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Harnessing Lignocellulosic Wastes for Nanomaterial Innovation: Advancing Sustainable Wastewater Treatment Technologies

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Article

Harnessing Lignocellulosic Wastes for Nanomaterial Innovation: Advancing Sustainable Wastewater Treatment Technologies

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Abstract: Industrial wastewater pollution has reached acute environmental levels; consequently, scientists are developing new sustainable treatment methods. Lignocellulosic Biomass (LB) stands as a promising raw material because it originates from agricultural waste, forestry residues, and energy crop production. This review examines the application of nanomaterials derived from lignocellulosic resources in wastewater management, highlighting their distinctive physical-chemical properties, including a large surface area, adjustable porosity structure, and multifunctional group capability. The collection of nanomaterials incorporating CNCs with lignin nanoparticles, as well as biochar and carbon-based nanostructures, demonstrates high effectiveness in extracting heavy metals, dyes, and organic pollutants through adsorption, membrane filtration, and catalysis mechanisms. Nanomaterials have benefited from recent analytical breakthroughs that improve both their manufacturing potential and eco-friendly character through hybrid catalysis methods and functionalization procedures. This research demonstrates the capacity to simultaneously turn waste into value while cleaning up the environment through its connection to circular bioeconomic principles and the United Nations Sustainable Development Goals (SDGs). This review addresses hurdles related to feedstock variability, production costs, and lifecycle impacts, demonstrating the capability of lignocellulosic nanomaterials to transform wastewater treatment operations while sustaining global sustainability.

Keywords: lignocellulosic biomass; nanomaterials; sustainable remediation

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1. Introduction

Substantial environmental destruction has emerged from the rising non-renewable energy usage, which includes oil, coal, and natural gas, as well as increased greenhouse gas production and climate warming. The worldwide transformation has begun to prioritize renewable energy solutions and sustainable waste management strategies because of worsening non-renewable energy dependency [1–3]. Lignocellulosic biomass is the most abundant renewable resource and it plays a crucial role in biofuel production [4,5]. Lignocellulosic biomass which is composed of cellulose, hemicellulose, and lignin, plays a vital role in determining the efficiency of biofuel production [6]. There is a necessity for innovative and sustainable pretreatment methods to effectively disintegrate lignocellulosic biomass and transform into biofuels [7]. LCB sources from energy crops, agricultural residues, and forestry by-products exist as one of Earth's most widespread renewable materials. Its application benefits the circular bioeconomy through two key actions. It minimizes our reliance on fossil fuels as well as fights environmental pollution [8–10]. Nanomaterials derived from this substance provide innovative solutions to worldwide problems related to waste management and water pollution and energy security, according to [11,12]. Green nanomaterials, especially lignocellulosic nanomaterials, create a sustainable solution that simultaneously benefits environmental relationships and health protection through the use of renewable ingredients and harmless manufacturing procedures [13]. Plant-based nanomaterials represent an emerging contemporary antibiotic alternative that provides improved medical outcomes through reduced toxic effects on human cells [14]. Wastewater treatment methods benefit significantly from the adoption of nanomaterials derived from lignocellulosic biomass. These nanomaterials possess important functional attributes, which include significant surface area, adjustable functionalities, and tunable characteristics alongside porosity and catalytic efficiency [15–18]. These features make them effective for pollutant extraction and environmental cleanup operations. The applications of nanomaterials focus on solving vital problems caused by heavy metal accumulation as well as dye and organic substance pollutants in industrial waste streams [19,20]. New adsorbent development like biochar enhances the effective treatment of lignocellulosic biomass wastewater since it recovers nutrients and reduces environmental impacts of wastewater treatment procedures [21]. A study demonstrates how bacterial-algae co-culture serves as a reliable solution to detoxify wastewater from lignocellulosic pretreatment while simultaneously lowering carbon pollution levels. This advances sustainable resource management strategies [22]. The innovative material satisfies several United Nations Sustainable Development Goals (SDGs), which aim to establish clean water access and sustainable industrial practices [1]. Lignocellulosic biomass provides an environment-friendly biosorbent to extract toxic wastewater pollutants effectively through chemical adjustment of adsorption capacity [23]. The mechanical advantages of CNCs combined with their sustainable nature make them suitable for different applications when used to enhance the properties of lignocellulosic nanomaterials [24]. Lignocellulosic biomass presents a sustainable and cost-effective solution for wastewater treatment which supports its natural properties to efficiently remove pollutants while promoting carbon neutrality and resource recovery [25]. The integration of biochar derived from lignocellulosic biomass enhances wastewater treatment efficiency as well as contributes to carbon sequestration [26]. Biopolymers obtained from lignocellulosic biomass enhance wastewater treatment processes by delivering sustainable solutions which replace synthetic materials and generate better environmental consequences [27].

1.1. Lignocellulosic Biomass

Lignocellulosic biomass is primarily composed of three biopolymers: cellulose (35–60%), hemicellulose (20–40%), and lignin (10–25%) [28,29]. These components provide structural integrity to plants but also present challenges due to their recalcitrant nature. Cellulose is a crystalline homopolymer characterized by strong hydrogen bonding networks that confer mechanical strength and chemical stability. Hemicellulose is an amorphous heteropolymer that contributes flexibility to plant cell walls. Lignin, a complex phenolic polymer with aromatic structures and diverse functional groups such as hydroxyl (-OH) and carboxyl (-COOH), provides rigidity but is highly resistant to degradation. [30,31]. The complex structures of these materials create obstacles for their transformation into valuable products; yet, their potential remains high due to their renewable nature. [32,33]. Sources of lignocellulosic biomass include agricultural residues (e.g., sugarcane bagasse, rice straw), forestry waste, municipal solid waste, and dedicated energy crops. The global production of lignocellulosic biomass is estimated to be approximately 1 × 10^10 metric tons annually. [34]. Despite its abundance and renewability, the structural complexity of lignocellulosic biomass necessitates advanced pretreatment methods, such as thermal decomposition or γ-valerolactone-based fractionation, to unlock its potential for conversion into high-value products, including biochar, bio-oil, syngas, or nanomaterials. [11,35].

1.2. Nanomaterials Derived from Lignocellulosic Biomass

Nanomaterials derived from lignocellulosic biomass include nanocellulose (for instance, cellulose nanocrystals [CNCs]), carbon-based nanostructures (e.g., graphene oxide [GO], carbon

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nanotubes [CNTs]), lignin nanoparticles (LiG NPs), and biochar. These materials exhibit exceptional properties, including high surface area-to-volume ratios, tunable porosity, mechanical strength, chemical reactivity, and functional group diversity. For example:

i. CNCs possess high adsorption capacities for heavy metals like Pb^{2+} and Cr^{6+} due to their surface charge tunability [29].

ii. GO effectively removes dyes and organic pollutants via electrostatic interactions [36].

iii. MnO_2-modified lignin nanoparticles demonstrate adsorption capacities up to 806 mg/g for methylene blue dye removal [37].

These attributes make lignocellulosic-derived nanomaterials ideal candidates for wastewater treatment applications such as adsorption of pollutants, catalytic degradation of contaminants, antimicrobial coatings, and membrane filtration technologies [38,39].

1.3. Nanomaterials in Wastewater Treatment

Water pollution caused by industrial effluents containing heavy metals, dyes, pharmaceuticals, and other hazardous contaminants poses significant risks to human health and ecosystems. Conventional wastewater treatment methods often fail due to inefficiency at low pollutant concentrations, high operational costs, or the generation of secondary waste. Utilizing lignocellulosic biomass for wastewater treatment addresses both environmental pollution and transforms waste into valuable resources, thereby enhancing sustainability through closed-loop systems and recycling waste materials into biofuels. [40]. Nanotechnology offers a promising alternative by enabling the development of advanced materials with superior adsorption capacities and catalytic efficiencies. [20,41]. Nanomaterials such as magnetite nanoparticles (Fe_3O_4) have unique physicochemical properties, including high surface area and reactivity, which make them ideal for pollutant adsorption and biodegradation processes. Their integration with biological systems enhances the efficiency of wastewater treatment. [42]. In Figure 1, the process of utilizing nanomaterials in wastewater treatment is illustrated.

Nanomaterials derived from lignocellulosic biomass address these challenges effectively:

i. Biochar exhibits excellent adsorption properties for heavy metals like Zn^{2+} through ion exchange mechanisms.

ii. Functionalized CNCs enhance selectivity for specific contaminants such as Cr(VI) or methylene blue via carboxylation or phosphorylation processes [29].

iii. Magnetite nanoparticles derived from lignocellulose offer superparamagnetic behavior for easy recovery using magnetic fields while efficiently adsorbing pollutants like Pb(II) or Cu(II) [43].

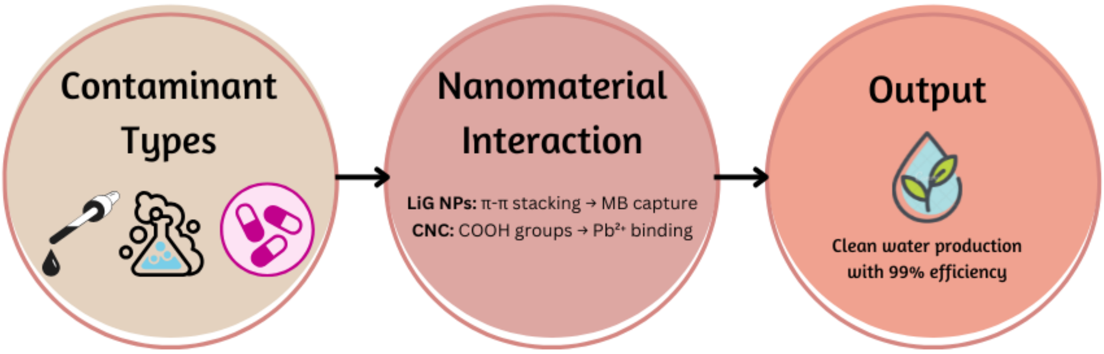

Figure 1. Process of using nanomaterials in wastewater treatment.

This review aims to critically explore the potential of lignocellulosic waste as a pioneer for nanomaterial innovation in advancing sustainable wastewater treatment technologies. It emphasizes key aspects, including extraction methods, material properties, pollutant removal mechanisms, scalability challenges, economic feasibility, and prospects. By integrating insights from diverse studies across the field, this work aims to provide a comprehensive understanding of how lignocellulosic-derived nanomaterials can revolutionize wastewater treatment, addressing pressing

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environmental concerns globally. In Figure 2, a detailed overview of lignocellulosic nanomaterials in wastewater treatment, from feedstock to application, is presented.

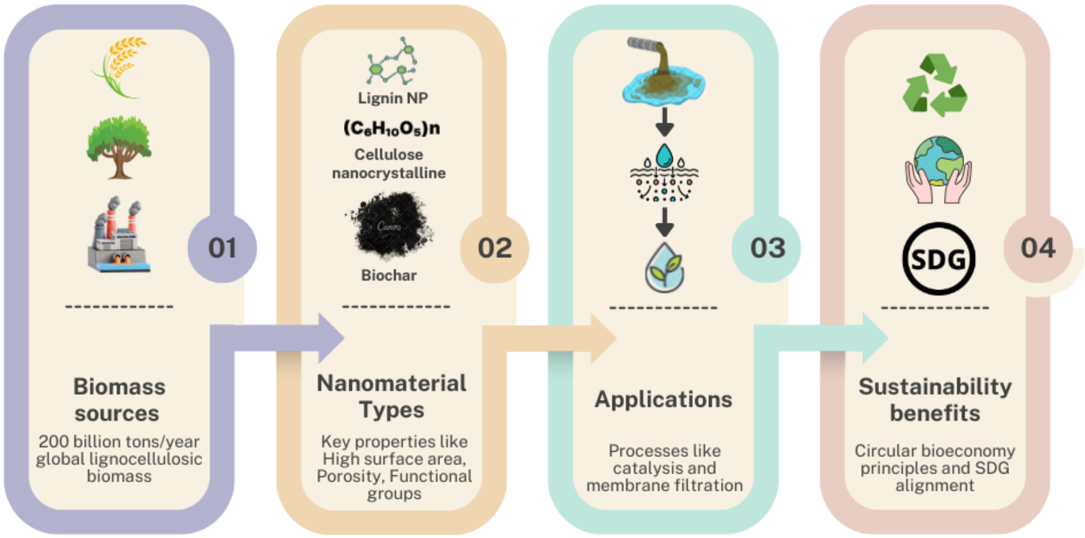

Figure 2. Overview of Lignocellulosic Nanomaterials in Wastewater Treatment.

2. Lignocellulosic Biomass: A Renewable Resource

2.1. Sources and Availability

Lignocellulosic biomass (LB) is a widely available, renewable resource derived from agricultural residues (e.g., sugarcane bagasse, rice straw, corn stover, wheat straw), forestry by-products (e.g., sawdust, wood chips), and industrial waste streams (e.g., paper pulp, sewage sludge). Dedicated energy crops, such as switchgrass and Miscanthus, also contribute significantly to its supply. Global production of lignocellulosic biomass exceeds 200 billion tons annually, making it an abundant and cost-effective feedstock for bio-based applications. (1,8,9,11,19,31,32,34,37,44–50). Agricultural residues, such as sugarcane bagasse, alone account for approximately 25–45% of processed cane, generating around 1.9 billion tons annually. Similarly, corn stover in the U.S. produces approximately 75 million dry tons annually. Forestry residues and non-wood sources, such as flowers and leaves, further expand the biomass pool [20,35,51]. Industrial wastes, such as xylose residue (XR) and oil palm trunk fibers, are also promising sources for nanomaterial synthesis. [52]. Importantly, LB does not compete with food production systems, making it a sustainable second-generation feedstock. [34].

1.2. Structural Composition

Lignocellulosic biomass is composed primarily of three biopolymers: cellulose, hemicellulose, and lignin. These components are intricately organized to provide structural integrity to plants.

Cellulose: Constituting approximately 30–50% of LB, cellulose is a linear polymer of β-D-glucose units linked by β- (1→4) glycosidic bonds. It forms crystalline microfibrils that impart mechanical strength and rigidity. [11,12,15]. Its crystalline regions are highly resistant to enzymatic degradation but are valuable for nanocrystal production. [29].

Hemicellulose: Representing about 20–40% of LB, hemicellulose is an amorphous heteropolymer composed of pentoses (e.g., xylose) and hexoses (e.g., mannose). It serves as a matrix linking cellulose and lignin but has lower thermal stability compared to cellulose. [8,11].

Lignin: Making up about 15–30% of LB, lignin is a complex aromatic polymer composed of monolignols such as p-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol. It provides rigidity and hydrophobicity but hinders enzymatic hydrolysis due to its recalcitrance. [28,53]. Other minor components include extractives, such as terpenes, and ash content, which add chemical complexity to LB [10].

1.3. Current Utilization

Despite its abundance, lignocellulosic biomass remains underutilized due to its structural recalcitrance. Traditional applications include:

Bioenergy Production: LB is extensively used for bioethanol production through enzymatic hydrolysis and fermentation. Other biofuels, such as biodiesel and biohydrogen, are also derived from LB using dark fermentation processes. [35,51].

Biochar Generation: Pyrolysis of LB produces biochar for soil amendment or environmental remediation applications [45].

Pulp and Paper Industry: Cellulose fibers from LB are used in paper manufacturing. However, this process underutilizes hemicellulose and lignin components [54].

Emerging applications aim to valorize all components of LB into high-value products:

Nanomaterials: Cellulose nanocrystals (CNCs) and lignin nanoparticles are being explored for their potential in composites, aerogels, and membranes with applications in water treatment technologies [29].

Bioplastics: Hemicellulose and cellulose derivatives are being developed into bio-based plastics with enhanced biodegradability [55].

Carbon-Based Materials: Lignin is being converted into carbon fibers and activated carbons for pollutant adsorption [56].

Advanced pretreatment methods, such as acid hydrolysis or deep eutectic solvents (DES), have enabled the efficient fractionation of LB into its functional components. This has expanded its utility in producing platform chemicals, such as furfural, and specialty materials, including nanocellulose composites [52,57]. Only 10–15% of lignocellulosic waste is currently valorized, primarily for low-value applications such as animal feed or combustion. High-value applications, such as nanocellulose production, remain underexplored. [58,59].

3. Nanomaterials from Lignocellulosic Waste

3.1. Types of Nanomaterials

Lignocellulosic biomass serves as a versatile precursor for various nanomaterials, including:

Nanocellulose: Comprises cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs), known for their high mechanical strength, biocompatibility, and biodegradability [11,15,60,61]. CNCs are characterized by high crystallinity and functional groups, such as sulfate or carboxyl groups, which enhance adsorption. [29,62]. Fe-Cu composites with CNCs adsorb Pb^{2+} (85.8 mg/g) through chelation. [29,62–64]. CNFs exhibit high aspect ratios and tunable surface chemistry. [16,38].

Lignin-Based Nanoparticles: Offer antioxidant properties, UV resistance, and hydrophobicity, making them suitable for pollutant adsorption, drug delivery, and environmental remediation [12,28,55]. Functionalized lignin nanoparticles, such as MnO_2-modified variants, enhance adsorption capacities due to hierarchical structures [37].

Carbon-Based Nanomaterials: Includes carbon nanotubes, graphene oxide, and biochar-derived nanoparticles produced via pyrolysis or hydrothermal processes [9,11,65]. Carbon quantum dots (CQDs) derived from sugarcane bagasse exhibit photoluminescence and pollutant detection capabilities [36].

Metal/Metal Oxide Nanoparticles: Synthesized using lignin or cellulose as reducing agents, these nanoparticles exhibit catalytic activity and pollutant binding potential [9,43]. Magnetite Nanoparticles (Fe_3O_4) are applied for pollutant adsorption and microbial immobilization [42].

Other Nanomaterials: Magnetic nanoparticles (MNPs) are used for enzyme immobilization and pollutant recovery [16]. Nanohemicelluloses and silica nanoparticles enhance film-forming properties and chemical stability, respectively [20,66]. In Table 1, different types of lignocellulosic biomass-derived nanomaterials and their properties has been given.

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Table 1. Types of Lignocellulosic Biomass-Derived Nanomaterials and Their Properties.

Nanomaterial Type	Source Biomass	Key Properties	Applications	References
Cellulose Nanocrystals	Sugarcane bagasse	Surface area: 500 m^2/g; Tensile strength: 220 GPa	Heavy metal adsorption, membranes	[29]
Lignin Nanoparticles	Rice straw	Thermal stability: >300°C; Functional groups: -OH, -COOH	Dye removal, catalytic supports	[37]
Biochar	Forestry residues	Porosity: 0.8 cm^3/g; Adsorption capacity: 806 mg/g	Organic pollutant degradation	[15]
Graphene Oxide	Wheat straw	Electrical conductivity: 10^3 S/m; Surface charge: -25 mV	Photocatalysis, sensors	[36]
Magnetic Fe_3O_4 NPs	Corn stover	Superparamagnetic; Adsorption capacity: 95% Pb(II)	Magnetic recovery systems	[43]

3.2. Extraction Techniques

Achieving a uniform distribution of nanoparticles in lignocellulosic biomass is critical for maximizing their effectiveness in treatment applications. Emerging green technologies like nanobiotechnology are addressing this challenge while focusing on sustainable processing methods [67]. In Table 2, a comparative overview of pretreatment methods for nanomaterial extraction is provided. The extraction of nanomaterials from lignocellulosic biomass involves a variety of mechanical, chemical, thermal, and biological methods:

Mechanical Methods: High-pressure homogenization, ball milling, and ultrasonication are employed to isolate CNFs, but are energy-intensive [34,38].

Chemical Pretreatments: Acid hydrolysis dissolves amorphous cellulose regions to yield CNCs with high crystallinity [29]. Alkaline treatments remove lignin to expose cellulose fibers for further processing [11].

Thermal Processes: Pyrolysis and hydrothermal carbonization convert biomass into biochar or carbon-based nanostructures under controlled conditions [1,68].

Biological Methods: Enzymatic hydrolysis using cellulases or fungi like Aspergillus oryzae reduces energy consumption while preserving structural integrity [8,28].

Emerging Technologies: Techniques such as microwave-assisted extraction and solvent-based fractionation using green solvents like γ-valerolactone optimize yield while minimizing environmental impact [35,52].

Functionalization Techniques: Methods like TEMPO oxidation introduce carboxyl groups to enhance adsorption capacities for dyes and heavy metals [29].

Table 2. Comparative Analysis of Pretreatment Methods for Nanomaterial Extraction.

Method	Energy Use	Yield (%)	Environmental Impact	Scalability	References
Acid Hydrolysis	High	45–60	Toxic effluent generation	Moderate	[8]
Enzymatic Hydrolysis	Low	30–40	Biodegradable by-products	High	[28]
Pyrolysis	Very High	50–70	CO_2 emissions	Low	[45]
Microwave-Assisted	Moderate	55–65	Reduced solvent use	High	[52]

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γ-Valerolactone	Low	60–75	Solvent recyclability	High	[35]

3.3. Properties of Nanomaterials

Nanomaterials derived from lignocellulosic waste exhibit unique properties that make them suitable for diverse applications:

Surface Area and Porosity: High surface area-to-volume ratios (>500 m^2/g) and mesoporous structures enhance adsorption capacities for pollutants such as heavy metals and dyes [16,19].

Mechanical Strength: Nanocellulose exhibits tensile strengths up to ~220 GPa, making it ideal for durable membranes and composites [54].

Functional Group Diversity: Abundant oxygenated functional groups (-OH, -COOH) enable chemical modifications for specific applications like catalysis or pollutant binding [9,15].

Thermal Stability: Lignin-based nanoparticles demonstrate high thermal stability suitable for biomedical applications [28].

Biocompatibility and Biodegradability: These properties minimize secondary pollution while supporting environmental sustainability in wastewater treatment systems [17,20].

Catalytic Activity: Carbon-based nanostructures exhibit excellent electrical conductivity and enhanced catalytic activity in environmental remediation processes [65,69]. In Table 3, a comparison has been shown which provides detailed information on the feedstock sources, properties, pollutant removal efficiencies, and cost range of different lignocellulosic-derived nanomaterials.

Table 3. Comparison of Different Lignocellulosic-Derived Nanomaterials.

Features	CNC	Lignin NPs	Biochar
Feedstock sources	Sugarcane bagasse	Hardwood	Rice husk
Key properties	High crystallinity (220 GPa)	Antioxidant and UV-resistant	Mesoporous (500 m^2/g)
Pollutant removal efficiency	Pb^{2+} (96% removal)	Methylene blue (806 mg/g)	Zn^{2+} (85% ion exchange)
Cost range	$50-100/kg	$20-50/kg	$5-20/kg

4. Applications in Wastewater Treatment

4.1. Nanocellulose-Based Composites

Nanocellulose-based composites have emerged as efficient materials for wastewater treatment due to their high surface area, functional groups, and biodegradability. These composites are widely used for adsorbing heavy metals (for example, Pb^{2+}, Cd^{2+}) and organic pollutants like dyes and pharmaceuticals. Functionalized nanocellulose membranes demonstrate high selectivity for contaminants through adsorption, size exclusion, or electrostatic interactions [11,15,16,55]. For instance, carboxylated nanocellulose crystals (CNCs) exhibit adsorption capacities of up to 1237 mg/g for Pb(II), while CNC-based aerogels effectively remove Cu(II) due to their porous structure [41]. Additionally, nanocellulose composites such as chitosan-CNC multilayers achieve over 99% oil-water separation, demonstrating their versatility [29]. The integration of nanomaterials into wastewater treatment processes enables innovative solutions for industrial effluents containing harmful contaminants. This includes the use of biochar as a catalyst and nanocatalysts to improve energy efficiency and pollutant degradation [67,70]. Nanocellulose composites are also utilized in membrane filtration systems, enhancing mechanical strength and fouling resistance. Modified CNCs improve water flux and chlorine resistance in thin-film composite membranes [20]. Real-world applications include CNC/graphene aerogels used for oil spill remediation and CNC-based adsorbents achieving 96% removal of Cr(VI) from industrial effluents [29,71]. Chitosan-CNC multilayers on stainless steel achieve 99.5% oil-water separation [29,62–64]. A study highlights the potential of amino-functionalized lignocellulosic biopolymers as effective and sustainable adsorbents for removing toxic anionic contaminants, such as Congo red and Cr(VI), from wastewater, demonstrating their excellent reusability and eco-friendly nature [72]. Another study highlights that chemically modified cellulosic biofibers, such as those derived from okra, can significantly enhance the adsorption capacity for heavy metal ions, offering a sustainable and cost-effective solution for wastewater remediation [73]. In Table 4, the pollutant removal efficiencies of various lignocellulosic nanomaterials are provided.

Table 4. Pollutant Removal Efficiencies of Lignocellulosic Nanomaterials.

Pollutant	Nanomaterial	Removal Efficiency	Mechanism	References
Pb(II)	Carboxylated CNCs	1,237 mg/g	Electrostatic interaction	[29]
Methylene Blue	MnO_2-Lignin nanocomposites	806 mg/g	Chemical adsorption	[37]
Cr(VI)	TEMPO-oxidized cellulose	96%	Redox reaction	[29,71]
Tetracycline	CNC-chitosan membranes	97%	Size exclusion	[20]
Cu(II)	Biochar-ZnO hybrid	92%	Ion exchange	[19]

4.2. Catalytic Applications

Lignin-derived nanoparticles and biochar serve as catalysts or catalyst supports in advanced oxidation processes (AOPs), enabling the degradation of organic pollutants like dyes and phenols. Functionalized biochar enhances the adsorption kinetics of heavy metals, such as Pb2+, Zn2+, and Cu2+, while maintaining a high recycling capacity over multiple cycles [52]. Similarly, MnO_2-lignin nanocomposites exhibit superior adsorption capacities for dyes, such as methylene blue, due to chemical interactions between the MnO_2 nanodots and dye molecules [37]. Biochar derived from lignocellulosic waste exhibits excellent catalytic properties due to its high porosity and environmental sustainability. Current research focuses on producing and activating biochar-based catalysts for wastewater remediation, with significant potential for removing hazardous contaminants [74]. Fe-modified lignocellulosic biochar simultaneously performs wastewater treatment by combining adsorption with catalytic performance thus boosting treatment efficiency [75]. CNC-supported ZnO/TiO_2 composites degrade organic dyes (e.g., 97% methylene blue removal) via photocatalysis [29,62–64]. Photocatalysis using nanocellulose-metal oxide hybrids or lignin-derived materials is another promising approach. For example, CNC-supported ZnO/TiO_2 composites achieve over 97% methylene blue removal under UV light [29]. Fe_3O_4-lignin nanocomposites facilitate Fenton reactions, achieving a 95% reduction in phenol within two hours [36]. Magnetic nanoparticles immobilized with enzymes further enhance catalytic efficiency in pollutant degradation processes [34]. The integration of enzyme-based nanobiocatalysts in the treatment of lignocellulosic biomass wastewater can significantly enhance resource recovery and it also minimizes environmental pollutants [76].

4.3. Lignin Valorization

Lignin valorization involves converting lignin into value-added products such as activated carbon, biochar, or nanoparticles for wastewater treatment. Lignin-derived biochar exhibits high adsorption capacities for pollutants like methylene blue and phenols due to its porous structure and functional groups [15,19]. Lignin nanoparticles are also utilized as adsorbents for toxic metals, such as Hg(II) and Cd(II), through ion exchange mechanisms, or as precursors for activated carbon production. [2,56]. Lignin-derived carbon quantum dots exhibit photocatalytic activity for degrading pharmaceuticals, while DES-based flocculants achieve over 99% turbidity reduction and simultaneous sterilization of harmful microorganisms like *E. coli* [52]. Additionally, lignin fractions from gamma-valerolactone processes can be used to produce carbon foams or battery anodes, contributing to environmental sustainability [35].

4.4. Case Studies: Real-World Applications

Numerous case studies highlight the practical efficacy of lignocellulosic nanomaterials in industrial wastewater treatment:

Methylene Blue Adsorption: Biochar derived from rice straw achieved maximum adsorption capacities of up to 160.5 mg/g due to its porous structure and oxygen-functional groups [15].

Oil-Water Separation: Nanocellulose-based membranes demonstrated effective separation of oil from water in industrial settings [61].

Heavy Metal Removal: Sugarcane bagasse-derived nanomaterials achieved significant removal efficiencies for heavy metals in industrial wastewater experiments [51].

Pharmaceutical Contaminants: CNC-based membranes effectively removed tetracycline through electrostatic interactions [16].

Integrated Solutions: Sequential treatment using lignin-derived materials achieved drinkable water quality by combining flocculation, adsorption, and photocatalysis [52].

Antifouling Properties: CNF-based membranes retained bacteria and viruses through size exclusion mechanisms while exhibiting antifouling properties [38,54].

Sequential Treatment Systems: Lead-zinc mineral processing wastewater was treated sequentially using lignocellulosic nanomaterials, integrating flocculation, adsorption, and photocatalysis to achieve drinkable water quality [52].

Klang Valley Water Treatment: CNC/graphene aerogels restored water quality following an oil spill in Klang Valley, Malaysia, demonstrating the practical utility of these materials in emergency scenarios [29].

Silver Nanoparticles for Antibacterial Activity: Biogenic silver nanoparticles incorporated into membranes exhibited potent antibacterial activity against pathogens like *E. coli*, offering dual benefits of pollutant removal and microbial disinfection [20].

Rice Husk-Derived SiO_2 Nanoparticles: SiO_2 nanoparticles synthesized from rice husk ash effectively remove heavy metals, such as lead, from wastewater, showcasing cost-effective and sustainable solutions for industrial effluents [20].

Carbon-Silicon Nanostructures: Rice husk-derived carbon-silicon nanostructures achieved a removal efficiency of up to 90% for arsenic from groundwater, providing a novel approach to addressing toxic metal contamination [36,77,78].

Functionalized Biochar for Heavy Metals: Functionalized biochar demonstrated high recycling capacity over multiple cycles while efficiently adsorbing heavy metals such as Pb^{2+}, Zn^{2+}, and Cu^{2+} due to its porous structure and enhanced adsorption kinetics [52].

5. Related Challenges

The production and scaling up of nanomaterials from lignocellulosic biomass face multifaceted challenges across technical, economic, and environmental dimensions. These challenges are crucial to address to achieve industrial scalability, cost-effectiveness, and sustainability. The primary challenge in utilizing lignocellulosic biomass lies in its recalcitrant structure. Lignin's resistance to microbial degradation and hemicellulose's hydrophilicity necessitate innovative pretreatment strategies for the efficient conversion of these materials into value-added products. Additionally, the underutilization of industrially produced lignin, of which only about 2% is currently valorized, represents a significant opportunity for research into high-value applications, such as binders or dispersants [28]. High energy costs for pyrolysis (≥700°C) and enzymatic pretreatment (approx. 20% of total cost) hinder commercialization [58,59].

5.1. Technical Barriers

Energy-Intensive Processes: Pretreatment methods such as pyrolysis, hydrothermal liquefaction, and acid hydrolysis demand significant energy inputs, raising concerns about scalability [1,44,61].

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Feedstock Variability: The heterogeneous composition of lignocellulosic biomass complicates the standardization of extraction processes and achieving consistent quality in nanomaterials [31,34,53].

Process Optimization: Achieving high yields and purity during extraction remains challenging due to the recalcitrant structure of biomass [32,79]. Additionally, maintaining uniform particle size distribution and material stability during synthesis is difficult [28,56].

Equipment Limitations: Scaling up laboratory processes to industrial levels is hindered by the complexity of techniques such as microwave-assisted pyrolysis and enzymatic hydrolysis [50,69].

Reusability Issues: Inefficient regeneration methods for solvents and declining adsorption capacity after multiple cycles pose additional hurdles [29,52].

5.2. Economic Viability

High Production Costs: The cost of advanced technologies like ionic liquids, green solvents, enzymatic hydrolysis, and mechanical disintegration limits commercial scalability [11,16,18,29].

Capital Investment: High initial capital costs for biorefineries and advanced equipment hinder widespread adoption despite long-term benefits [80,81].

Market Competition: Nanomaterials from lignocellulosic waste must compete with traditional materials like activated carbon, which are significantly cheaper (approx. $1–5/kg vs approx. $50/kg for CNC production) [29,62].

Cost-Effectiveness of By-Products: Developing value-added products like nanocomposites or biofuels is essential to offset production costs [35,82]. In Table 5, the economic and environmental metrics of lignocellulosic nanomaterial production are presented.

Table 5. Economic and Environmental Metrics of Lignocellulosic Nanomaterial Production.

Parameter	Conventional Materials	Lignocellulosic Nanomaterials	Improvement Factor	References
Production Cost ($/kg)	1–5	20–50	4–10x	[62]
Carbon Footprint (kg CO_2/kg)	8–12	2–4	3–4x reduction	[11]
Adsorption Capacity (mg/g)	100–300	500–1,200	2–5x	[41]
Reusability Cycles	3–5	8–12	2–3x	[52]

5.3. Environmental Considerations

Effluent Management: Chemical pretreatments generate toxic by-products and sulfate-rich wastewater that require effective disposal strategies to avoid secondary pollution [8,29].

Energy Consumption: The environmental footprint of energy-intensive processes like pyrolysis (approx. 700°C) must be minimized through renewable energy integration or process optimization [45,61].

Nanoparticle Toxicity: The potential ecotoxicity of nanomaterials such as carbon nanotubes necessitates rigorous lifecycle assessments to prevent unintended ecological impacts [36,39].

Green Chemistry Approaches: Transitioning to greener synthesis methods using supercritical CO_2 or recyclable solvents like GVL is critical to ensure sustainability [41,80].

Waste Minimization: Closed-loop systems for solvent recovery and zero-waste principles are essential for reducing environmental risks during large-scale production [52].

5.4. Integrated Challenges

The interplay between technical barriers, economic viability, and environmental considerations highlights the complexity of scaling up nanomaterial production:

i. Energy-intensive pretreatment methods exacerbate both economic and environmental challenges.

ii. High costs associated with advanced technologies limit their adoption despite their potential to reduce environmental impacts.

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iii. The toxicity of inevitable by-products demands innovative solutions that align with sustainability goals while maintaining economic feasibility.

6. Innovations and Future Prospects

6.1. Emerging Technologies

The development of choline-based ionic liquids and deep eutectic solvents as green solvents has revolutionized sustainable LB processing and pretreatment methods by diminishing environmental effects, according to [46,83]. The efficiency of producing lignocellulosic nanomaterials has increased via advancements in enzymatic hydrolysis methods, coupled with bio-based solvents, and integrated biorefineries [17,28]. The extraction of nanomaterials using microwave-assisted pyrolysis, combined with ultrasound pretreatments and hybrid catalytic approaches, demonstrates high potential for efficient extraction while simultaneously degrading pollutants, as shown in studies [2,11,32]. When lignocellulosic biomass is pretreated effectively, it can serve as a valuable feedstock in microbial fuel cells (MFCs) for both electricity generation and wastewater treatment [84]. Nanotechnology yields three distinct applications in pollutant management: multifunctional nanocomposites serve as pollution removal tools, blended membranes unite biological treatments with nanotechnology, and magnetic nanobiocatalysts provide reusable systems for pollutant degradation [16,58]. The application of microbe-derived enzymes combined with plant-based extracts in green synthetic methods both promotes eco-friendly characteristics and scales up performance [43]. Experts have integrated machine learning to enhance the biological reaction pathways of biochar during wastewater treatment [74]. Modern technological applications involving biological and physical treatments demonstrate improved process efficiency. Research on surface modifications with thiol and amine group attachment to lignin nanoparticles has improved the selective pollutant capture capacity of these nanoparticles for Hg(II) and Pb(II) [41]. Flash Nano Precipitation applies a sustainable production technique for generating uniformly sized nanoparticles at large-scale operational levels [28]. Bioaugmentation through engineered microbial consortia shows great promise to enhance pollutant degradation synergistically when combined with nanomaterials, according to [57]. In Table 6, innovations in functionalization techniques to improve performance are presented. In Figure 3, a framework for the circular bioeconomy for lignocellulosic nanomaterial applications has been presented.

Table 6. Innovations in Functionalization Techniques for Enhanced Performance.

Functionalization Method	Nanomaterial	Outcome	Applications	References
TEMPO Oxidation	Cellulose nanocrystals	Increased carboxyl groups (-COOH)	Selective Cr(VI) adsorption	[29]
MnO_2 Deposition	Lignin NPs	Hierarchical pore structure	Dye degradation	[37]
Fe_3O_4 Coating	Biochar	Magnetic separation capability	Heavy metal recovery	[43]
Chitosan Grafting	CNC membranes	Antifouling properties	Oil-water separation	[20]
DES Modification	Lignin-carbon	Enhanced dispersibility	Flocculation	[52]

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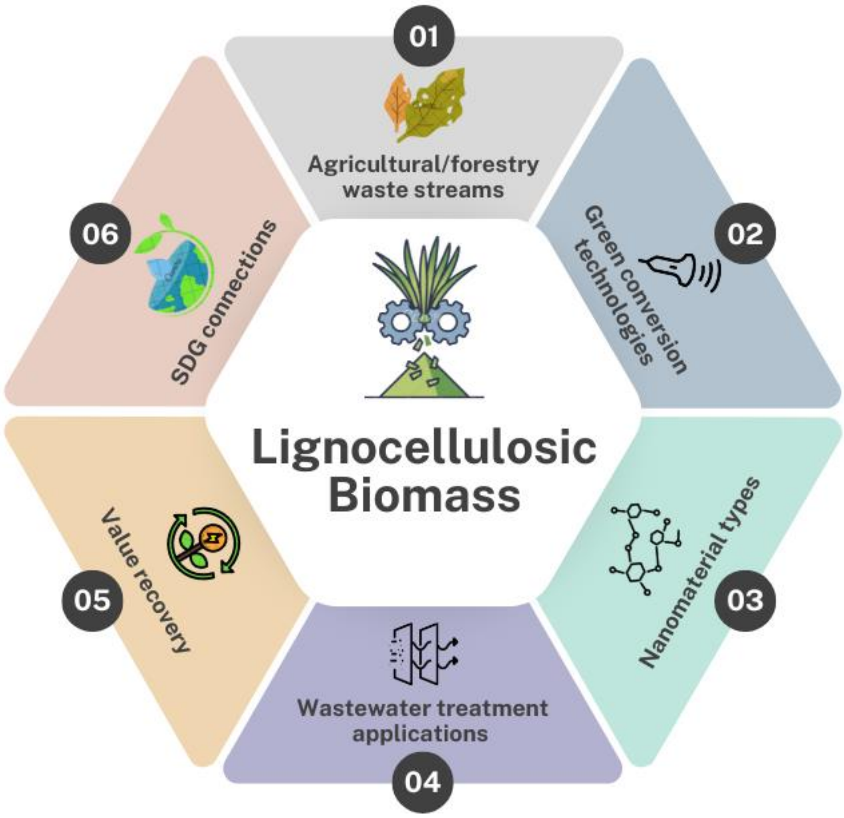

Figure 3. Circular Bioeconomy Framework for Lignocellulosic Nanomaterial Applications.

6.2. Circular Bioeconomy

Lignocellulosic waste valorization serves sustainability goals through waste conversion into valuable nanomaterials, along with biofuels, as well as bioplastics, while reducing environmental impacts, according to [45,61]. Research shows that the execution of closed-loop recycling systems that utilize solvents such as gamma-valerolactone (GVL), as well as all fractions of biomass, leads to improved resource utilization [35]. Integrated biorefineries produce nanomaterials together with bioenergy or biochemicals while minimizing waste to a degree of 70%, according to [36,77]. The conversion of agricultural waste into nanomaterials helps achieve zero-waste targets by resolving worldwide waste management problems and simultaneously generating usable products, such as bioethanol and biogas [57,85]. LB extraction for industrial purposes results in improved resource efficiency combined with better environmental sustainability because it decreases industrial-scale waste disposal quantities [86]. In Figure 4, the lifecycle of lignocellulosic biomass, from feedstock to nanomaterial synthesis, applications, and its role in a circular economy, is illustrated.

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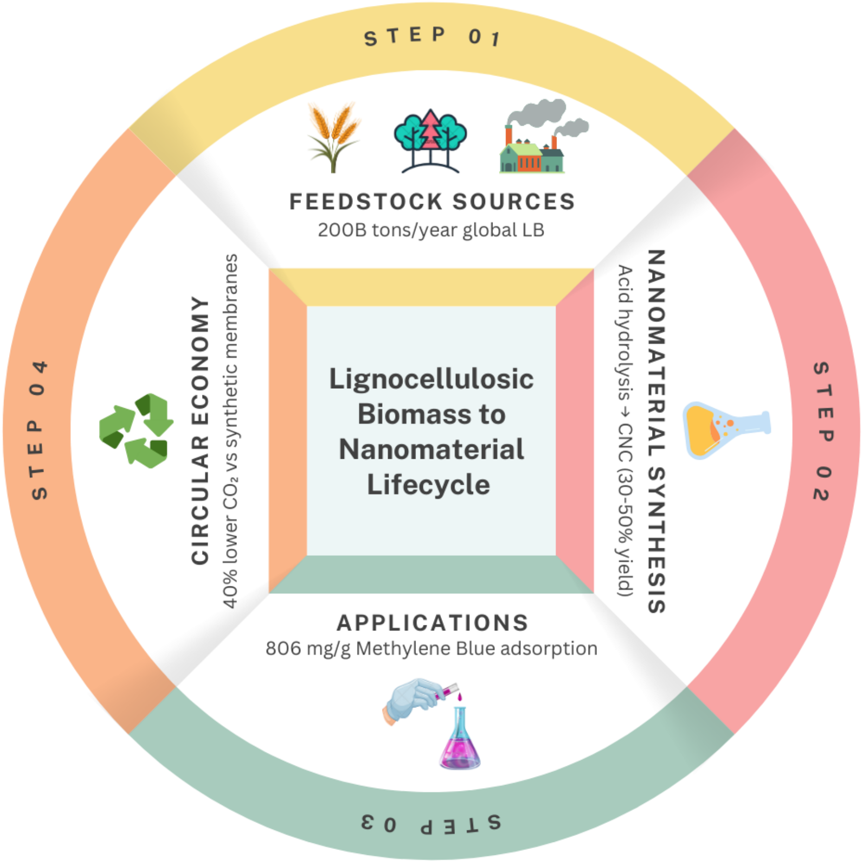

Figure 4. Lignocellulosic Biomass to Nanomaterial Lifecycle.

6.3. Policy and Industry Support

Government incentives play a key role in facilitating the large-scale deployment of sustainable technologies. Lignocellulosic-based innovations are gaining wider acceptance for wastewater treatment when governments implement renewable resource promotion alongside enhanced effluent regulations [19,55]. The commercialization of green nanotechnology requires critical research and development subsidies to accelerate its development process [29]. Technology transfer, together with industrial adoption, requires the strong support of public-private partnerships. Industry-academia partnerships create conditions that increase manufacturing scale yet maintain sustainability standards [54,83]. The use of renewable materials in wastewater treatment can accelerate global sustainability targets when policy frameworks support their utilization [65]. The convergence of modern green technology advancements with circular bioeconomic models and appropriate policy structures demonstrates great potential to transform bioenergy systems that utilize lignocellulosic materials. Advanced technology solutions address vital environmental problems while enabling the development of large-scale, sustainable industrial practices. Future investigations must establish affordable biomass fractionation procedures to enhance the complete utilization of biomass, advance LB-derived nanomaterials in environmental cleanup, and optimize bio-based plastics through improved manufacturing approaches.

7. Conclusions

The review provides in-depth measurements regarding the ability of nanomaterials from lignocellulosic biomass to transform ecological wastewater management methods. The development of novel wastewater treatment solutions relies on the exploitation of nanomaterials derived from lignocellulosic biomass, as these materials offer large surface areas along with adjustable porosity features and various functional groups, enabling the extraction of heavy metals, dyes, and organic pollutants through adsorption, catalytic effects, and membrane separation. Nanomaterials have gained environmental and scalable qualities through the application of green extraction technology combined with hybrid catalysis systems that adhere to bioeconomy principles and support the Sustainable Development Goals (SDGs). The industrial use of these promising nanomaterials presents significant challenges due to inconsistent feedstock requirements, high production costs, and the need for environmental assessments. The combination of policy assistance with green chemistry advancements and process enhancement will create sustainable economic stability that preserves ecological sustainability. Resource efficiency improvements become achievable through functionalized techniques that integrate with hybrid systems and closed-loop biorefineries, enabling environmental footprint reduction. Lignocellulosic nanomaterials represent a significant advancement in wastewater treatment, offering an effective solution to global pollution issues and facilitating waste transformation toward value creation. The future of material and scalability research in water treatment needs functionalization strategies and full industrial integration to establish sustainable treatment systems at all levels worldwide.

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