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Phyto-Fabrication of Transition Metal Oxides: A Comparative Review of Plant-Extracted Reducing Agents for CuO and NiO

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Abstract: *The transition toward "green chemistry" has catalyzed interest in the phyto-fabrication of transition metal oxide (TMO) nanoparticles. Unlike traditional physical and chemical synthesis methods, which often involve toxic reagents and high energy consumption, plant-mediated synthesis utilizes the inherent bio-reductive potential of flora. This review compares the efficacy of various plant-extracted reducing agents in the synthesis of Copper Oxide (CuO) and Nickel Oxide (NiO) nanoparticles. We analyze how specific phytochemical profiles ranging from polyphenols to terpenoidsinfluence particle size, morphology, and catalytic activity.*

Keywords: Green Nanotechnology, Phyto-fabrication, Transition Metal Oxides, Phytochemical Reduction

I. INTRODUCTION

The rapid evolution of nanotechnology has necessitated the development of sustainable and environmentally benign synthetic protocols to produce transition metal oxide (TMO) nanoparticles [1, 2]. Among the various TMOs, copper oxide (CuO) and nickel oxide (NiO) have garnered significant research interest due to their exceptional physicochemical properties, including high surface-to-volume ratios, tunable bandgaps, and chemical stability [3, 4]. These materials find extensive applications in diverse fields such as heterogeneous catalysis, optoelectronics, wastewater treatment, and biomedicine [5, 6]. Traditionally, these nanoparticles are synthesized via physical and chemical methods, including sol-gel, hydrothermal, and chemical vapor deposition [7, 8]. However, these conventional routes often involve the use of toxic reducing agents (e.g., sodium borohydride), high energy consumption, and the generation of hazardous byproducts, raising substantial ecological concerns [9, 10].

To address these challenges, "phyto-fabrication" a subset of green nanotechnology has emerged as a viable alternative that utilizes plant extracts as biological scaffolds for nanoparticle synthesis [11, 12]. Plants serve as prolific reservoirs of bioactive phytochemicals, such as polyphenols, flavonoids, alkaloids, terpenoids, and proteins, which act as natural reducing and capping agents [13, 14]. These biomolecules facilitate the reduction of metal precursors into zero-valent atoms or oxides while simultaneously providing steric stabilization to prevent agglomeration [15, 16]. The use of aqueous plant extracts not only circumvents the need for harsh chemicals but also enhances the biocompatibility of the resulting CuO and NiO nanoparticles, making them suitable for pharmacological applications [17, 18].

Copper oxide, a p-type semiconductor with a narrow bandgap of approximately 1.2 eV to 1.7 eV, is widely utilized for its antimicrobial potency and photocatalytic efficiency in degrading organic pollutants [1, 19]. Conversely, nickel oxide is a p-type semiconductor with a wider bandgap (typically 3.4 eV to4.0 eV), valued for its high electrochemical stability in supercapacitors and sensing devices [20, 21]. While both oxides can be phyto-fabricated, the choice of plant species ranging from medicinal herbs like *Morindacitrifolia* to agricultural waste like *Samaneasaman* pods drastically influences the final particle morphology, size distribution, and crystallinity [22, 23].

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This comparative review systematically examines the influence of different plant-extracted reducing agents on the structural and functional characteristics of CuO and NiO. By analyzing various botanical sources, from leaves and roots to flowers and seeds, we evaluate how the specific phytochemical profile of an extract dictates the synthesis kinetics and material performance. Furthermore, this review highlights the mechanistic pathways of phyto-reduction and provides a critical assessment of the scalability of green synthesis for industrial-scale transition metal oxide production.

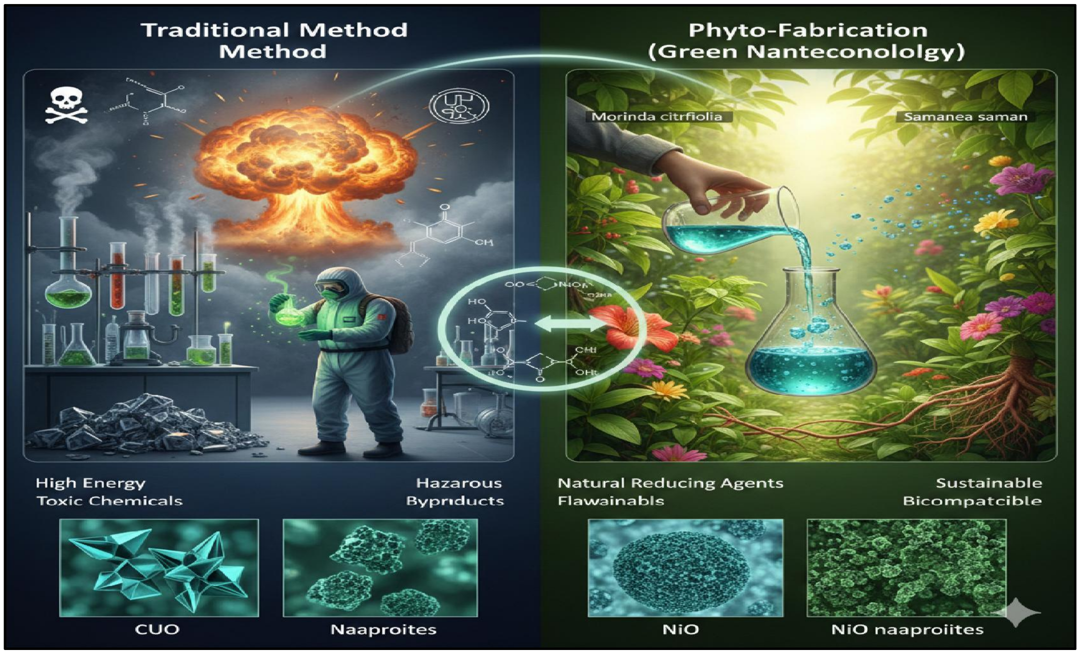

Figure 1: Comparative relation between traditional method and Phyto-fabrication.

II. MECHANISM OF PHYTO-FABRICATION

The synthesis of Copper Oxide (CuO) and Nickel Oxide (NiO) via plant extracts is a multifaceted "bottom-up" approach. The process generally initiates with the complexation of metal precursors typically nitrates or chlorides like $Cu(NO_3)_2.3H_2O$ or $NiCl_{2.}6H_2O$with the secondary metabolites present in the aqueous plant extract [24]. This is followed by the reduction of metal ions to a lower oxidation state or the formation of metal hydroxide intermediates. Finally, thermal stabilization (calcination) is often employed to convert these precursors into their stable crystalline oxide forms [25,26].

2.1 The Role of Phytochemicals

The inherent diversity of plant species results in a varied "chemical cocktail" that dictates the kinetics of nanoparticle nucleation and growth. The specific outcome of the synthesis such as particle size, surface charge, and phase purity is heavily dependent on the concentration and type of bioactive compounds [27].

Polyphenols & Flavonoids: These are considered the primary drivers for the reduction of Cu^{2+} and Ni^{2+} ions. Rich in phenolic hydroxyl (^{-}OH) groups, these compounds act as electron donors. During the reaction, the hydroxyl groups undergo oxidation to quinone forms while simultaneously reducing the metal ions [28,29]. For instance, in the synthesis of CuO, the high reduction potential of polyphenols facilitates the formation of $Cu(OH)_2$ or Cu_2O intermediates, which are subsequently oxidized or dehydrated into stable CuO [30].

Terpenoids: While polyphenols handle the bulk of the reduction, terpenoids often play a critical role in the stabilization and capping of the resulting oxides. These molecules possess various functional groups (carbonyl, leaf-like structures) that adsorb onto the surface of the growing nanoparticles [31]. This adsorption creates a protective "capping" layer that provides steric hindrance, effectively preventing the nanoparticles from aggregating into bulk materials [24, 32].

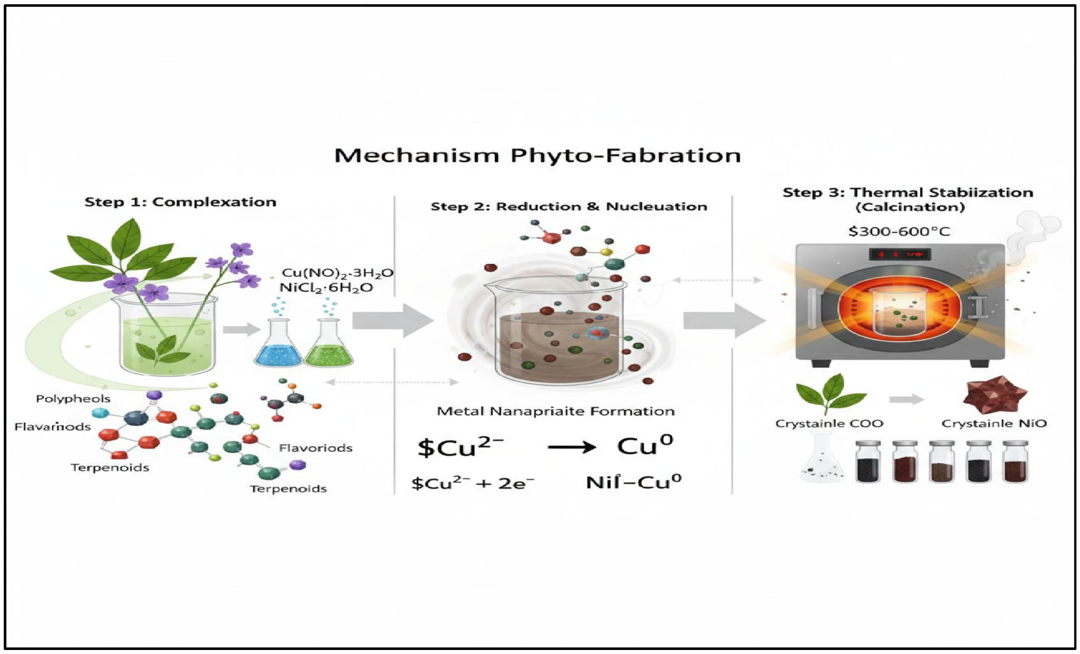

Figure 2: Schematic representation of mechanism of Phyto-fabrication.

Alkaloids: These nitrogenous compounds often act as structural templates or pH-directing agents. By interacting with the metal ions through their amine or amide groups, alkaloids can influence the growth direction of the crystals. This guidance is what leads to the formation of diverse morphologies, such as nanospheres, nanorods, or nanoflowers, depending on the specific alkaloid structure present in the extract [26,33].

III. COMPARATIVE ANALYSIS: CUO VS. NIO SYNTHESIS

While both Copper Oxide (CuO) and Nickel Oxide (NiO) can be synthesized through the green pathway of phyto-fabrication, the inherent chemical nature of the metal ions and their interaction with plant secondary metabolites lead to distinct synthesis requirements and material characteristics [34].

The following table summarizes the key technical differences observed in the green synthesis protocols for these two transition metal oxides:

Feature	**Copper Oxide (CuO)**	**Nickel Oxide (NiO)**
Common Precursors	Copper acetate, Copper sulfate [35, 36]	Nickel chloride, Nickel nitrate [37,38]
Preferred Extracts	*Aloe vera*, *Azadirachtaindica* [39]	*Moringaoleifera*, *Camellia sinensis* [40,41]
Typical Morphology	Monoclinic, often leaf-like or spherical [42,43]	Cubic, often porous or granular [44,45]
Key Phytochemicals	High phenolic content for rapid reduction [34,46]	Saponins and tannins for size control [47,48]
Calcination Temp	Typically 300°C - 500°C [49,50]	Typically 400°C - 600°C[51,52]

3.1 Case Studies in CuO Fabrication

The fabrication of CuO nanoparticles is highly sensitive to the concentration of specific biomolecules in the plant extract. For instance, studies employing *Camellia sinensis* (Green Tea) extract have demonstrated that high

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concentrations of epigallocatechin gallate (EGCG) act as potent reducing agents, resulting in CuO nanoparticles with high surface areas [35,53]. These high-surface-area materials are particularly effective for the photocatalytic degradation of organic dyes like methylene blue [54,55]. In contrast, using *Citrus limon* (Lemon) extract yields significantly smaller, spherical particles [56]. This is attributed to the high citric acid content, which acts as a natural chelating agent, controlling the nucleation rate and preventing the overgrowth of the particles [57,58].

3.2 Case Studies in NiO Fabrication

Research into the green synthesis of NiO has focused heavily on its energy storage capabilities. The synthesis of NiO using *Hibiscus rosa-sinensis* extract has been shown to produce nanoparticles with superior electrochemical properties for supercapacitor applications [42,43]. The anthocyanins present in the *Hibiscus* extract facilitate a controlled growth rate by forming stable complexes with the nickel ions. This regulation leads to the formation of highly crystalline, cubic structures with an optimized pore distribution, which is essential for high charge-discharge efficiency [44,45].

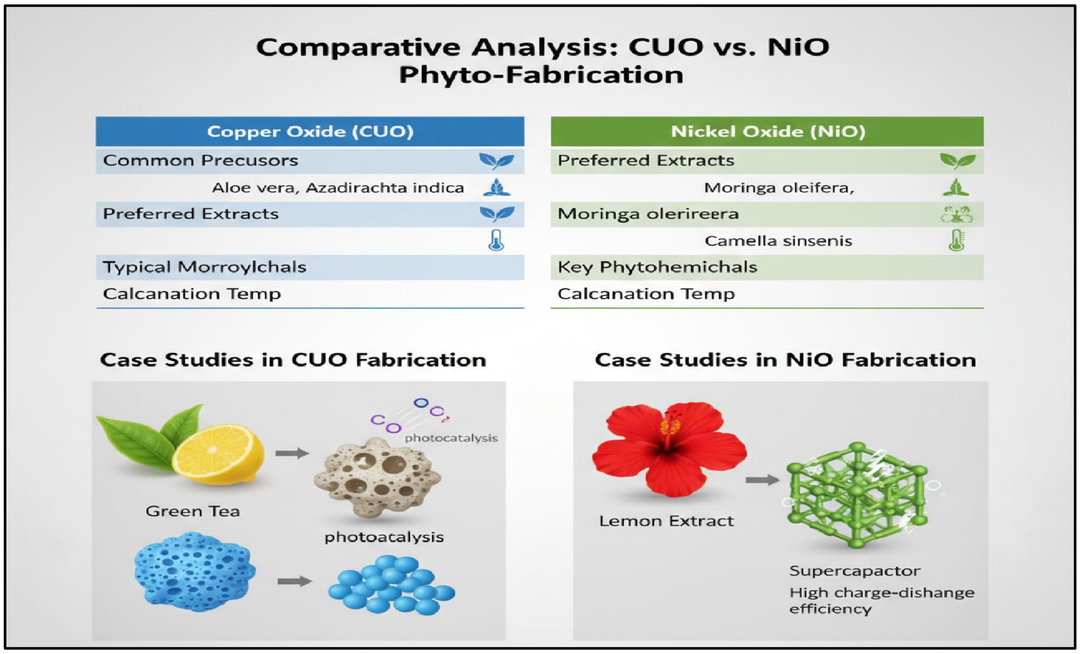

Figure 3: Comparative analysis of CuO vs NiOphyto-fabrication.

IV. CHARACTERIZATION AND PERFORMANCE EVALUATION

The verification of successful phyto-fabrication requires a suite of analytical techniques to confirm the reduction, crystallinity, and elemental composition of the transition metal oxides. Because plant extracts introduce a complex layer of organic capping agents, characterization is essential to distinguish between the metal oxide core and the biological shell [60,61].

4.1 Structural and Morphological Analysis

X-ray Diffraction (XRD) is the primary tool used to determine the phase purity and crystallite size of the fabricated oxides. For CuO, researchers typically look for the monoclinic phase, characterized by prominent peaks at the (111) and (111) planes [62]. In contrast, NiO synthesized via plant extracts generally exhibits a face-centered cubic (FCC) structure [63]. The average crystallite size is often calculated using the Scherrer equation:

$$D = \beta \cos \theta$$

where D is the crystallite size, lambda is the X-ray wavelength, and beta is the full width at half maximum (FWHM) [64].

Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) are employed to visualize the morphology. While chemical synthesis often produces uniform particles, phyto-fabrication typically results in a distribution of shapes such as nanospheres, hexapods, or clusters due to the non-uniform distribution of phytochemicals in the extract [65], [66].

4.2 Spectroscopic and Thermal Studies

Fourier-Transform Infrared Spectroscopy (FTIR) is critical in green synthesis to identify the functional groups (e.g., -OH, C=O, N-H) responsible for reduction and capping [67]. A shift in the absorption peaks of the plant extract after the reaction confirms the involvement of polyphenols or proteins in the stabilization process [68]. Furthermore, Thermogravimetric Analysis (TGA) is used to determine the optimal calcination temperature, ensuring that the organic botanical residues are removed to yield pure CuO or NiO [69].

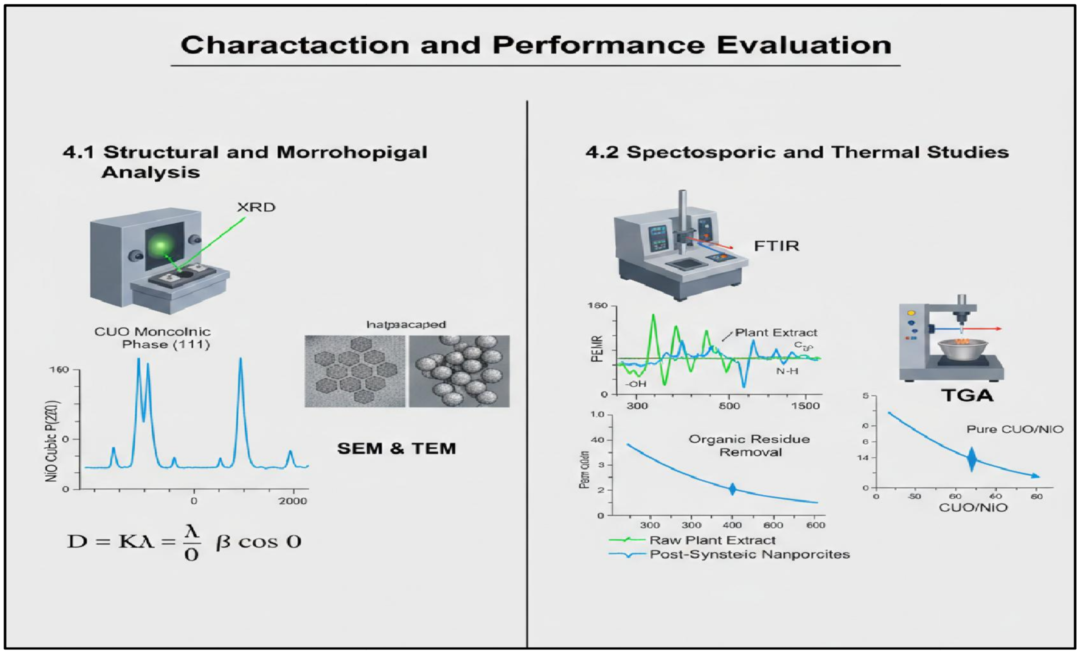

Figure 4: Characterisation and Performance Evaluation.

V. CHALLENGES AND FUTURE PERSPECTIVES

While the green synthesis of CuO or NiO offers a sustainable pathway for nanotechnology, transitioning these processes from controlled laboratory environments to commercial industrial applications presents significant hurdles. Addressing these challenges is essential for the long-term viability of phyto-fabrication [70].

5.1 Standardization and Reproducibility

The primary obstacle in phyto-fabrication is the inherent variability of botanical precursors. Unlike reagent-grade chemicals, the concentration of active phytochemicals such as polyphenols, alkaloids, and terpenoidsfluctuates based on the plant's geographical location, seasonal changes, and the specific extraction parameters (e.g., temperature and solvent polarity) [71]. This inconsistency often leads to variations in the size, morphology, and crystallinity of the resulting CuO or NiOnanoparticles, making it difficult to establish standardized protocols required for high-precision electronics or pharmaceutical regulations [70, 72].

5.2 Scalability and Economic Viability

Moving from "beaker chemistry" to industrial-scale production remains a bottleneck. While plant-mediated synthesis is cost-effective at small scales, the collection, transport, and stabilization of large volumes of biomass require significant logistical infrastructure [73]. Furthermore, maintaining uniform reaction kinetics in large-scale bioreactors is complex, as the mass transfer of phytochemicals to metal ions must be precisely controlled to prevent polydispersity [71, 74].

5.3 Surface Purity and Functional Interference

The residual biomolecules that remain as a capping layer on the nanoparticle surface present a double-edged sword. In biomedical applications, this biological shell typically enhances biocompatibility and reduces cytotoxicity, making green CuO or NiOsuperior for antimicrobial use [70]. However, for electronic and optoelectronic applications, these organic residues can act as insulating barriers, interfering with charge transfer and reducing the efficiency of the nanoparticles in semiconductors or sensors [72, 74]. Future research must focus on post-synthesis purification techniques or controlled calcination processes that preserve the desired nanostructure while removing unwanted organic artifacts.

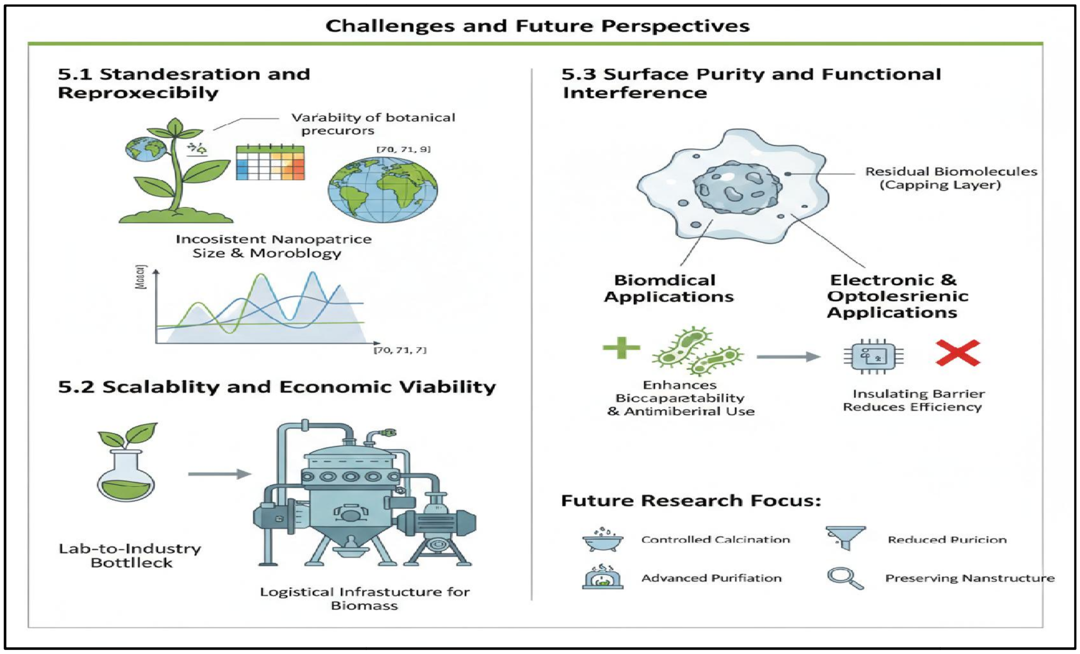

Figure 5: Challenges and Future Prospectives.

VI. CONCLUSION

Phyto-fabrication represents a robust, eco-friendly bridge between material science and botany, offering a sustainable paradigm shift from traditional pyrometallurgical and chemical synthesis routes. This review highlights that for both CuO and NiO, plant extracts serve as more than just solvents; they provide a highly tunable biochemical environment that allows researchers to customize nanoparticle traits such as size, surface area, and crystallinity by simply selecting specific botanical taxa.The comparative analysis reveals distinct kinetic and structural behaviors between the two oxides. CuO synthesis is generally characterized by faster reaction rates, driven by the higher redox potential of copper ions, which interact aggressively with phenolic hydroxyl groups to form stable monoclinic structures. Conversely, NiO synthesis often exhibits a more controlled nucleation process, benefiting immensely from the structural capping provided by complex plant proteins and tannins. These biomolecules act as superior templates, yielding cubic NiO nanoparticles with high electrochemical stability. Despite the challenges of standardization and industrial scalability,

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the integration of plant-based reducing agents into transition metal oxide fabrication paves the way for a "blue economy" where waste biomass is transformed into high-value functional materials for energy storage, environmental remediation, and advanced medicine.

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