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Application and Prospects of Nanomaterials in Medical and Environmental Sensing

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Abstract: Driven by the increasing demand for sensing technologies in the field of healthcare and environmental protection, nanomaterials have emerged as critical materials for advancing sensor performance, largely due to their unique physical, chemical, and biological properties that enhance various sensing techniques. This paper examines the application of nanomaterials in medical and environmental sensing, and explores both carbon-based (e.g., graphene, carbon nanotubes) and metal-based nanomaterials, focusing on their contributions to sensor sensitivity, specificity, as well as real-time monitoring. Key applications include early disease detection, blood glucose monitoring, and pollutant detection, particularly for carbon dioxide and nitrates. In addition, the bottom-up and top-down synthesis methods of nanomaterials are compared, highlighting their versatility across various sensing scenarios. Nevertheless, despite the broad application potential of nanomaterials in sensing technology, high production costs, insufficient stability, and processing challenges remain key obstacles. Future research should focus on reducing production costs, enhancing material stability, and minimizing environmental impact to facilitate the practical application of nanomaterials in sensor technology.

Keywords: Nanomaterials, Medical Sensors, Environmental Sensors, Carbon-based Materials, Metal-based Materials

1. Introduction

The rapid development of nanotechnology has shown the potential of nanomaterials for application in medical and environmental sensors, given their distinctive physical, chemical, as well as biological properties. Nanomaterials have great specific surface area, excellent catalytic properties, and quantum effects, which make them ideal for enhancing sensitivity, specificity, and response speed in sensor technology. In recent years, the application of nanomaterials in early disease detection, blood glucose monitoring, and pollutant detection has been advancing, greatly improving the performance and real-time monitoring capabilities of sensors. However, despite the great potential nanomaterials show in sensor technology, practical applications still face many challenges. These challenges include high production costs, stability issues, environmental impacts and reliability when applied in complex environments. Thus, the paper reviews the current state of nanomaterials in medical and environmental sensing, which seeks to investigate how the distinctive properties of carbon-based and metal-based nanomaterials can be effectively utilized to enhance the performance of sensors in these

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fields. It also studies ways to enhance nanomaterial preparation, stability, and production costs to encourage their practical use. The study emphasizes nanoparticles' potential for early illness detection and pollution monitoring in medical and environmental sensing.

2. Advances in Nanomaterials for Medical Sensing

High-sensitivity sensors identify diseases early. Early diagnosis and treatment improves outcomes and lowers expenses. Cancer is one of the world's most dangerous diseases, and early diagnosis improves patient prognosis. Early cancer detection can decrease disease development, lower treatment costs, and increase therapy options, improving patient survival [1]. Thus, the application of medical sensors in the early identification of diseases not only has significant importance in improving treatment outcomes, but also provides strong technical support for the realization of precision medicine and the development of individualized treatment strategies [2].

2.1. Applications of Advanced Nanomaterials

The core role of sensor materials in electrochemical sensing technology cannot be overlooked [3]. With the rapid advancement of nanotechnology, nanomaterials, due to their unique physical, chemical, and electronic properties, have demonstrated advantages in the field of medical sensors that traditional materials cannot match. In particular, nanomaterials derived from carbon and metals have emerged as pivotal materials in the enhancement of sensor sensitivity, selectivity, and stability, largely due to their exceptional electrical, thermal, catalytic, and mechanical properties. In recent years, the use of these nanomaterials in biosensing, early disease detection, and personalized medicine has gained widespread attention, and significant progress has been made in improving sensor performance, achieving rapid detection, and enabling convenient integration.

2.1.1. Carbon-based Nanomaterials: Structural Characterization and The Applications in Cancer Diagnostics

Due to their exceptional physicochemical properties, particularly their high specific surface area, superior electrical conductivity, and chemical stability, carbon-based nanomaterials have become a central focus of research in biosensing. The electrical conductivity, mechanical strength, and chemical stability of graphene and carbon nanotubes (CNTs) make them popular for cancer biomarker detection and early diagnosis [4,5]. A classification flowchart based on these carbon nanomaterials is presented in Figure 1 [6].

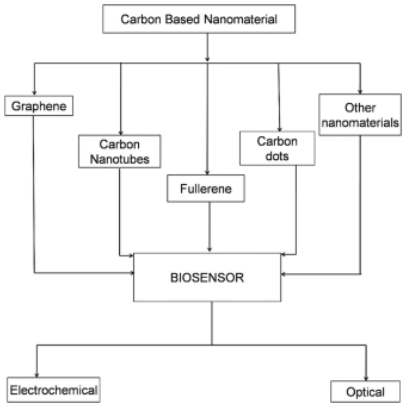


Figure 1: Carbon-based Nanomaterials Classification

Graphene, a two-dimensional material consisting of a single layer of carbon atoms arranged in sp2 hybridization, boasts a unique electronic structure that imparts outstanding conductivity and

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sensitivity, making it an excellent material for biosensors [6]. Its high specific surface area offers abundant active sites, significantly enhancing the sensor's ability to adsorb target molecules and thus improving sensitivity. In early cancer diagnosis, graphene's surface can be chemically modified to bind specific antibodies or DNA probes, enabling efficient and targeted recognition of cancer-related biomarkers [7]. For instance, graphene-modified sensors can maintain exceptional sensitivity even at trace levels of biomarkers. Laser-induced graphene (LIG), a three-dimensional porous form, offers enhanced surface activity and chemical reactivity, which significantly boosts its efficacy in biosensing applications. The preparation process of LIG is simple and cost-effective, as it directly writes a porous structure onto a polymer surface using a laser, reducing manufacturing costs while significantly enhancing sensor performance. The porous structure of LIG greatly increases its interaction with biomolecules, thereby improving the sensor's sensitivity and selectivity [8]. LIG-based sensors have been applied in urea detection, capable of detecting urea concentrations as low as 10-4 M within 60 seconds, showing its enormous potential for monitoring biological fluids [9]. In addition, CNTs are a type of nanomaterial with a unique tubular structure, existing in single-walled (SWCNTs) and multi-walled (MWCNTs) forms. The exceptional electrical and mechanical properties of CNTs make them important materials in the field of medical sensing [10]. CNTs can be surface-functionalized to specifically bind with various biomolecules, significantly enhancing the sensor's selectivity and sensitivity. For example, Feng et al. developed a sensor using MWCNT-modified paper-based electrodes that can detect prostate-specific antigen (PSA) [11]. This sensor is capable of detecting PSA levels as low as 1 pg/mL, showcasing the great potential of CNTs in early cancer diagnosis.

2.1.2. Metal-based Nanomaterials: Applications in the Glucose Monitoring and Bio-sensing

The metal-based nanomaterials, particularly noble metals such as gold and platinum, are extensively used in biosensors, especially glucose sensors, due to their excellent electrical conductivity and catalytic properties. The catalytic ability of these metal nanomaterials, particularly in neutral conditions for glucose oxidation, makes them ideal for wearable glucose sensors. Noble metal alloys, such as gold-platinum (Au-Pt) nanoparticles, are frequently employed as catalysts in glucose sensors, owing to their high catalytic activity and stability, enabling precise glucose concentration measurements in biological samples [3]. For instance, Xuan et al. utilized gold-platinum alloy nanoparticles to catalyze the oxidation of glucose, generating hydrogen peroxide, which was then monitored through changes in its concentration to assess glucose levels. This sensor not only enhances detection sensitivity but also demonstrates strong anti-interference capabilities, making it particularly suitable for long-term monitoring in diabetic patients [12].

2.1.3. Diverse Applications and Frontier Advances of Nanomaterials in Bio-sensing

The application of nanomaterials in bio-sensing has far surpassed traditional electrochemical and optical detection methods. For instance, conductive polymer (CP) nanomaterials, recognized for their unique tunable conductivity and excellent structural flexibility, have emerged as a key focus in the development of next-generation biosensors. By adjusting their conductivity through redox reactions, conductive polymers' high surface area and tunable structures enable rapid responses to specific chemicals or biological molecules [13]. Silicon nanowires (SiNWs), a key semiconductor nanomaterial, have seen widespread use in biosensors due to their excellent electrical, optoelectronic, and mechanical properties. SiNWs are typically synthesized through vapor deposition methods, and their high surface area and carrier mobility allow for high-sensitivity detection of DNA, proteins, and viruses. SiNW-based field-effect transistors (FETs) have been employed for detecting biomarkers such as cell signals, DNA, and proteins [13].

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In nucleotide-based biosensors, detection primarily involves immobilising single-stranded DNA (ssDNA) on a nanomaterial to achieve DNA hybridisation, thus identifying complementary target sequences. Staii et al. utilised this principle with single-walled carbon nanotubes (swCNTs) to create DNA-decorated sensors for gas detection [14]. ssDNA was immobilised on the swCNT surface via π-π stacking, and interactions between ssDNA and gas molecules created minor perturbations in the swCNT. The sensor could detect dimethyl methylphosphate (DMMP) at 25 ppm, serving as an economical option since the recognition layer can be reused up to 50 times. For receptor-based biosensors, olfactory receptors are employed to detect a wide range of odors. Kim et al. engineered a bioelectronic nose by immobilizing human olfactory receptor (hOR) proteins, expressed in Escherichia coli, onto single-walled carbon nanotube field-effect transistors (swCNT-FETs) [15]. This integration results in a biosensor with exceptional sensitivity and selectivity, offering significant potential for applications in medical diagnostics and bacterial infection detection.

2.2. Comparison of Nanomaterial Sensors and Traditional Sensors

Nanomaterial sensors offer distinct advantages over traditional sensors across a range of applications, particularly in terms of sensitivity, response speed, integration, and miniaturization. These benefits position nanomaterial sensors as increasingly vital in modern detection technology. The following data is derived from research and analysis of current sensor technologies.

Table 1: Comparison of Materials, Methods, and Performance of Current Sensor Technologies

Materials	Method	Detection range	LOD
Multilayered graphene	Electrochemistry	1.67–16.7 mM	0.65 mM
Wearable film	Electrochemistry	1–100 mM	0.1 mM
Urease attached probe with an ionovolatic transducer	Electrochemistry and enzymatic catalysis	1–50 mM	Not reported
Optical fiber	Enzymatic catalysis	4–50 mM	4.25 mM
Hypobromite solution	Electrochemistry	1–16 mM	Not reported
LIG	Enzymatic catalysis	Not reported	0.1 mM

As shown in Table 1, sensors based on graphene and LIG demonstrate significant advantages in sensitivity and detection limits, particularly excelling in the detection of low-concentration substances. These nanomaterials leverage their unique physicochemical properties to markedly enhance molecular interactions with the sensor surface, thereby improving both sensitivity and specificity. For instance, a sensor developed by Ozaki et al. has a response time of only 1 second [16], while the LIG-based sensor has a response time of 1 minute [7]. Compared to traditional sensors, nanomaterial sensors exhibit notable advantages on several levels. Firstly, the high specific surface area of nanomaterials provides more active sites, allowing for more effective capture and reaction with target molecules, thus enhancing both sensitivity and specificity. This attribute makes nanomaterial sensors particularly effective in complex detection environments, especially in cases involving low concentrations and trace amounts. Secondly, the small size of nanomaterials not only contributes to faster response times but also enhances the potential for integration, enabling seamless incorporation into portable and wearable devices [13]. Table 1 shows that conventional sensors may have faster response times but narrower detection ranges and thresholds. The choice between nanomaterial and conventional sensors should be adjusted to specific needs in actual applications. Application environment, detection accuracy, and reaction time priority influence this selection. Thus, each application situation must balance sensitivity, response speed, and detection range.

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3. Advances in Nanomaterials for Environmental Sensing

3.1. Role of Nanomaterials in Environmental Sensing

Environmental pollution in air, water, and soil is growing, endangering ecosystems and humans. Pollution harms health, ecology, and biodiversity. Thus, pollutant concentration monitoring must be prompt and accurate for environmental protection. Demand for rapid pollutant identification and quantitative analysis has led to efficient and sensitive sensor technologies, enabling accurate pollution source control and improving environmental governance [17]. Due to their exceptional physicochemical properties, including a high specific surface area, excellent electrical conductivity, and significant surface reactivity, these materials are being increasingly utilized in the development of sensors. These qualities improve the sensor's sensitivity, selectivity, and real-time monitoring, making it suitable for environmental pollution monitoring.

3.2. Key Pollutant Detection Using Nanotechnology

Nanomaterials have significant advantages in enhancing sensor sensitivity, miniaturization, selectivity, and real-time monitoring capability, making them widely applicable in industrial and environmental monitoring [18]. Electrochemical sensors, characterized by their low cost and high sensitivity, are extensively used in the detection of air pollutants, such as harmful gases like CO_2 and SOX, as well as heavy metal contaminants, which have adverse effects on both flora, fauna, and human health. Therefore, developing low-cost, highly sensitive, and reliable environmental sensors is of paramount importance. In terms of CO_2 detection, CO_2 is an important component of the atmosphere and one of the major greenhouse gases. Its concentration has increased by 47% from 280 ppm since industrialization, greatly contributing to global warming and ocean acidification, and constituting a major challenge in combating climate change. Furthermore, long-term exposure to high CO_2 concentrations may also adversely affect human health, thus making CO_2 monitoring particularly important [19]. CO_2 sensors typically operate by detecting changes in resistance and capacitance of nanomaterials upon interaction with CO_2 molecules, using commonly employed materials like SnO_2 as an inorganic metal oxide, serving as a p-type semiconductor substrate for the sensing layer [19]. Nitrate detection is crucial, as nitrates serve as essential nutrients for plant growth. However, elevated concentrations in water and food can lead to environmental and health issues, such as blue baby syndrome and an increased risk of cancer. While moderate nitrate intake supports blood circulation and cardiovascular health, excessive intake highlights the necessity of monitoring [20]. Nitrate sensors are able to detect nitrates with much more sensitivity and selectivity when enhanced with nanomaterials due to their biocompatibility, conductivity, catalytic capabilities, and large surface area. One way to enhance detection performance is by adding conductive polymers, metal nanoparticles, or carbon nanotubes to the electrochemical reaction occurring at the interface between the electrode and electrolyte. There are several advantages of using sensors based on nanotechnology to monitor environmental and food safety, including a wider linear response range, lower detection limits, and improved stability [20].

4. Conclusion

The results indicate that nanomaterials hold great promise in advancing medical and environmental sensing technologies. Their unique characteristics, such as high surface area, chemical stability, and catalytic activity, significantly enhance sensor sensitivity, specificity, and response speed, making them suitable for detecting a variety of biological and environmental indicators. In medical sensing, carbon-based and metal-based nanomaterials enable early and precise detection of biomarkers like cancer markers and glucose levels, thus improving disease diagnosis. Similarly, in environmental

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monitoring, nanomaterials support the detection of pollutants like CO_2 and nitrates, aiding efforts to address pollution and climate change challenges. It successfully addresses the research questions outlined in the introduction, demonstrating nanomaterials' potential to enhance sensor capabilities and push measurement limits. Despite their benefits, nanomaterial-based sensors face challenges in their practical applications, such as high nanomaterial production costs, sensor accuracy variability across environmental conditions, and potential environmental and health impacts of nanomaterial waste. Future study should optimize synthesis procedures to cut costs, improve stability under varied situations, and investigate safe disposal techniques to lessen ecological impact. Nanomaterial sensors in wearable devices and remote monitoring systems for real-time data collecting and other applications could also improve accessibility. New biomimetic nanomaterials and versatile sensor platforms will expand applications. Nanotechnology's potential for global health and environmental sustainability requires addressing these crucial concerns.

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