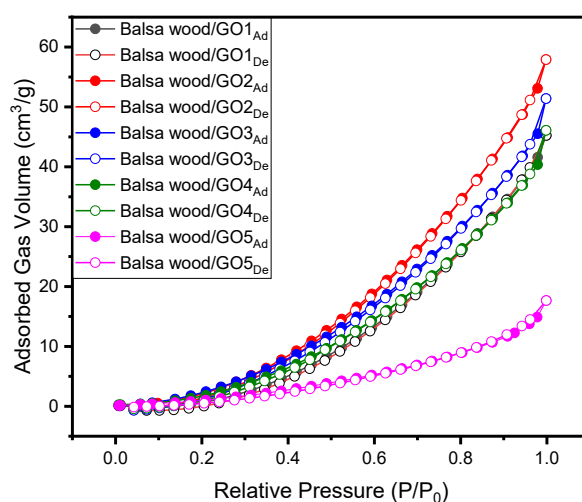


Fig. 10 N₂ adsorption/desorption isotherms of balsa wood/GO composites

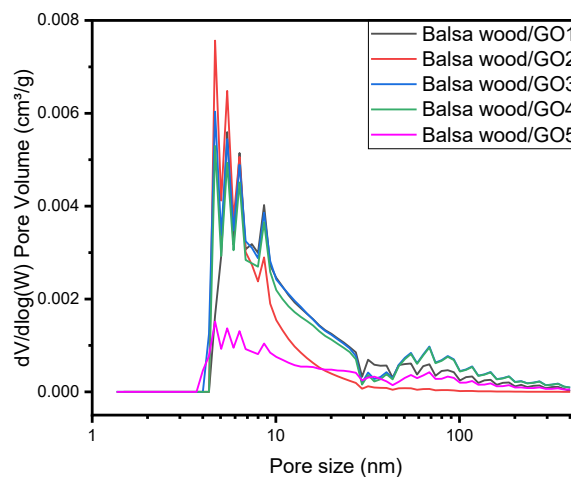


Fig. 11 Micropore-mesopore size distribution of balsa wood/GO composite

Table 4 Micropore structure of balsa wood/GO composites

Groups	Micropore volume (cm ³ /g)	micropore specific surface area (m ² /g)	Average pore diameter (nm)
Balsa wood/GO1	0.07	14.05	5.0
Balsa wood/GO2	0.09	19.00	4.3

Balsa wood/GO3	0.08	16.66	4.3
Balsa wood/GO4	0.07	14.44	4.3
Balsa wood/GO5	0.03	5.19	4.3

4. Conclusion

This study used balsa wood as the matrix, which was first subjected to pore expansion treatment with a $\text{Na}_2\text{SO}_3/\text{NaOH}$ mixed solution and then composited with GO, with the aim of constructing a hierarchical pore structure and enhancing the pore connectivity of the wood. Systematic characterization (SEM, EDS, FTIR) confirmed that after entering the wood pores, GO uniformly adhered to the inner walls of the pores, and a stable interfacial bonding between the two was achieved mainly through hydrogen bonding. XRD analysis demonstrated that the crystalline structure of the wood cellulose was well preserved in the balsa wood/GO composites. In addition, thermogravimetric analysis indicated that the introduction of GO effectively promoted the charring process at high temperatures, resulting in a more stable char layer structure. When the concentrations of both Na_2SO_3 and NaOH were 55 g/L, the treatment temperature was 70 °C, and the treatment time was 2 h, the resulting pretreated balsa wood exhibited the largest average pore size and the best pore connectivity. When the GO concentration was 3%, the prepared composite material possessed a hierarchical pore size distribution and maintained relatively good pore connectivity. Either excessively high or excessively low GO concentrations were unfavorable for the construction of hierarchical pores and reduced pore connectivity.

Acknowledgments

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Author contributions

Xinyu Li designed and performed the experiments, conducted data analysis, and drafted the manuscript. Shijie Lu contributed to part of the experimental work and manuscript preparation. Shijie Li offered guidance on experimental optimization and data analysis. Hongyan Zhu provided support for partial sample testing. Jianguo Zhao provided support regarding experimental conditions and funding. All authors reviewed the manuscript.

Declarations

Conflict of interest: The authors declare no competing interests.

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