

Wood Waste Derived Carbon Materials and Catalysts: Preparation, Characterization, Applications and Future Perspectives

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DOI: <https://doi.org/10.51244/IJRSI.2026.1309000022>

Received: 11 September 2026; Accepted: 16 September 2026; Published: 30 September 2026

ABSTRACT

Wood processing activities generate considerable quantities of sawdust and other lignocellulosic residues, and their disposal or uncontrolled burning can reduce the value of a potentially useful carbon resource. Conversion of such residues into functional carbon materials provides a route for waste valorization while reducing dependence on fossil derived carbon precursors. This review discusses the preparation, characterization and application of wood waste derived carbon materials and catalysts, with particular attention to activation, surface functionalization and heteroatom doping, especially nitrogen doping. The relationship between precursor composition, thermal treatment, pore development, surface chemistry and application performance is considered rather than treating preparation and application as independent topics. Wood derived carbons have been investigated as heterogeneous catalysts, catalyst supports, adsorbents, electrochemical electrodes, sensor materials and functional components in energy related devices. Their use in organic synthesis, environmental remediation, supercapacitors, rechargeable batteries, electrocatalysis, sensing and antimicrobial systems demonstrates the broad utility of biomass derived carbon. Teakwood sawdust is discussed separately because published studies have already demonstrated its suitability as a precursor for porous and activated carbon, including materials with high surface area and useful electrochemical properties. However, the literature is more developed for adsorption and energy storage applications than for deliberately designed catalytic materials, particularly N-doped teakwood sawdust derived catalysts. The review therefore identifies the need for better control of pore architecture, surface functional groups, nitrogen speciation, reproducibility, regeneration, scale up and life cycle performance. The broader literature suggests that teakwood sawdust can serve as a promising renewable precursor for multifunctional carbon materials, while N doping offers a practical route for tuning surface chemistry and electronic properties for catalytic and other advanced applications.

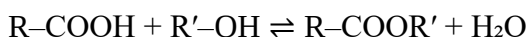
Keywords: Wood waste; Teakwood sawdust; N-doped carbon; Biomass derived carbon; Heterogeneous catalysis

INTRODUCTION

Wood processing generates sawdust, shavings, bark and other lignocellulosic residues containing cellulose, hemicellulose and lignin. These components can be converted into biochar, activated carbon and functional carbon materials, providing a route for waste valorization and reducing dependence on fossil derived carbon precursors [7–18, 20–23].

The final material is controlled by precursor composition and processing history. Carbonization temperature, heating rate, atmosphere, activation method and post treatment determine carbon yield, pore architecture, surface oxygen groups, defect density and graphitic ordering. Comparisons based only on biomass name or

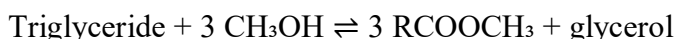
BET surface area can therefore be misleading; precursor analysis and matched processing conditions are needed [14, 17, 20, 32].



Catalytic studies show why surface chemistry must be considered separately from porosity. Sulfonated biomass derived carbons provide Brønsted acid sites for esterification [18, 63, 70, 77].

The reaction represents conversion of a carboxylic acid and an alcohol to an ester and water. Biomass derived sulfonated carbon catalysts have been reported for esterification and transesterification, including biodiesel

related systems [18, 63, 70, 77]. These results should not be transferred directly to N doped teakwood carbon because nitrogen functionalities can alter basicity and electronic structure but do not by themselves create SO_3H acid sites.



For future N doped teakwood carbon, transesterification can be used as a model reaction to test whether controlled nitrogen speciation, pore accessibility and surface chemistry produce measurable catalytic activity and recyclability. The reaction below is proposed as a future test system, not as an established performance claim for N doped teakwood carbon [70].

The interest in biomass derived carbon is not based only on the availability of the raw material. The structure of the final carbon can be adjusted through the selection of carbonization temperature, heating rate, atmosphere, activation agent and post treatment. These variables influence pore volume, surface area, surface oxygen groups, degree of graphitization and accessibility of active sites. As a result, one biomass precursor can produce materials with quite different properties and application performance. Reviews on biomass derived catalytic materials have emphasized that the relationship between physicochemical properties and application is central to rational catalyst design [14, 17, 32].

Wood Waste as A Renewable Carbon Precursor

Wood is heterogeneous rather than a single chemical feedstock. Cellulose, hemicellulose and lignin decompose at different stages, while extractives and minerals influence char formation, ash content and surface chemistry. Species, growth conditions, heartwood/sapwood ratio, moisture and processing history therefore affect reproducibility [16, 19, 48].

Carbonization produces a carbon rich framework, but activation is often required when higher accessible porosity is needed. Chemical activation can generate high surface area at lower temperatures but consumes activating agents and requires washing; physical activation reduces chemical use but may require higher temperatures. Process selection should therefore consider carbon yield, energy demand, chemical consumption, wastewater burden and regeneration, not surface area alone [14, 17, 55].

The diversity of wood residues can be useful, but it also creates a reproducibility problem. Species, age, growth conditions, heartwood/sapwood ratio, moisture content and processing history can influence the composition of sawdust. This is one reason why reporting only the name of a biomass source is not sufficient for comparing two carbon materials. Proximate analysis, elemental analysis and thermogravimetric analysis can provide a more meaningful basis for comparison.

Teakwood Sawdust: Composition, Preparation and Current Status

Teak (*Tectona grandis*) is a high value hardwood widely used in furniture, construction and other wood products. Sawdust generated during processing is consequently an accessible wood residue in regions where teak processing is established. The chemical composition of teak is complex and includes lignocellulosic fractions together with extractives. Analytical studies have reported substantial chemical differences

between heartwood and sapwood, which is relevant because precursor composition can affect thermal conversion and surface chemistry [16, 19, 48].

Direct *Tectona grandis* evidence establishes a strong porous carbon baseline. Ismadji et al. obtained activated carbon from vacuum pyrolysis char with a BET surface area of about 1150 m² g⁻¹ and pore volume of 0.43 cm³ g⁻¹ [26]. Cansado et al. produced CO₂ activated teak carbon with micro/mesoporosity and demonstrated pesticide removal [13]. Singh and Mishra reported 1270 m² g⁻¹ and 0.673 cm³ g⁻¹ after chemical activation, while Nguyen et al. demonstrated teak hydrochar derived activated carbons for methylene blue, copper and cadmium removal [42, 56].

Teak derived carbon has also been applied to energy storage. Jain et al. prepared mesoporous carbon from teak sawdust for lithium ion capacitors [27]. Hegde and Bhat reported *Tectona grandis* sawdust derived porous graphitic carbon with a BET area of 1767.66 m² g⁻¹, pore volume of 1.43 cm³ g⁻¹, specific capacitance of 572 F g⁻¹ at 0.5 A g⁻¹ and 95.83% retention after 4500 cycles [24]. Tjahjana et al. used teak wood powder as a carbon source in LiFePO₄/C cathodes [62]. These data support application specific potential, but they do not establish universal superiority over commercial activated carbon or conventional electrode materials.

The evidence boundary is therefore clear: *Tectona grandis* is established as a precursor for activated carbon, adsorption media and electrochemical materials, whereas deliberately engineered N doped teak carbon for heterogeneous catalysis remains sparsely studied. Negara et al. provide direct evidence that nitrogen assisted processing can alter teak carbon properties; however, their study reports material and adsorption characteristics rather than catalytic conversion. A key next step is to connect nitrogen source, N speciation, pore accessibility and catalytic kinetics under matched conditions [41, 66].

Table 2. Quantitative comparison of selected *Tectona grandis* sawdust derived carbons reported in the literature.

Study	Processing / condition	BET / pore data	Reported performance	Benchmark / evidence boundary
Ismadji et al., 2005 [26]	Vacuum pyrolysis char + activation	≈1150 m ² g ⁻¹ ; 0.43 cm ³ g ⁻¹	Activated carbon; porous structure	Direct teak evidence; no matched commercial benchmark reported
Cansado et al., 2018 [13]	CO ₂ activation; 873–1073 K	Micro/mesoporosity; numeric BET not used here	Pesticide removal	Direct <i>Tectona grandis</i> evidence; matched commercial comparison needed
Singh & Mishra, 2021 [56]	KCl + sodium thiosulfate activation	1270 m ² g ⁻¹ ; 0.673 cm ³ g ⁻¹	Activated carbon; yield ≈52%	Direct teak evidence; high area alone does not establish superiority
Nguyen et al., 2019 [42]	KOH/K ₂ CO ₃ activation of teak hydrochar	Well developed microporosity	Methylene blue, Cu and Cd removal	Direct teak evidence; adsorption conditions differ across studies
Jain et al., 2017 [27]	Mesoporous carbon from teak sawdust	Mesoporous; study specific values	Lithium ion capacitor electrode	Direct teak evidence; not a commercial carbon benchmark
Hegde & Bhat, 2024 [24]	FeCl ₃ assisted carbonization, 650–850 °C + KOH	1767.66 m ² g ⁻¹ ; 1.43 cm ³ g ⁻¹	572 F g ⁻¹ at 0.5 A g ⁻¹ ; 95.83% retention after 4500 cycles	Strong electrochemical result under study specific conditions
Suriadi	Teak sawdust	Best: 126.279 m ² g ⁻¹ ;	13.48 mg g ⁻¹	Shows strong processing

et al., 2024 [61]	activation; heating rate study	0.235 cm ³ g ⁻¹	methylene blue adsorption at reported optimum	dependence
Negara et al., 2023 [41]	N assisted activation; 8–12 °C min ⁻¹ ; 600 °C activation	409.698 m ² g ⁻¹ ; 0.369 cm ³ g ⁻¹ ; 3.61 nm average pore diameter	N ₂ adsorption: 239.102 cm ³ g ⁻¹ ; optimum at 10 °C min ⁻¹	Direct N assisted teak study; reports material/adsorption data, not catalytic conversion
Tjahjana et al., 2024 [62]	Teak wood powder carbon source in LiFePO ₄ /C	Study specific	LiFePO ₄ /C cathode performance	Direct teak evidence for composite battery use

Preparation and Modification of Wood Derived Carbon Materials

Carbonization

Carbonization is generally performed under an inert atmosphere to limit complete combustion and promote the formation of a carbon rich solid. The selected temperature influences mass yield, aromatic condensation, pore development and surface functionality. Lower temperatures may retain more oxygen containing groups, whereas higher temperatures generally increase carbon ordering and conductivity while removing volatile functional groups. There is therefore no universal optimum carbonization temperature; the appropriate condition depends on the intended application.

Activation

Activation may be physical or chemical. CO₂ or steam can develop porosity with limited chemical residues, whereas KOH, K₂CO₃, ZnCl₂ or H₃PO₄ can produce stronger pore development but require chemical handling and washing. The appropriate route depends on target pore size, surface chemistry, yield and downstream application [26–40, 42]. High BET area alone is not evidence of catalytic superiority because active site identity and accessibility can control reaction rate.

Surface Functionalization

Carbon surfaces can be modified by oxidation, sulfonation, amination or metal loading. Sulfonated carbons are solid acid catalysts because SO₃H groups provide Brønsted acidity [18, 77]. This chemistry should be distinguished from N doping: pyridinic, pyrrolic and graphitic nitrogen mainly modify basicity, electronic structure, polarity and defect chemistry rather than generating sulfonic acid sites [1, 68, 75].

Nitrogen Doping

Nitrogen doping is especially relevant to the present research direction. Nitrogen can be introduced from external precursors such as urea, melamine, ammonia and nitrogen containing organic compounds, or can originate from naturally nitrogen rich biomass. Wood generally has less nitrogen than protein rich biomass, so controlled external doping may be useful when a high or specific nitrogen content is required. The temperature and nitrogen source influence whether pyridinic, pyrrolic or graphitic nitrogen becomes dominant. These differences can alter basicity, electron transfer and interaction with reactants or ions [1, 68, 75].

For N doped teak carbon, optimization should vary the N source, N/C ratio, carbonization temperature and activation severity. XPS N 1s speciation, elemental nitrogen, BET/pore data and application performance should be evaluated together. One step and post carbonization doping should be compared under matched conditions because increased nitrogen content can also block pores or alter conductivity.

Table 1. Representative preparation and modification routes for wood derived carbon materials.

Route	Typical treatment	Main effect	Application relevance
Carbonization	Inert atmosphere; controlled heating	Carbon rich aromatic framework; yield and ordering depend on temperature	Base material for adsorbents, supports and electrodes
CO ₂ /steam activation	Physical activation after or during carbonization	Pore development with limited chemical residues	Adsorption and electrodes
KOH/K ₂ CO ₃ activation	Chemical activation followed by washing	Strong pore development; higher chemical burden	Adsorption and energy storage
Hydrothermal carbonization	Aqueous thermal treatment	Hydrochar formation at lower temperature	Precursor and adsorption materials
N doping	Urea, melamine, ammonia or other N sources	Changes nitrogen speciation, defects and surface chemistry	Catalysis, sensing and energy storage

Characterization of Wood Waste Derived Carbon Materials

A complete description requires complementary characterization. TGA/DTG supports precursor decomposition and carbonization selection; FTIR identifies surface groups; XRD and Raman assess structural ordering; SEM/TEM and EDS describe morphology and elemental distribution; and N₂ adsorption gives BET area and pore size distribution. XPS is particularly important for N doped materials because it distinguishes surface nitrogen environments, while elemental analysis provides bulk composition.

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide morphological information, while energy-dispersive X-ray spectroscopy (EDS/EDX) can provide semi-quantitative elemental mapping. Nitrogen adsorption–desorption analysis is important for BET surface area, pore volume and pore size distribution. X-ray photoelectron spectroscopy (XPS) is particularly important for N-doped materials because it can distinguish different nitrogen environments at the surface. Elemental analysis provides bulk C/H/N/O information and should not be confused with the surface sensitive information obtained from XPS.

Application specific testing is essential. Catalysis should include acidity/basicity or redox site measurements, kinetics, leaching and post reaction characterization; electrochemical studies should report CV, GCD, EIS and cycling; sensing studies should report sensitivity, response/recovery, selectivity, hysteresis and stability. These measurements prevent a material from being judged by one structural parameter alone.

Applications of Wood Waste Derived Carbon Materials

Heterogeneous Catalysis and Organic Synthesis

Wood derived carbon can serve as a catalyst, catalyst support or precursor for metal containing catalysts. The strongest established catalytic evidence in the cited literature concerns functionalized carbons, particularly sulfonated materials used in acid catalyzed biodiesel chemistry [14, 18, 20, 28, 32, 69–70, 77]. Biomass derived sulfonated catalysts have been evaluated in esterification of fatty acids and transesterification of triglycerides; performance depends on acid site density, porosity, mass transfer and reaction conditions [70]. This supports carbon surface functionalization as a design strategy but does not demonstrate equivalent activity for N doped teak carbon.

For N doped teakwood carbon, the relevant question is whether nitrogen sites provide sufficient basic or electronic functionality and whether reactants can reach those sites. Catalytic evaluation should therefore report conversion or yield, catalyst loading, temperature, time, kinetic model, site density where measurable,

recyclability and leaching. These data would permit comparison with commercial activated carbon and established biomass catalysts under matched conditions.

Adsorption and Environmental Applications

Teak derived activated carbons have been applied to dye, phenol and pesticide removal, while broader biomass carbon studies cover metals, antibiotics and gases [13, 25–26, 42]. The evidence supports a pore and surface chemistry driven adsorption mechanism, but direct comparisons with commercial activated carbon are not consistently reported under identical conditions. Matched comparisons are therefore needed before claims of competitiveness are made.

Supercapacitors and Energy Storage

Porous biomass carbon is widely investigated for supercapacitors because pore accessibility, conductivity and surface chemistry influence ion storage. For teakwood, the strongest quantitative evidence is Hegde and Bhat's 572 F g⁻¹ at 0.5 A g⁻¹ with 95.83% retention after 4500 cycles [4–5, 24, 47, 50, 52–54, 74, 76, 78]. The result demonstrates strong electrode performance for one formulation, but cross study comparisons remain limited because electrolyte, loading, current density and cell configuration differ.

Batteries and Related Energy Conversion

Biomass derived carbon is used in battery electrodes, conductive additives and composites, with performance governed by conductivity, pore architecture and structural stability [2–3, 11, 43, 51–52, 59]. Teak wood powder has been used as a carbon source in LiFePO₄/C cathodes [62]. This supports precursor versatility but does not establish direct superiority over commercial conductive carbon.

Solar and Photovoltaic Applications

Biomass derived carbon quantum dots and carbon interfaces have been explored in photovoltaic systems. One reported biomass derived CQD study gave 13.65% photovoltaic efficiency in an EVA/polycrystalline silicon system [8, 46, 58]. These results concern carbon containing composites or quantum dots rather than bulk teak activated carbon, so extrapolation to N doped teak electrodes should be avoided.

Sensors and Humidity Sensing

Biomass derived carbons and carbon dots have been investigated for electrochemical, optical and humidity sensing [33, 45, 49, 64, 72–73]. Practical sensors require sensitivity, response/recovery, selectivity, hysteresis and long term stability. N doping may change surface polarity and charge transport, but its benefit must be demonstrated experimentally.

Antibacterial and Antifungal Applications

Antimicrobial carbon research is less mature than adsorption and energy storage. Biomass derived carbon dots and functional composites have shown activity through surface interactions and reactive species pathways [40, 57]. Direct evidence for pristine *Tectona grandis* activated carbon remains limited; standardized microbial assays and appropriate controls are required before assigning antimicrobial functionality to N doped teak carbon.

Scale up and Industrial Potential

Industrial relevance depends on feedstock consistency, carbon yield, energy use, activating agent consumption, washing, regeneration and product lifetime. Existing biomass carbon studies illustrate potential in adsorption and gas separation [6, 44, 65], but teakwood specific techno economic and life cycle datasets are limited. Future scale up studies should report process energy, chemical consumption, carbon yield, wastewater and emissions, followed by regeneration testing and minimum cost/life cycle analysis under defined system boundaries.

Structure–Property–Performance Relationships

A critical comparison can be expressed as a structure–property–performance chain: precursor composition → thermal history → carbon yield and ordering → pore architecture → surface chemistry → active site accessibility → application performance. Wood composition controls devolatilization and mineral content; carbonization establishes the carbon framework; activation changes pore volume and accessibility; and N doping changes surface chemistry and electronic character.

The design rule is application specific. Adsorption generally benefits from an accessible pore network and favorable surface affinity; supercapacitors require a balance of accessible surface, ion transport and conductivity; batteries require stable conductive pathways and controlled pore architecture; and catalysis requires accessible sites with appropriate acid/base or redox character. Maximizing BET area is therefore not a universal optimization target.

For N doped teak carbon, two testable relationships follow. First, precursor composition and carbonization severity should influence the balance of pyridinic, pyrrolic and graphitic nitrogen and therefore catalytic or electrochemical behavior. Second, one step and post carbonization N doping should produce different nitrogen distributions and pore accessibility at matched N/C ratios. These hypotheses can be tested by combining XPS, elemental analysis, Raman/BET measurements and application specific kinetics or electrochemical testing.

Table 3. Structure–property–performance links used to compare application requirements.

Application	Critical properties	Useful evidence
Catalysis	Active site density/accessibility; acidity/basicity; pore transport	XPS, TPD, BET, kinetics, leaching, recyclability
Adsorption	Accessible pore volume; pore size; surface affinity	BET, pore distribution, FTIR, adsorption isotherms
Supercapacitors	Accessible surface; conductivity; ion transport; stability	BET, Raman, CV, GCD, EIS, cycling
Batteries	Conductivity; pore architecture; structural stability	XRD, SEM/TEM, XPS, EIS, cycling
Sensors	Conductivity; analyte interaction; response/recovery	XPS/FTIR, electrical response, selectivity, stability
Antimicrobial use	Surface chemistry; reactive species; active additives	XPS/FTIR plus standardized microbiological controls

Critical Research Gaps and Future Perspectives

The literature is difficult to compare because precursor composition, activation severity, measurement conditions and application protocols vary. Many studies optimize a single metric such as BET area or adsorption capacity without simultaneously reporting yield, energy demand, chemical consumption, regeneration or active site evidence. For catalytic materials, activity is also sometimes inferred from surface characterization without sufficient control experiments.

For teakwood, the direct evidence is strongest for activated carbon, adsorption and electrochemical materials [13, 24, 26–27, 41–42, 56, 61–62]. The research gap is therefore not the preparation of porous teak carbon itself, but the controlled design of N doped teak carbon with a demonstrated structure–activity relationship. Priority experiments are matched N source/N:C ratio studies, one step versus post doping comparisons, XPS nitrogen speciation, catalytic model reactions, kinetics, leaching and recyclability.

Scale up should be evaluated using carbon yield, activation temperature, residence time, energy input, reagent consumption and wastewater generation. Real sawdust variability should be included rather than relying on a single laboratory batch. Techno economic and life cycle calculations should then identify

dominant cost and environmental burdens instead of assuming that waste derived feedstock automatically gives a low impact product [55].

Table 4. Priority experiments and scale up questions for N doped teakwood carbon.

Priority	Question	Recommended evidence
Nitrogen speciation	Which N environments arise from different N sources and temperatures?	XPS N 1s + elemental N + Raman
Structure–activity	Does higher BET area actually increase catalytic conversion?	Matched loading, kinetics and site accessibility
Process optimization	How do carbonization, activation and N/C ratio interact?	Design of experiments using yield + BET + XPS + performance
Recyclability	Are activity and nitrogen sites retained after use?	Repeated cycles, post use XPS/BET and leaching
Scale up	What controls energy and chemical demand?	Mass balance, carbon yield, energy input, reagent/water use
Sustainability	Where are the environmental hotspots?	Defined boundary life cycle and techno economic analysis

CONCLUSION

Wood waste can be converted into porous and functional carbon through carbonization, activation and surface modification. Across the literature, performance is governed by the interaction of pore architecture, surface chemistry, conductivity and application specific active sites rather than by precursor identity or BET area alone.

Tectona grandis sawdust has direct evidence for activated carbon, adsorption and electrochemical applications, including high area porous carbon and supercapacitor electrodes [13, 24, 26–27, 41, 56, 60–62, 67, 71, 74, 78]. The evidence does not yet establish N doped teak carbon as a catalytic material. The most useful next step is a controlled structure–property–performance study linking precursor composition, carbonization, N doping, nitrogen speciation, pore accessibility, catalytic kinetics and recyclability, together with scale up and sustainability assessment.

Declarations

Conflict of Interest: The authors declare that there is no conflict of interest related to this review.

Funding: Not applicable; this review was prepared from published literature.

Data Availability: Not applicable; this article is a review of published literature.

Author Contributions: Both authors contributed to the preparation and critical revision of the manuscript and approved the final version.

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