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Advances in Functionalized Nanocellulose-based Composites for Chemical Sensing Applications

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Introduction

Nanocellulose-based composites have emerged as a promising class of materials in the development of chemical sensors due to their unique structural, mechanical, and physicochemical properties. Derived from natural cellulose, nanocellulose exhibits high surface area, excellent mechanical strength, biocompatibility, and tunable functional groups, making it an attractive material for sensor applications. The integration of nanocellulose with various functional materials, including metals, metal oxides, conductive polymers, and carbon-based nanostructures, has led to the development of advanced composites with enhanced sensitivity, selectivity, and stability for chemical sensing. These nanocomposites have shown significant potential in detecting a wide range of chemical analytes, including gases, organic compounds, heavy metals, and biomolecules, making them valuable in environmental monitoring, healthcare diagnostics, food safety, and industrial process control. Nanocellulose exists in three primary forms: Cellulose Nanocrystals (CNCs), Cellulose Nanofibers (CNFs), and Bacterial Nanocellulose (BNC).

Description

CNCs are rod-like structures obtained through acid hydrolysis, offering high crystallinity and surface charge, which facilitates functionalization. CNFs, produced by mechanical or enzymatic fibrillation, possess high flexibility and large aspect ratios, making them suitable for film and membrane applications. BNC, synthesized by bacteria, features a highly porous and interconnected structure, providing excellent water retention and mechanical properties. The inherent hydroxyl groups in nanocellulose enable surface modification and functionalization, allowing it to interact with diverse sensing elements and target analytes. The functionalization of nanocellulose plays a crucial role in enhancing its sensing capabilities. Various chemical modifications, including oxidation, esterification, and grafting with functional moieties, improve its stability, selectivity, and binding affinity for specific analytes. The incorporation of metal nanoparticles, such as gold, silver, and platinum, into nanocellulose matrices enhances their electrical and optical properties, enabling highly sensitive detection through plasmonic and electrochemical mechanisms. Similarly, metal oxide nanoparticles like zinc oxide, titanium dioxide, and iron oxide contribute to improved catalytic and semiconducting behavior, facilitating gas sensing and pollutant detection [1].

Conductive polymers, including polyaniline, polypyrrole, and polythiophene, have been integrated with nanocellulose to produce flexible and responsive sensing platforms. These composites exhibit significant changes in electrical conductivity upon interaction with target analytes, making them suitable for resistive and capacitive sensing applications. The combination of nanocellulose with carbon-based nanomaterials, such as graphene, carbon nanotubes, and reduced graphene oxide, has further enhanced the sensitivity and stability of chemical sensors. These hybrid materials benefit from the synergistic effects of nanocellulose's structural integrity and the exceptional conductivity and adsorption properties of carbon nanomaterials. Chemical sensors based on functionalized nanocellulose composites operate through various detection mechanisms, including electrochemical, optical, and piezoelectric transduction. Electrochemical sensors utilize nanocellulose composites as electrode materials, enabling the detection of chemical species through amperometric, potentiometric, and impedimetric responses. The high surface area and tunable functional groups of nanocellulose enhance the immobilization of recognition elements, such as enzymes, antibodies, and molecular receptors, improving the sensor's sensitivity and specificity [2].

Optical sensors rely on fluorescence, colorimetry, and Surface Plasmon Resonance (SPR) to detect analytes based on their interaction with nanocellulose-based composites. The unique optical properties of metal and semiconductor nanoparticles embedded in nanocellulose matrices facilitate label-free and real-time detection of chemicals in various media. Piezoelectric sensors leverage the mechanical properties of nanocellulose, where interactions with target molecules induce measurable changes in resonance frequency or mechanical deformation. Environmental monitoring has been a key application area for nanocellulose-based chemical sensors. These sensors have demonstrated high sensitivity in detecting hazardous gases, volatile organic compounds (VOCs), heavy metal ions, and water contaminants. For example, nanocellulose composites functionalized with silver nanoparticles have shown excellent performance in detecting mercury and lead ions in water, providing a cost-effective and sustainable alternative to conventional analytical techniques. Gas sensors utilizing nanocellulose-carbon nanotube hybrids have exhibited remarkable selectivity toward ammonia, carbon monoxide, and nitrogen dioxide, offering potential solutions for air quality monitoring. The biodegradability and renewability of nanocellulose also make these sensors environmentally friendly, aligning with sustainable development goals [3].

In healthcare and biomedical applications, nanocellulose-based sensors have been explored for detecting biomarkers, pathogens, and drug residues. The integration of nanocellulose with biomolecules, such as antibodies, DNA probes, and aptamers, has enabled highly specific biosensors for disease diagnostics and point-of-care testing. Functionalized nanocellulose membranes have been employed in wearable sensors for non-invasive monitoring of glucose, lactate, and cortisol levels in sweat, saliva, and interstitial fluids. These advances have paved the way for real-time health monitoring and personalized medicine, enhancing the accessibility and efficiency of diagnostic technologies. Food safety is another critical area where nanocellulose-based sensors have made significant contributions. Sensors developed from nanocellulose composites have been utilized to detect foodborne pathogens, pesticide residues, and spoilage indicators. Colorimetric sensors based on nanocellulose-gold nanoparticle hybrids have demonstrated high sensitivity in detecting bacterial contamination in food samples. Electrochemical sensors incorporating nanocellulose-polymer composites have been used to monitor pesticide residues in agricultural products, ensuring compliance with food safety regulations. The adaptability of these sensors for rapid and on-site analysis has improved food quality control and consumer protection [4].

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Industrial process control and quality assurance have also benefited from the development of nanocellulose-based chemical sensors. These sensors have been employed in monitoring chemical reactions, detecting impurities in raw materials, and ensuring the integrity of manufacturing processes. The ability of nanocellulose composites to function in diverse environments, including harsh chemical conditions, high temperatures, and varying humidity levels, makes them suitable for industrial applications. Their integration into smart packaging and intelligent labeling systems has further expanded their utility in tracking product freshness and detecting contamination. Despite the numerous advantages of nanocellulose-based chemical sensors, several challenges remain in their commercialization and large-scale deployment. The reproducibility of sensor fabrication, long-term stability, and response consistency are critical factors that need to be addressed. The functionalization and integration of nanocellulose with sensing elements must be optimized to achieve uniform performance across different batches. Additionally, sensor selectivity remains a challenge, as cross-sensitivity to multiple analytes can affect accuracy and reliability. Advanced strategies, including molecular imprinting, hybrid nanostructure design, and machine learning-based signal processing, are being explored to overcome these limitations.

Recent advancements in nanotechnology, material science, and sensor engineering have driven the continuous improvement of nanocellulose-based chemical sensors. Emerging fabrication techniques, such as 3D printing, electrospinning, and self-assembly, have enabled precise control over sensor architecture and material composition. The development of flexible and wearable sensors using nanocellulose composites has opened new possibilities for real-time and mobile sensing applications. Moreover, the integration of nanocellulose sensors with wireless communication technologies and Internet Of Things (IoT) platforms has facilitated remote monitoring and data analytics, enhancing their functionality and applicability. The sustainability and environmental benefits of nanocellulose-based sensors further reinforce their potential in future sensing technologies. The utilization of renewable resources, coupled with eco-friendly fabrication processes, aligns with the growing demand for green and biodegradable sensor solutions. Research efforts are focused on optimizing the scalability of nanocellulose production, reducing processing costs, and developing recyclable sensor materials. Collaborative efforts between academia, industry, and regulatory agencies are essential in accelerating the translation of nanocellulose-based sensors from research laboratories to commercial markets [5].

Conclusion

In conclusion, functionalized nanocellulose-based composites represent a versatile and highly promising class of materials for chemical sensing applications. Their unique properties, coupled with the ability to integrate with various functional materials, have enabled the development of highly sensitive, selective, and sustainable sensors for environmental, healthcare, food safety, and industrial applications. While challenges related to sensor stability, selectivity, and large-scale production remain, ongoing research and technological advancements continue to drive the evolution of nanocellulose-based chemical sensors. As the demand for innovative and eco-friendly sensing solutions grows, nanocellulose-based composites are poised to play a crucial role in the next generation of chemical detection technologies.

Acknowledgement

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Conflict of Interest

None.

References

1. McAdam, Blaithín, Margaret Brennan Fournet, Paul McDonald and Marija Mojicevic. "Production of Polyhydroxybutyrate (PHB) and factors impacting its chemical and mechanical characteristics." *Polym* 12 (2020): 2908.

2. Asyraf, M. R. M., M. R. Ishak, M. N. F. Norrrahim and N. M. Nurazzi, et al. "Recent advances of thermal properties of sugar palm lignocellulosic fibre reinforced polymer composites." *Int J Biol Macromol* 193 (2021): 1587-1599.

3. Bacakova, Lucie, Julia Pajorova, Maria Tomkova and Roman Matejka, et al. "Applications of nanocellulose/nanocarbon composites: Focus on biotechnology and medicine." *Nanomater* 10 (2020): 196.

4. Cunha-Silva, Hugo and M. Julia Arcos-Martinez. "Development of a selective chloride sensing platform using a screen-printed platinum electrode." *Talanta* 195 (2019): 771-777.

5. Janudin, Nurjahirah, Noor Azilah Mohd Kasim, Victor Feizal Knight and Mohd Nor Faiz Norrrahim, et al. "Fabrication of a nickel ferrite/nanocellulose-based nanocomposite as an active sensing material for the detection of chlorine gas." *Polym* 14 (2022): 1906.

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