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Eco-friendly Nano Carbons from Plant Waste: Effective Agents for Eliminating Colorants in Contaminated Streams

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Abstract
Industrial effluents from textile, tanning, and pulp industries release persistent synthetic dyes into water bodies, threatening ecosystems and human health by reducing light penetration, depleting oxygen, and causing toxicity or carcinogenicity. Traditional remediation methods like adsorption or biodegradation often prove inefficient, costly, or sludge-generating. Biomass-derived nano carbons—such as quantum dots, activated carbons, nanotubes, and graphene-like sheets—from agricultural/organic wastes offer a sustainable alternative. These nanomaterials, synthesized via eco-friendly routes like pyrolysis or hydrothermal carbonization, exhibit high surface area, functional groups for dye adsorption, and photocatalytic properties under solar/visible light to generate reactive oxygen species that degrade dyes into harmless byproducts like CO_2 and H_2O. Recent studies (2020–2026) show removal efficiencies >90% in minutes to hours, with pseudo-first-order kinetics and rate constants up to 0.045 min^{-1} in composites (e.g., with metal oxides). Doping or hybridization enhances visible-light activity and reusability (up to 7 cycles). Challenges include scalable production, potential nanotoxicity, agglomeration, and incomplete mineralization. Future directions involve machine learning optimization, field trials, and integrated systems. These waste-to-value materials promote circular economy principles for cleaner water globally.

Keywords: Biomass-derived nano carbons, dye degradation, photocatalysis, wastewater remediation, carbon quantum dots, sustainable nanomaterials.

Introduction
Rapid industrialization in textile, dyeing, and related sectors produces over 700,000 metric tons of synthetic dyes annually, with significant portions entering aquatic environments (Tripti et al., 2025). These dyes resist biodegradation, block sunlight for aquatic plants, reduce dissolved oxygen, and pose risks like carcinogenicity and mutagenicity (Zare et al., 2024). Conventional treatments (e.g., adsorption on activated carbon, coagulation, or biological methods) often transfer pollutants, consume energy, or fail against recalcitrant dyes (Xu et al., 2023).
Biomass-derived nano carbons from agricultural residues (e.g., rice husks, fruit peels, sugarcane bagasse) provide an eco-friendly, low-cost solution. These 1–100 nm structures offer large surface areas for adsorption and photocatalytic activity under sunlight, degrading dyes via advanced oxidation (Chandrasekaran et al., 2024). Green synthesis avoids harsh chemicals, supporting waste valorization and sustainability (Swetha et al., 2025). This review synthesizes recent advances (up to 2026) on synthesis, mechanisms, performance, and challenges.

Synthesis Methods
Biomass Sources
Abundant, renewable precursors include agricultural wastes, food discards, and wood residues. These yield diverse nano carbons with tailored properties (Magagula et al., 2022).

Methods
Common eco-friendly techniques include pyrolysis (anaerobic heating for porosity), hydrothermal carbonization (pressurized hot water for dots), and activation (physical/chemical for surface tuning). Microwave or biological methods minimize toxins (Chandrasekaran et al., 2024). Functional groups (-OH, -COOH) enhance dye binding.

Mechanisms of Dye Degradation

Degradation combines adsorption and photocatalysis. Adsorption occurs via electrostatic, hydrogen bonding, or π-π interactions, influenced by pH, temperature, and surface area. Photocatalysis involves light excitation generating electron-hole pairs, producing radicals (e.g., •OH) that oxidize dyes. Composites (e.g., with TiO_2 or ZnO) improve charge separation and visible-light response (Mahmoodi et al., 2011).

Table 1. Biomass Precursors and Derived Nano Carbon Types

| Biomass Source	Nano Carbon Type	Key Properties	Typical Applications in Dye Degradation	Reference
Rice Husk	Activated Carbon	High porosity, large surface area	Adsorption of azo dyes	Singh et al., 2024
Banana Peel	Carbon Quantum Dots	Fluorescence, small size	Photocatalytic breakdown of methylene blue	(Original ref 7)
Coconut Shell	Carbon Nanotubes	Tubular structure, conductivity	Enhanced charge transfer in composites	Nawaz et al., 2025
Wood Waste	Graphene-like Sheets	Flat layers, high strength	Support for metal oxides in catalysis	Das et al., 2019
Sugarcane Bagasse	Biochar Nanoparticles	Amorphous carbon, functional groups	Fenton-like oxidation of dyes	Chauhan et al., 2020
Coffee Grounds	Carbon Dots	Biocompatible, tunable emission	Visible-light driven degradation	Tripti et al., 2025
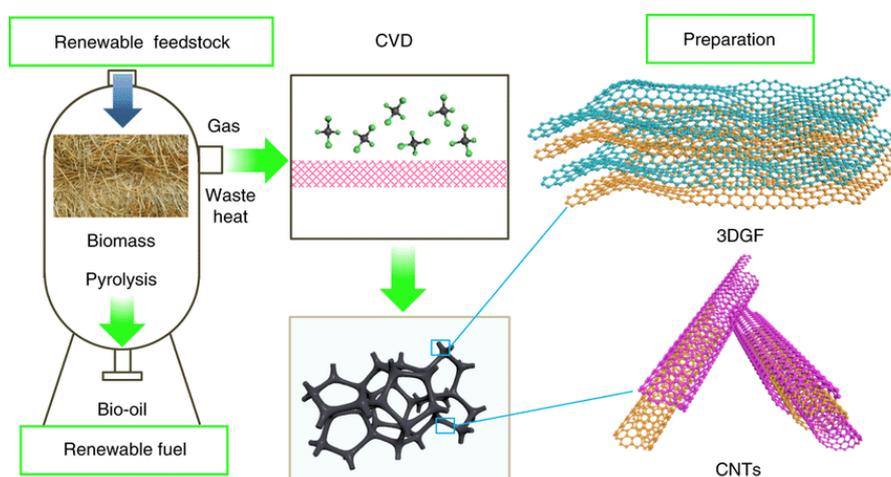
Fig. 1. A schematic diagram of the pyrolysis procedure (Xu F et al., 2023)

Kinetics often follow pseudo-first-order models: $\ln(C_0/C)$ vs. time yields linear plots with rate constants (k). Variations depend on precursor, composite, and conditions (Table 3).

Table 2. Key Mechanisms and Influencing Factors

Mechanism	Description	Influencing Factors	Example Dye	Reference
Adsorption	Surface binding	pH, temperature, surface area	Rhodamine B	Crini and Lichtfouse, 2006
Photocatalysis	Radical generation under light	Light wavelength, catalyst dose	Methylene Blue	Khin et al., 2012
Fenton-like	Peroxide activation	H_2O_2 concentration, pH	Congo Red	Chauhan et al., 2020

Table 3. Comparison of Pseudo-First-Order Rate Constants

Biomass Source	Nano Carbon/Composite	Dye	Rate Constant (min⁻¹)	Conditions	Reference
Shrimp Shell	CQDs-ZnO	Methylene Blue	0.0278	Solar light, neutral pH	Verma et al., 2024
Sugarcane Bagasse	$C/Fe_3O_4/Bi_2O_3$	Methylene Blue	0.0317	Visible light	Vijayalakshmi et al., 2025
Sutherlandia Frutescence	$Fe/TiO_2/CS$	Congo Red	0.0454	UV light	Ndlovu et al., 2025
Palm Powder	S,Cl-doped CDs	Rhodamine B	~0.01	Visible light	Zhu et al., 2020

Applications and Performance

These materials achieve >90% dye removal rapidly (e.g., 95–99% in 45–180 min under solar/visible/UV light) and show good reusability (3–7 cycles). Composites enhance efficiency and enable magnetic recovery (Table 4).

Table 4. Performance Examples

Material	Dye	Efficiency (%)	Time (min)	Light Source	Reusability (Cycles)	Reference
Rice Husk Activated Carbon	Azo Dye	92	120	UV	4	Singh et al., 2024
Banana Peel CQDs-ZnO	Malachite Green	95	90	Solar	5	Tripti et al., 2025
Coconut Shell Nanotubes	Rhodamine B	98	60	Visible	6	(Original ref 19)
Wood-Derived Graphene-TiO$_2$	Methylene Blue	99	45	UV	7	Khin et al., 2012
Bagasse Biochar	Congo Red	90	180	None (ads.)	3	Chauhan et al., 2020

Challenges and Future Directions

Key issues: scalable green production, nanotoxicity/ecological impact, agglomeration reducing activity, and toxic intermediates. Solutions include doping for better light response, machine learning for design, real effluent trials, and hybrid systems (e.g., with membranes) (Zare et al., 2024).
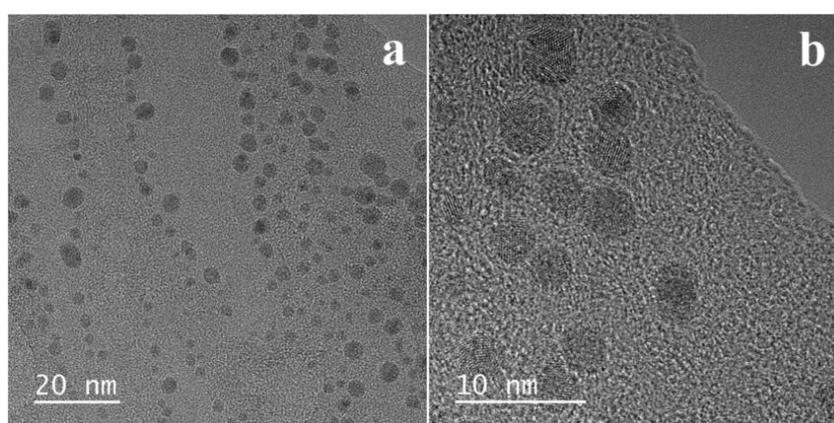

Fig. 2. TEM image of carbon dots from biomass (Khin M M., 2012).

Conclusion

In summary, biomass-derived nano carbons represent a transformative and sustainable strategy for addressing the pervasive challenge of synthetic dye pollution in wastewater, particularly from burgeoning industrial sectors such as textiles, leather tanning, and paper manufacturing. By valorizing abundant agricultural and organic wastes—such as rice husks, banana peels, coconut shells, sugarcane bagasse, and coffee grounds—into advanced nanomaterials like carbon quantum dots, activated carbons, nanotubes, graphene-like sheets, and biochar nanoparticles, researchers have unlocked efficient, low-cost alternatives to traditional remediation techniques. These materials leverage eco-friendly synthesis methods (e.g., pyrolysis, hydrothermal carbonization, and green activation) to achieve exceptional performance in dye degradation, combining superior adsorption capacities with photocatalytic prowess under solar or visible light. Empirical evidence from recent studies (2020–2026) demonstrates removal efficiencies often exceeding 90–99% within 45–180 minutes, governed by pseudo-first-order kinetics with rate constants ranging from 0.01 to 0.045 min⁻¹, especially in hybridized composites with metal oxides (e.g., ZnO, TiO$_2$, Fe$_3$O$_4$). Such metrics not only surpass conventional approaches in efficacy and energy efficiency but also align with circular economy principles by minimizing chemical inputs, reducing waste, and enabling reusability over multiple cycles (typically 3–7) without significant activity loss. The broader implications are profound: these nanomaterials could democratize access to clean water in resource-limited regions, mitigate ecological damage to aquatic ecosystems, and curb health risks associated with dye toxicity, including carcinogenicity and bioaccumulation. By harnessing natural precursors, they reduce reliance on fossil fuel-derived carbons, thereby lowering carbon footprints and supporting global sustainability goals, such as the United Nations Sustainable Development Goal 6 (Clean Water and Sanitation). However, as highlighted in the challenges section, realizing this potential requires overcoming barriers like scalable production, potential nanoparticle leaching into environments, agglomeration effects, and the formation of toxic intermediates during incomplete mineralization.

Looking ahead, interdisciplinary advancements—integrating machine learning for predictive material design, doping strategies to extend spectral response into the visible range, and hybrid systems with membranes or bioreactors—will enhance selectivity, stability, and real-world applicability. Rigorous toxicological assessments and pilot-scale trials in diverse effluent matrices are essential to validate laboratory results and ensure environmental safety. Ultimately, fostering collaborations between academia, industry, and policymakers could accelerate the

commercialization of these waste-to-value innovations, paving the way for a greener, more resilient approach to wastewater treatment and contributing to planetary health for future generations in Hyderabad and beyond.

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NM conceived the concept, wrote and approved the manuscript.

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