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Graphene-biomass Composite Sensor: A Novel Paradigm for Environmentally Friendly Monitoring Devices

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ABSTRACT
To meet the sustainable development demands of environmental monitoring, developing high-efficiency and low-environmental-footprint sensing technologies has become a critical industry priority. This study focuses on graphene-biomass composites, systematically elucidating the molecular interaction mechanisms between biomass components and graphene, along with interface modulation strategies. It comprehensively reviews three breakthroughs in green fabrication technologies: biomolecular template-induced self-assembly, biomimetic mineralization enhancement, and solid waste resource utilization. The research delves into multidimensional performance optimization principles including electrochemical sensitivity, mechanical flexibility, and multimodal response capabilities. Through validation applications in real-time heavy metal monitoring in water bodies, intelligent identification of atmospheric volatile organic compounds, and distributed soil pollutant detection, the study identifies industrialization bottlenecks such as mass production quality control, environmental signal interference mitigation, and biosafety assessment. Future trends including AI-assisted design, self-powered system integration, and closed-loop recycling system development are explored, providing systematic material science theories and technical implementation pathways for environmentally friendly monitoring equipment development.

KEYWORDS
Graphene; Biomass composites; Environmental sensors; Green electronics

1 Introduction

Sustainable development demands the transition of environmental monitoring technologies toward greener solutions. However, traditional electronic sensors rely on non-renewable metals and petroleum-based polymers, leading to resource depletion and surging e-waste generation. Their complex multi-layer structures further hinder recycling processes, creating fundamental contradictions with environmental protection objectives[1]. Graphene-biomass composites achieve precise molecular-level integration of bio-renewable resources and advanced nanomaterials, establishing a new paradigm for monitoring devices that combines "high performance, environmental friendliness, and industrial scalability." Leveraging the inherent biodegradability of biomass components and graphene's superior electrical properties, this system significantly reduces lifecycle environmental impact while maintaining core sensor performance, providing critical material science solutions to address sustainability bottlenecks in environmental monitoring [2]. This study systematically elucidates molecular interaction mechanisms and interface modulation strategies between biomass components and graphene. It reviews breakthroughs in green fabrication technologies including biomimetic template-induced self-assembly, biomimetic mineralization enhancement, and solid waste resource utilization. The research delves into performance optimization principles for electrochemical sensitivity, mechanical flexibility, and multimodal responsiveness. Through application validation in aquatic, atmospheric, and soil environments, it analyzes industrialization challenges such as mass production quality control, complex environmental signal interference, and biosafety assessments. Future trends including AI-assisted design, self-powered system integration, and closed-loop recycling systems are explored, offering material science theories and technical pathways for developing environmentally friendly monitoring devices.

2 Material System Design and Molecular Construction Principles

2.1 Interface Functional Properties of Biomass Building Blocks

Cellulose nanocrystals (CNC/CNF) serve as the fundamental building blocks for constructing composite frameworks. Cellulose nanocrystals (CNC) exhibit rod-shaped morphology, possess a large specific surface area, and are rich in hydroxyl groups. Through strategies such as esterification, they can be modified with charges or functional groups to enhance dispersion stability and interfacial compatibility. Cellulose nanofibers (CNF), characterized by their flexible fibers, readily form three-dimensional networks. The morphological differences between these two forms result in surface energy heterogeneity, which enables precise control over interfacial adsorption behavior[3-4].

Lignin is a naturally abundant aromatic polymer whose phenolic hydroxyl groups can formπ-πstacking interactions with graphene,enhancing its dispersibility and preventing oxidative degradation.Its ultraviolet absorption andantioxidant properties protect the graphene structure, thereby improving the environmental stability of composite materials [5].

Silk fibroin regulates secondary structure transitions through mesoscopic doping, addressing the brittleness issue of pure silk fibroin membranes and endowing the composite material with flexibility, biocompatibility, and modifiability,

making it suitable for wearable sensing applications [6].

2.2 Graphene Interface Modification Strategies

The surface modification strategy of graphene determines the balance between electrical performance and stability in composite materials. Covalent modifications (e. g., graphene oxide preparation) introduce functional groups through chemical bonds, offering good stability but compromising the sp^2 conjugated structure, leading to reduced conductivity. Non-covalent modifications (e. g., phthalocyanine molecular modification) rely on physical interactions such as π - π stacking to preserve graphene's intrinsic electrical properties while enhancing electron transport efficiency and signal response sensitivity through synergistic effects. Bioassisted synthesis utilizes microbial metabolites to achieve graphene reduction and functionalization, retaining inherent properties while improving dispersity, though challenges persist in product structural uniformity and scalability. Interface engineering crucially balances functionalization levels with intrinsic performance, requiring precise modulation of excessive covalent modifications and non-covalent modifications according to specific sensing applications[7-9].

3 Breakthrough in Green Preparation Technology

3.1 Biological Template-Induced Self-Assembly

Multi-level structural precision control is achieved through orientation guided by the spatial structure of biomacromolecules. Lignin evaporation-induced self-assembly (EISA) coupled with KHCO3 activation enables the preparation of ultra-thin graphene-like nanosheets (LGLNs), significantly enhancing electrochemical active surface area [11]. Silk fibroin-derived silk nanofibers (SNF) can guide the ordered self-assembly of reduced graphene oxide (RGO) and glucose oxidase (GOx) to form sandwich-type composite electrodes, achieving in-situ enzyme immobilization and resolving detachment issues, thereby providing highly stable interfaces for flexible sensors [12].

3.2 Bionic Mineralization Enhancement Strategies

The biomimetic mineral deposition mechanism synergistically enhances mechanical strength and structural stability. The ice-induced assembly and in situ mineralization strategy achieves a compression strength of 110 kPa and an ultimate oxygen index of 38.5% for the cellulose/MXene composite aerogel, enabling simultaneous optimization of mechanical and flame-retardant properties [13]. Polyethyleneimine-modified eggshell membrane-induced biomimetic mineralization increases the mineralization rate by 2.3-fold [14]; peptide self-assemblies specifically bind to collagen fibers, guiding directional calcium phosphate deposition (binding energy: -8.2 kcal/mol) for precise biomimetic microstructural repair [15].

3.3 Resource Recovery of Solid Waste

The high-value utilization of agricultural and forestry waste can reduce environmental footprint. Lignin waste is converted into LGLNs through EISA and $KHCO_3$ activation (mass ratio 1:3, carbonization at 900℃), achieving low-cost and high-performance carbon-based component preparation [11]. Wood-based biomass undergoes a three-step process of delignification-carbonization-activation to construct three-dimensional graphene structures, with ultra-microchannels of 0.5-1.2 nm exhibiting a heavy metal adsorption capacity of 298 mg/g, representing a 40% improvement over commercial activated carbon [16]. Bio-graphite prepared via biochar-catalyzed graphitization (ID/IG=0.051, grain size 42.3 nm) outperforms spheroidal natural graphite in performance [17].

4 Multidimensional Regulation of Sensor Performance

4.1 Electrochemical Sensitivity and Selectivity

Sensitivity enhancement relies on achieving a wide linear range and low detection limit. The molecular imprinting technology combined with graphene quantum dots significantly reduces electron transfer resistance through synergistic effects of specific recognition and electron conduction, thereby improving the detection sensitivity of trace pollutants[10]. Cerium oxide-modified electrochemically exfoliated graphene (CeO/eGr) optimizes surface electronic structure, achieving a detection limit of 3.3 nM for 4-bromophenoxyoacetic acid with a linear range spanning four orders of magnitude [18].

Selective regulation is achieved through multi-component synergy and molecular imprinting dual pathways. Polypyrrole/rGO/Fe_2O_3 ternary composite utilizes conductive polymers, electronic conduction, and catalytic activity synergistically to enhance the recognition capability of specific biomarkers and reduce interference from coexisting substances [19].

4.2 Mechanical Flexibility and Environmental Stability

The flexible design meets the requirements for dynamic deformation and seamless adhesion to complex interfaces. The graphene/Ecoflex composite mesh strain sensor combines high conductivity with exceptional deformation capability, distributing stress through its mesh structure and maintaining stable signal output even after thousands of cycling tests [20]; the fully biomass-based flexible sensor features cellulose/lignin carbon nanospheres at its core, leveraging a natural flexible framework and intermolecular forces to achieve seamless skin adhesion and environmental biodegradability [21].

In terms of environmental stability, graphene-MnPO composites maintain long-term stability under varying acid-base conditions and humidity through hydrothermal regulation of crystal structure [22]; MXene/graphene composites address self-stacking challenges via proportion control, broaden charge transfer pathways, and enhance durability in corrosive media [15].

4.3 Multimodal Signal Response

Multimodal response overcomes the limitations of single signals and expands monitoring dimensions. The three-dimensional electrochemical sensor based on functional graphene foam integrates EIS and CV modes to capture metabolic impedance changes and perform product quantification respectively, enabling real-time non-invasive monitoring of cellular metabolism [23]; the vertical graphene multi-parameter sensing array utilizes high electrochemical activity and rapid electron transfer to simultaneously detect multiple analytes such as glucose and urea [24]; the polyaniline/graphene/PDMS hybrid temperature sensor achieves precise thermal signal response through component synergy and negative temperature coefficient compensation [25].

5 Validation of Typical Environmental Monitoring Application Scenarios

5.1 Water Heavy Metal Detection System

In aqueous heavy metal detection, the core of glucose oxidase (GOx)/reduced graphene oxide (rGO)/metal - organic framework (MOF) composite sensors is to enhance electrochemical sensing sensitivity, selectivity, and stability. The binary rGO - MOF composite is the basis for ternary systems. For example, Fe - MOF - rGO composites have enhanced electrochemical response to nitrofuranones, with rGO providing high conductivity and large surface area for electron transfer and Fe - MOF showing excellent catalytic activity and stability. GOx has limited direct use in heavy metal detection but offers new ideas for sensor optimization: it catalyzes glucose oxidation to produce hydrogen peroxide for modulating electrochemical signals and regulates microenvironments for ion accumulation and signal amplification. Binary MOF - rGO systems can be used for heavy metal ion detection.

The integration of the CRISPR - Cas12a system enables ultra - sensitive real - time early warning for heavy metals. It converts heavy metal ion recognition into nucleic acid signals, triggering Cas12a's "trans - splicing" activity for signal output. Mercury ions can activate the system for fluorescent signals, and in cadmium ion detection, DNAzyme and hybrid chain reaction are combined with it, and appropriate amounts of Cas12a activators can enhance detection sensitivity [26].

5.2 Atmospheric VOCs Sensor Array

Atmospheric VOCs Sensor Array: Selective regulation of ZnO/graphene hybrid materials for atmospheric VOCs monitoring can be achieved through material design, surface modification, heterostructure construction, and electronic structure modulation. The combination of ZnO and graphene is the basis for VOCs sensing [27-28]; organic molecular functionalization enhances selectivity for specific VOCs [29]; heterostructure construction is an effective approach, such as the AlO/ZnO interface design concept to improve adsorption selectivity in ZnO/graphene systems [30]. Graphene variable capacitor arrays with machine learning - assisted recognition have great potential in VOCs detection. An array with 108 sensors and 36 receptors paired with a supervised model can rapidly identify five typical VOCs with high accuracy and strong interference resistance [31].

5.3 Distributed Monitoring Network for Soil Pollutants

Distributed Monitoring Network for Soil Pollutants: Graphene - biomass composites lead the way in innovative distributed monitoring networks for soil pollutants. RFID tag sensors integrated with rGO/ISM enable rapid detection of soil lead, establishing the hardware foundation for monitoring nodes [32]; SMS sensors on a 3D - printed graphene platform simultaneously detect multiple pollutants, while NMG heterostructure electrodes enhance detection sensitivity [33-34]; an ML - driven plasma spectroscopy system overcomes soil matrix interference, enabling real - time online analysis of heavy metal concentrations [35].

6 Current Technical Bottlenecks and Future Prospects

6.1 Industrialization Challenges

Large-scale production faces prominent quality control challenges: the complex synthesis process of industrial-grade graphene results in poor batch reproducibility, low material dispersion leads to uneven electrode deposition, while the inherent heterogeneity of biomass feedstocks further increases standardization difficulties [36-37].

6.2 Environmental Interference and Safety Controversies

Complex environmental deployment is constrained by multiple interference factors: graphene's non-selective response can easily interfere with mixed pollutant signals, fluctuations in water body ionic strength and pH alter interfacial charge distribution, coexistence of oxygen may cause 13-fold deviations in ammonia detection, and soil organic matter obscures target active sites [38-39]. The biosafety assessment system remains incomplete, with existing

studies predominantly focusing on high-dose acute toxicity while lacking chronic exposure data at environmentally relevant concentrations. Additionally, systematic evaluations are lacking regarding synergistic biological effects and degradation pathways between biomass degradation products and graphene [40-41]. Although ISO has initiated a graphene safety assessment framework, there is still no unified standard for bioavailability distribution and ecological chain transfer risks specific to composite materials [42-43].

6.3 Path to Technological Breakthrough

Future technological breakthroughs require coordinated advancement across four dimensions: intelligent design, energy self-sufficiency, closed-loop recycling, and industrial transfer. Machine learning-based material genome engineering can optimize molecular structure-performance ratios, significantly reducing experimental trial-and-error costs through high-throughput virtual screening. Integration of piezoelectric power generation, photothermal conversion, and triboelectric nanogenerator technologies enables biomimetic dual-mode energy systems, overcoming energy conversion efficiency bottlenecks to achieve environmentally adaptive energy self-sufficiency. Closed-loop recycling systems utilizing covalent adaptive networks or microbial enzymatic degradation technologies facilitate controlled dissociation of composite materials and simultaneous recovery of inorganic carbon and organic monomers, preventing environmental accumulation from discarded sensors. Ultimately, resolving the low-cost-high-performance-scale triad challenge involves optimizing production processes using agricultural waste as raw materials, establishing standardized end-to-end systems from ultrasonic dispersion control to aerosol jet printing, and facilitating the translation of laboratory technologies into practical applications for complex field monitoring scenarios.

7 Conclusion

This study establishes a novel paradigm for graphene-biomass composite sensors characterized by "high performance, environmental friendliness, and industrial scalability." It elucidates the molecular interaction mechanisms between biomass components and graphene, along with interface modulation strategies. The research reviews breakthroughs in green fabrication technologies such as biomolecular template-induced self-assembly, validates the application potential of multi-medium monitoring systems (water/gas/soil), and analyzes industrialization bottlenecks. By integrating structural-functional-environmental design principles with green manufacturing and intelligent technologies, the work promotes coordinated development of environmental monitoring systems toward greener, smarter, and more industrialized solutions.

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