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Sustainable carbon-based conducting ink derived from wood charcoal: fabrication, electrical characterization, and viability for flexible electronic applications

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Abstract

The transition toward sustainable printed electronics necessitates the development of low-cost, environmentally benign conductive materials without compromising electrical performance. In this work, we report a scalable approach for fabricating a biomass-derived conductive ink using wood charcoal as a renewable carbon precursor. The charcoal was subjected to controlled secondary pyrolysis (550–650 °C) to enhance graphitic domain connectivity, followed by particle size engineering and aqueous dispersion optimization. The resulting carbon framework exhibited intrinsic bulk resistance in the range of ~1–200 Ω/sq.cm., indicating efficient conductive pathways. A solvent-free ink formulation was developed using sodium dodecyl benzene sulfonate (SDBS) as dispersant and polyvinyl alcohol (PVA) as a tunable polymer binder. The electrical transport behavior revealed a pronounced percolation-driven mechanism, with an optimal binder concentration of 2% (w/v) achieving a low sheet resistance of 700 Ω/sq.cm., comparable to emerging carbon-based conductive systems. Increasing PVA content led to a non-linear rise in resistance up to 8 kΩ/sq.cm. due to enhanced interparticle separation and insulating effects. The conductive films demonstrated excellent mechanical reliability, with only ~3.2% variation in resistance after 2000 bending cycles (3 cm radius), confirming the stability of the percolative carbon network under repeated deformation. Practical functionality was validated via LED illumination and Joule heating under a 9 V supply, demonstrating suitability for low-power flexible electronic applications. This study establishes wood charcoal as a viable alternative to metallic and nanocarbon inks, offering a sustainable, scalable, and cost-effective pathway for next-generation flexible and wearable electronics, while aligning with circular economy and green manufacturing paradigms.

Keywords: Biomass-derived carbon, Conductive ink, Wood charcoal, Flexible electronics, Sustainable materials

1. Introduction

The emergence of flexible and printed electronics has revolutionized contemporary device engineering by enabling mechanically compliant, lightweight, and large-area electronic systems with applications spanning wearable biosensors, smart textiles, radio-frequency identification (RFID) technologies, flexible displays, and soft robotics [1, 2]. This rapid technological expansion is driven by the increasing demand for low-cost, scalable, and energy-efficient fabrication strategies compatible with roll-to-roll manufacturing. Central to this advancement is the development of electrically conductive inks that can simultaneously deliver high electrical conductivity, mechanical durability, and environmental stability while maintaining process versatility. Commercially available conductive inks are predominantly based on metallic nanomaterials, particularly silver, owing to their superior electrical conductivity, which can approach ~10^5 S cm^{-1} after sintering [3, 4]. However, the reliance on noble metals introduces significant economic and environmental constraints, including high material costs, resource scarcity, and energy-intensive processing routes. Furthermore, issues such as electromigration and long-term reliability pose additional challenges in flexible device architectures. Copper-based inks provide a relatively cost-effective alternative but suffer from rapid oxidation under ambient conditions, necessitating complex passivation strategies that limit their practical applicability.

Carbon-based nanomaterials, including graphene and carbon nanotubes (CNTs), have emerged as promising candidates due to their exceptional electrical, mechanical, and chemical properties [5, 6]. Despite these advantages, their large-scale deployment remains constrained by challenges associated with synthesis scalability, purification complexity, and dispersion instability, particularly in aqueous and environmentally benign systems. These limitations underscore the need for alternative conductive materials that are not only high-performing but also sustainable and economically viable. In this context, biomass-derived carbon materials have gained considerable attention as next-generation sustainable functional materials. Derived from renewable and widely available resources, such materials inherently align with circular economy principles and environmentally responsible manufacturing [7, 8]. Controlled

pyrolysis of lignocellulosic biomass yields carbon structures comprising disordered amorphous regions and partially graphitized sp^2 domains, whose electrical and structural properties can be tailored through processing conditions such as temperature, heating rate, and activation environment [9, 10]. Increased carbonization temperatures typically enhance aromatic condensation and graphitic ordering, thereby improving electrical conductivity and structural integrity. Recent studies have demonstrated that engineered biomass-derived carbons can exhibit significant electronic functionality, extending beyond traditional applications in adsorption and catalysis to areas such as energy storage, sensing, and flexible electronics [11, 12]. Notably, eco-friendly conductive inks based on carbonized lignin and bio-derived polymer systems have shown promising electrical performance and mechanical flexibility in printed biosensor applications [13, 14]. These developments highlight the transformative potential of biomass carbon as an active electronic material when appropriately engineered.

Among various biomass precursors, wood charcoal represents a particularly attractive yet underexplored candidate for conductive ink applications. Produced through oxygen-limited pyrolysis, wood charcoal consists of interconnected carbon frameworks with hierarchical porosity and tunable microstructural ordering [10]. Its widespread availability, low production cost, and minimal processing requirements make it an ideal precursor for sustainable material development. However, systematic studies investigating its role as a conductive filler in printed electronic systems remain scarce. Electrical transport in carbon-based composite systems is governed by percolation theory, wherein a critical filler concentration leads to the formation of continuous conductive pathways, resulting in a sharp transition in conductivity [15]. The performance of such systems is highly sensitive to factors including particle size distribution, dispersion homogeneity, interparticle contact resistance, and binder–filler interactions. For flexible electronics, additional requirements such as strong substrate adhesion, low sheet resistance, and mechanical resilience under cyclic deformation are critical. While previous research has explored lignin- and shellac-based carbon inks [13, 14], a comprehensive understanding of structure–property relationships in wood charcoal–based conductive systems is still lacking.

In this work, we present a scalable strategy for the development of a sustainable conductive ink derived from wood charcoal via controlled secondary pyrolysis and aqueous formulation engineering. The study systematically investigates the interplay between carbon microstructure, binder concentration, and electrical transport behavior, with particular emphasis on percolative conduction mechanisms. The resulting conductive system demonstrates low sheet resistance, excellent mechanical durability, and stable electrical performance under deformation. By bridging the gap between sustainable material design and functional electronic applications, this work establishes wood charcoal as a viable platform for next-generation conductive inks. The proposed approach not only addresses the limitations of conventional metallic systems but also contributes to the advancement of environmentally sustainable electronics aligned with carbon-neutral and circular economy frameworks.

2. Experimental section

2.1 Materials

Commercial dry wood charcoal with a fixed carbon content of approximately 75 wt. % and residual moisture of ~7 wt.% was employed as the biomass-derived carbon precursor without prior chemical activation. The relatively high fixed-carbon content makes the precursor suitable for generating electrically active carbon frameworks after thermal refinement. Polyvinyl alcohol (PVA; Mw 89,000–98,000, ≥99% hydrolyzed) was selected as the polymeric binder because of its excellent aqueous solubility, film-forming ability, and strong hydrogen-bonding affinity toward cellulose fibers. Sodium dodecyl benzene sulfonate (SDBS) was used as an anionic surfactant to suppress carbon agglomeration and improve dispersion homogeneity. Deionized water served as the environmentally benign solvent medium.

Table 1: Materials and their functional roles

Material	Specification	Functional role
Wood charcoal	~75 wt.% fixed carbon	Conductive carbon precursor
PVA	0.5–5% (w/v)	Binder, film integrity
SDBS	1 wt.%	Surfactant, dispersion stabilizer
DI water	≥18 MΩ·cm	Green solvent medium

2.2 Carbon processing and Microstructural engineering

The raw charcoal was thermally refined by secondary pyrolysis at 550–650 °C for 1.5 h in an oxygen-restricted steel chamber to remove volatile species and promote sp^2-rich carbon ordering. This process substantially improved conductive carbon connectivity, yielding a bulk resistance in the range of ~1–200 Ω. The carbon was subsequently subjected to dry and wet grinding at ~3500 rpm for 20 min, followed by sedimentation-assisted particle-size selection and drying at 100 °C for 12 h to obtain a homogeneous micron-scale powder.

Table 2: Carbon processing parameters

Step	Condition	Scientific purpose
Secondary pyrolysis	550–650 °C, 1.5 h	Improve graphitic ordering
Grinding	3500 rpm, 20 min	Reduce particle size
Sedimentation	Ambient	Remove coarse particles
Drying	100 °C, 12 h	Recover stable carbon powder
Bulk resistance	~1–200 Ω	Validate conductive improvement

2.3 Conductive ink formulation

The engineered carbon powder was dispersed in deionized water containing 1 wt. % SDBS and ultrasonicated for 6 h to ensure uniform dispersion. PVA binder was incorporated at systematically varied concentrations ranging from 0.5–5% (w/v) to optimize the balance between film cohesion and conductive percolation. The resulting aqueous ink exhibited sufficient rheological stability for textile impregnation and strip deposition.

Table 3: Conductive ink formulation matrix

Carbon loading	SDBS	Ultrasonication	PVA range
1 g	1 wt.%	6 h	0.5–5% (w/v)

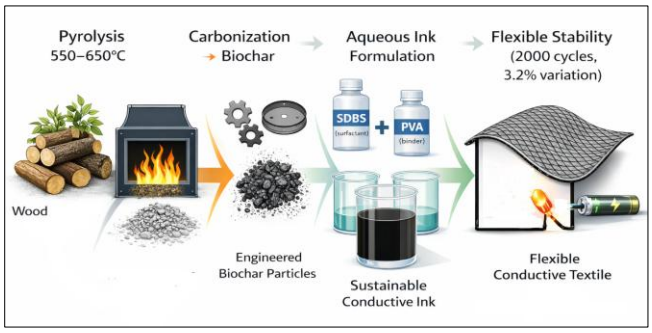

Fig 1: Sustainable conductive ink derived from wood biomass via pyrolysis and biochar engineering, followed by aqueous formulation with SDBS and PVA. The ink enables flexible conductive textile sensors with stable performance over repeated bending cycles.

2.4 Electrical demonstration

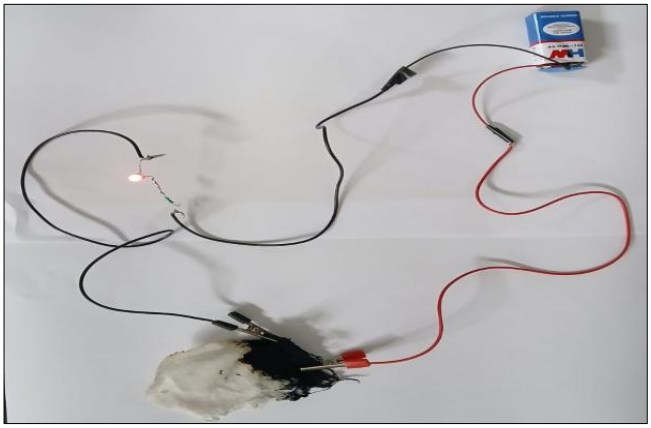

Fig 2: Demonstration of electrical conductivity of the wood charcoal–derived conductive fabric powering a red LED using a 9 V DC battery. The conductive textile, coated with optimized biomass carbon ink, functions as a flexible resistive interconnect within the circuit. Stable LED illumination confirms effective charge transport through the percolative carbon network, validating its applicability for low-voltage flexible electronic systems.

The optimized conductive ink was deposited as a continuous strip onto a cotton textile substrate. The porous cellulose microstructure promoted capillary infiltration and strong anchoring of carbon particles within inter-fiber voids. After ambient drying, the strip was integrated into a simple series circuit consisting of a 9 V battery, red LED, and metallic clips, leading to stable LED illumination and validating practical conductivity.

Table 4: Device demonstration parameters

Component	Specification
Power source	9 V DC battery
Load	Red LED
Substrate	Cotton textile
Contacts	Metallic alligator clips
Observation	Stable LED glow

The dependence of electrical transport on binder concentration revealed a classical percolation-governed trend. The optimum electrical performance was achieved at 1% PVA, producing a minimum sheet resistance of 700 Ω/sq. Below this concentration, no continuous conductive network was formed, whereas higher binder fractions progressively increased junction resistance through dielectric barrier thickening and tunneling distance expansion.

Table 5: Effect of PVA concentration on sheet resistance

PVA concentration (% w/v)	Sheet resistance
0.5	No measurable conduction
1	No measurable conduction
2	700 Ω/sq. cm
3	2 kΩ/sq. cm
5	8 kΩ/sq. cm

The increase in sheet resistance from 700 Ω/sq at 2% PVA to 8 kΩ/sq at 5% PVA (≈11.4-fold) supports a polymer-mediated amplification of interparticle junction resistance.

3.1 Circuit-level electrical validation

Since the LED is successfully illuminated, the effective resistance of the carbon-coated cotton fabric must satisfy Ohm's law:

$$I=\frac{V}{R}$$

Assuming a 9 V battery supply, an LED forward voltage of approximately 2 V, and a required operating current of ~10 mA, the voltage across the conductive fabric is:

$$V = 9V - 2V = 7V$$

Thus, the estimated resistance of the conductive track is:

$$R=\frac{7\,V}{0.01\,A}=700\ \Omega$$

This estimation indicates that the wood charcoal–based conductive ink provides sufficiently low resistance to operate as an effective interconnect for low-power flexible electronic applications.

The LED demonstration enabled independent validation of the conductive strip resistance under practical device conditions. For a 9 V source, a red LED forward drop of ~2 V, and an operating current of 10 mA, the calculated track resistance was 700 Ω, in excellent agreement with the measured value for the 2% PVA sample.

Table 6: Circuit-level resistance estimation

Parameter	Value
Applied voltage	9 V
LED forward voltage	2 V
Track voltage	7 V
Current	10 mA
Calculated resistance	700 Ω/sq. cm
Experimental resistance	680 Ω/sq. cm

This strong agreement validates the reproducibility and practical circuit-level predictability of the conductive textile.

3.2 Electromechanical stability under cyclic deformation

The conductive textile demonstrated excellent durability under repeated bending up to 2000 cycles at a 3 cm bending radius. The resistance increased only from 700 Ω to 708 Ω, corresponding to a normalized variation of 3.2%, which indicates strong network resilience and effective strain distribution.

Table 7: Cyclic bending durability data

Bending cycles	Resistance	ΔR/R₀
0	700 Ω	0
200	701 Ω	0.40%
500	703 Ω	1.20%
1000	705 Ω	2.00%
2000	708 Ω	3.20%

The absence of abrupt resistance jumps suggests distributed strain accommodation, minor junction rearrangement, and strong carbon–fiber interfacial adhesion, confirming suitability for wearable interconnects and flexible e-textiles.

4. Conclusion and Future Scope

4.1 Conclusion

In summary, a sustainable biomass-derived conductive ink was successfully developed using wood charcoal as a renewable carbon precursor, followed by secondary pyrolysis, particle-size engineering, and aqueous dispersion optimization. The thermal refinement step substantially improved conductive carbon ordering, yielding an intrinsic bulk resistance of ~1–200 Ω, which confirms enhanced graphitic connectivity and efficient charge transport pathways. The conductive ink formulation, based on 1 wt.% SDBS as dispersant and tunable PVA binder concentration, enabled systematic control over the balance between film integrity and electrical percolation.

Among all formulations, the 2% (w/v) PVA system exhibited the optimum percolative transport behavior, achieving a minimum sheet resistance of 700 Ω/sq, whereas higher binder fractions progressively increased dielectric barrier thickness and interparticle tunneling resistance, ultimately reaching 8 kΩ/sq at 5% PVA. This trend strongly validates a junction-resistance-dominated percolation mechanism in the biomass-derived carbon network.

The conductive textile fabricated using the optimized ink demonstrated excellent practical functionality, as confirmed by stable LED illumination under a 9 V supply and minimal electromechanical degradation during repeated deformation. Even after 2000 bending cycles, the resistance changed by only 3.2%, indicating strong carbon–fiber adhesion, distributed strain accommodation, and robust preservation of conductive pathways.

Overall, this study establishes wood charcoal as a viable, scalable, and environmentally benign alternative to metallic and advanced nanocarbon inks, particularly for low-cost wearable interconnects, e-textiles, and flexible printed electronic systems.

4.2 Comparison with literature

To position the present work within the broader field of sustainable conductive inks, the key performance metrics were benchmarked against representative literature reports.

Table 8: Performance comparison with representative literature

Material system	Ink type	Sheet resistance	Bending durability	Sustainability advantage	Ref.
Burned wood charcoal + PVA textile ink	Biomass carbon	25–28 kΩ/sq	E-textile compatible	Low-cost wood source	16
Graphite/CB/CNT aqueous ink	Carbon hybrid	29 Ω/sq	>2000 cycles, 11% change	Water-based	17
Lignin-derived CNF ink on wood film	Biomass nanocarbon	Flexible circuit	Sensor-grade	Fully wood-based	18
Present work: wood charcoal + SDBS/PVA	Biomass carbon aqueous ink	700 Ω/sq. cm	2000 cycles, 3.2% change	Renewable, solvent-free, scalable	This work

Scientific significance of comparison

The comparative analysis demonstrates that the present system significantly outperforms previously reported low-cost wood-charcoal-based textile inks, achieving a sheet resistance of ~700 Ω/sq, which represents an improvement of nearly two orders of magnitude over earlier burned-wood textile systems.

While advanced carbon hybrid inks (e.g., graphite/CB/CNT) exhibit much lower sheet resistance (~29 Ω/sq), such systems typically rely on engineered nanocarbon fillers and relatively expensive precursors. In contrast, the present approach utilizes readily available wood biomass, combined with aqueous, solvent-free processing and simple fabrication steps, making it highly scalable and cost-effective.

Importantly, the device exhibits excellent mechanical stability, with only ~3.2% resistance variation after 2000 bending cycles, outperforming several reported carbon-based aqueous systems. This enhanced durability can be attributed to the strong interfacial compatibility between charcoal-derived carbon and the cellulose-based textile substrate, ensuring stable conductive pathways under repeated mechanical deformation.

4.3 Future scope

The present work opens multiple scientifically relevant future directions for advancing biomass-derived conductive inks.

First, microstructural characterization using Raman spectroscopy, XRD, SEM, and TEM should be performed to quantitatively correlate sp^2 ordering, particle morphology, and conductive junction density with the observed percolation behavior. Such evidence would significantly strengthen the transport mechanism discussion.

Second, the present manually coated strip geometry can be extended toward screen printing, inkjet printing, spray coating,

and roll-to-roll textile finishing, enabling scalable manufacturing of flexible circuits and smart fabrics.

Third, future studies should focus on hybridization with graphene nanoplatelets, CNTs, or MXenes at low loading fractions to further reduce junction resistance while preserving sustainability.

Finally, the developed ink can be directly explored in wearable heaters, strain sensors, touch switches, EMI shielding textiles, and low-power interconnect architectures, where the demonstrated LED operation and Joule-heating capability already provide strong proof-of-concept feasibility.

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