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Review Article

Comprehensive Review of Functionalized Multi-Walled Carbon Nanotubes: Emerging Trends and Applications in Simultaneous Detection of Uric Acid, Dopamine and Ascorbic Acid

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ABSTRACT

This article explores the latest advancements in the use of functionalized multi-walled carbon nanotubes (MWCNTs) for the simultaneous detection of uric acid (UA), dopamine (DA), and ascorbic acid (AA) in various biological fluids. These analytes are crucial due to their association with numerous diseases and their vital roles in physiological functions. MWCNTs, especially when combined with zinc-nickel (ZnNi), offer promising attributes like high conductivity, large surface area, and excellent electrocatalytic properties. The synergy between MWCNTs and ZnNi enhances their effectiveness, making them ideal for constructing highly selective and sensitive electrochemical sensors. This review meticulously examines the synthesis and functionalization of MWCNTs, highlighting their improved solubility and reactivity. We discuss the sensor construction process, emphasizing the compatibility with electrode materials and functionalization techniques. In addition, we analyse the electrochemical properties and performance of these sensors. The key findings of this review aim to guide researchers in exploiting functionalized MWCNTs for developing highly selective and sensitive sensors for UA, DA, and AA, with potential applications in pathological, clinical, and biological studies.

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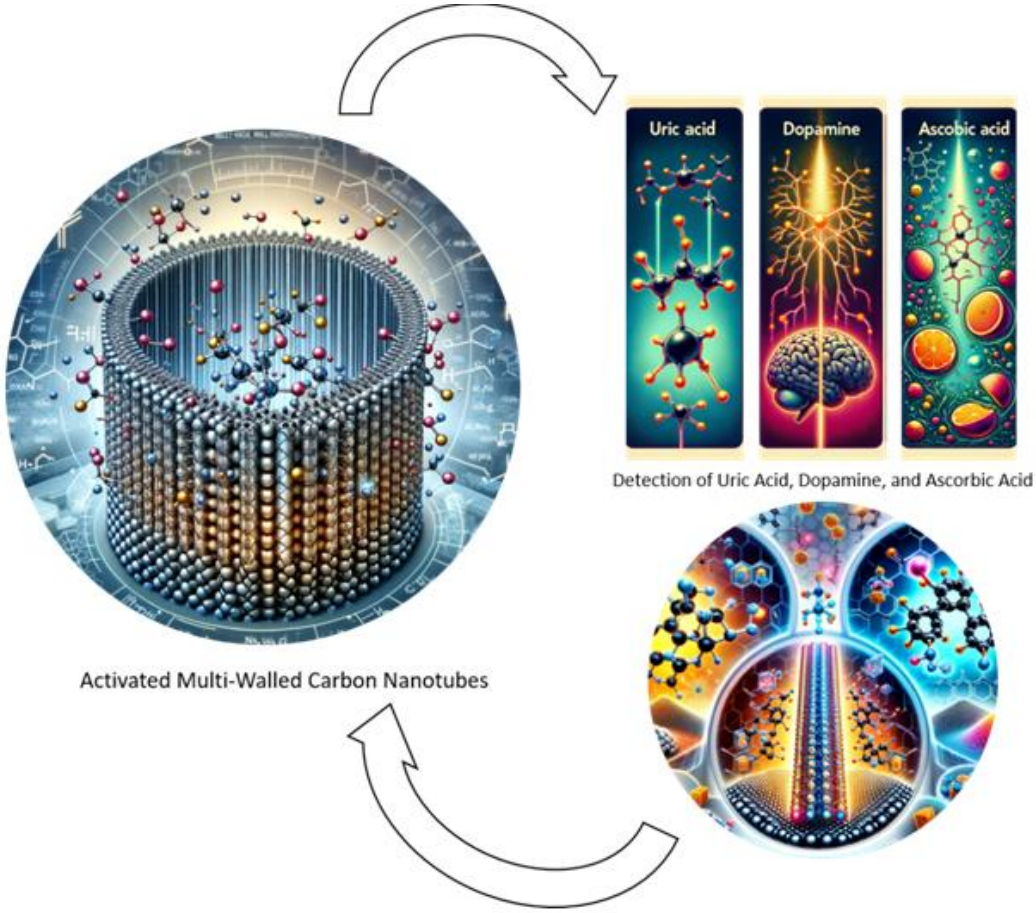
GRAPHICAL ABSTRACT



Introduction

This study centres on developing electrochemical sensors utilizing functionalized multi-walled carbon nanotubes (MWCNTs) [1-4]. Recognized for their vast surface area and exceptional conductivity, MWCNTs are promising nanomaterials in sensing applications. The simultaneous detection of three significant compounds in biological fluids-uric acid (UA), dopamine (DA), and ascorbic acid (AA)-is vital, given their essential roles in physiological processes and links to various diseases. This study aims to bridge the knowledge gap by exploring MWCNT synthesis and functionalization techniques, thereby enhancing their solubility and reactivity. It also delves into the sensor fabrication process, aligning it with electrode materials and functionalization approaches. Moreover, the investigation extends to the electrochemical properties of these sensors [5-7]. The gap identified in this study pertains to a comprehensive understanding of how functionalized MWCNTs can be leveraged to develop electrochemical sensors capable of concurrently detecting UA, DA, and AA in biological fluids. An additional objective is to elucidate the role of ZnNi as a reinforcing agent in these sensors [8-11]. The outcomes of this study are expected to be pivotal in crafting precise and sensitive electrochemical sensors, applicable across various fields including biological and medical sciences. This section provides an in-depth overview of the latest developments in electrochemical sensors that utilize multi-walled carbon nanotubes

(MWCNTs) for detecting substances such as ascorbic acid, dopamine, and uric acid. Recent research has highlighted significant progress in enhancing the sensitivity and efficiency of these MWCNT-based sensors. The nanotechnology integration in sensor design has opened up broader applications, particularly in medical and environmental fields, among others. Moving forward, the focus on developing more effective sensors and exploring diverse methods for functionalizing MWCNTs will be pivotal for advancing research in this domain.

In this context, Figure 1 dislplays the advancements and challenges in the realm of low-dimensional carbon nanomaterials, including carbon nanotubes, graphene oxide, and their derivatives. These materials have achieved significant milestones in preparation, composite processing, and applications, especially in environmental remediation. However, there remain unexplored opportunities and challenges in their practical application. While many of these innovations are currently confined to laboratory research, some have progressed to *in situ* testing or are on the commercialization verge. This emphasizes the dynamic nature of this field and the ongoing efforts to transition these technologies from the lab to real-world applications. Despite significant advancements in the preparation, composite processing, and applications of low-dimensional carbon nanomaterials, such as carbon nanotubes, graphene oxide, and their derivatives, within the realm of environmental remediation, this figure underscores the existing opportunities and challenges in their practical implementation that necessitate careful consideration. While noteworthy progress has been made in laboratory settings, several innovations are currently undergoing in situ testing or poised for imminent commercialization.

It is crucial to recognize that the journey from laboratory breakthroughs to real-world applications requires a concerted effort to bridge the gap between scientific exploration and practical utility. This modified figure, adapted from [12], serves as a visual testament to the ongoing exploration of these materials and the dynamic interplay between innovation, testing, and potential commercial viability.

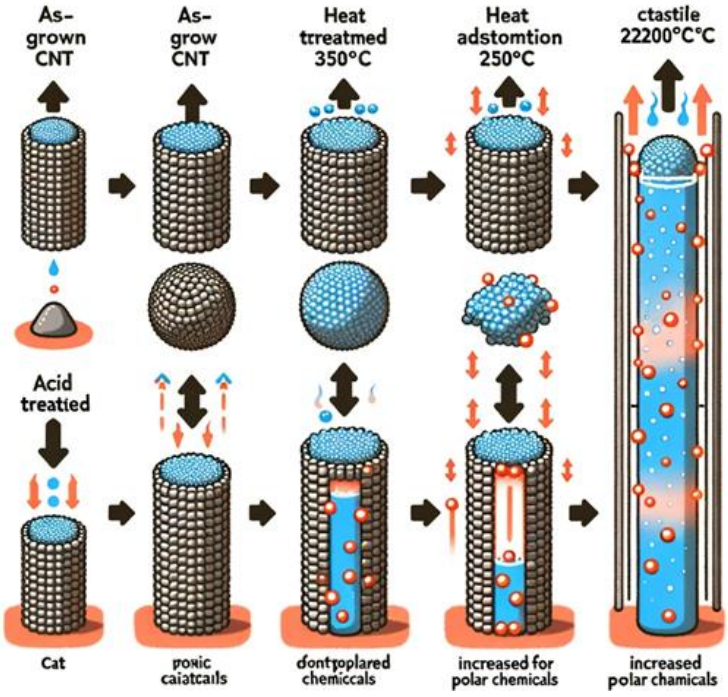


Figure 1. Navigating opportunities and challenges in the application of low-dimensional carbon nanomaterials.

The novelty of this study lies in its comprehensive examination of functionalized multi-walled carbon nanotubes (MWCNTs), particularly those modified with zinc-nickel (ZnNi), aimed at developing highly selective and sensitive electrochemical sensors for the simultaneous detection of ascorbic acid (AA), dopamine (DA), and uric acid (UA) in biological fluids [13-16]. The ZnNi incorporation as a nanocomposite material represents a novel approach to enhance sensor performance, despite the extensive attention MWCNTs have garnered in sensor applications. This study methodically investigates the synthesis, functionalization, and electrochemical properties of these MWCNT-based sensors, striving to advance sensor technology and contribute a valuable tool for biological, pathological, and clinical research [17-20].

The primary objective of this research is to develop and characterize highly sensitive electrochemical sensors based on functionalized multi-walled carbon nanotubes. This study specifically targets the simultaneous detection of uric acid (UA), dopamine (DA), and ascorbic acid (AA) in biological fluids, with the ultimate aim of propelling sensor technology forward in clinical and biomedical applications.

Synthesis methods in MWCNTs research

The synthesis of multi-walled carbon nanotubes (MWCNTs) is a sophisticated process that forms the backbone of much of the research in nanotechnology. Various studies [21-24] have delved into different synthesis methods, including chemical vapor deposition, arc-discharge, and plasma-enhanced synthesis. Each of these methods presents unique benefits in terms of control over the nanotube's diameter, length, and purity, which are crucial for their subsequent applications. This review will analyse these synthesis techniques, focusing on how they influence the physical and chemical properties of MWCNTs.

For instance, chemical vapor deposition allows for precise control over the growth conditions, leading to MWCNTs with specific characteristics suited for particular applications. The efficiency of these methods in terms of yield and scalability will be further discussed, as these factors are critical for the practical application of MWCNTs in industrial and research settings.

Functionalization and characterization of MWCNTs

The MWCNTs functionalization, especially with ZnNi, significantly enhances their properties and expands their applicability. This process, which involves the addition of functional groups or other materials to the surface of MWCNTs, alters their reactivity, conductivity, and solubility. The review will summarize key studies that have explored the impact of ZnNi functionalization on MWCNTs, including the resulting changes in electronic properties and surface chemistry. Furthermore, the role of characterization techniques like Brunauer-Emmett-Teller (BET) for surface area analysis, Scanning Electron Microscopy (SEM) for morphological analysis, and Fourier Transform Infrared Spectroscopy (FTIR) for chemical composition analysis [25-28,33-36], is crucial in assessing the quality of synthesized and functionalized MWCNTs.

These techniques provide essential insights into the structural integrity and functional capacity of the nanotubes, ensuring their suitability for specific applications such as electrochemical sensing, where material properties directly impact performance and sensitivity. The review will highlight the importance of these techniques in verifying the success of synthesis and functionalization processes, thereby ensuring the reliability and effectiveness of MWCNTs in various applications.

Optimization of environmental conditions for MWCNTs/ZnNi composites

The activity and effectiveness of multi-walled carbon nanotubes (MWCNTs) functionalized with zinc-nickel (ZnNi) are highly dependent on environmental conditions, a subject that has been extensively studied [29-32]. The optimization of these conditions is crucial in maximizing the sensing capabilities of the composites.

This review will focus on how pH, adsorbent dosage, contact time, and temperature play a pivotal role in influencing the performance of MWCNTs/ZnNi composites. For instance, the pH of the medium can significantly impact the electrochemical properties of the composites, altering their ability to interact with specific target molecules. Similarly, the adsorbent dosage determines the available surface area for interaction with analytes, influencing the sensitivity and detection limits of the sensors. This review will synthesize research findings on how these parameters are fine-tuned to optimize the performance of MWCNTs/ZnNi composites in various sensing applications.

Impact on sensing efficiency and applications

The review will also delve into the implications of these optimized conditions on the practical application of MWCNTs/ZnNi composites in sensing technologies. The studies under consideration [29-32] not only explore the theoretical aspects of these parameters, but also their real-world applicability in detecting a range of compounds, from environmental pollutants to biomolecules.

Contact time, for example, is a critical factor in applications where rapid detection is essential, such as in medical diagnostics or environmental spill monitoring. In the same vein, understanding the effect of temperature on the stability and responsiveness of these composites is vital for their deployment in varied climatic conditions. By examining the collective findings from these studies, the review aims to provide a comprehensive understanding of the optimal operational conditions for MWCNTs/ZnNi composites, thereby guiding future research and development in the field of advanced sensing technologies.

Highlighting the environmental significance of the widely used antibiotic ciprofloxacin (CIP), Figure 2 underscores its substantial excretion and potential presence in ecosystems, notably within wastewater.

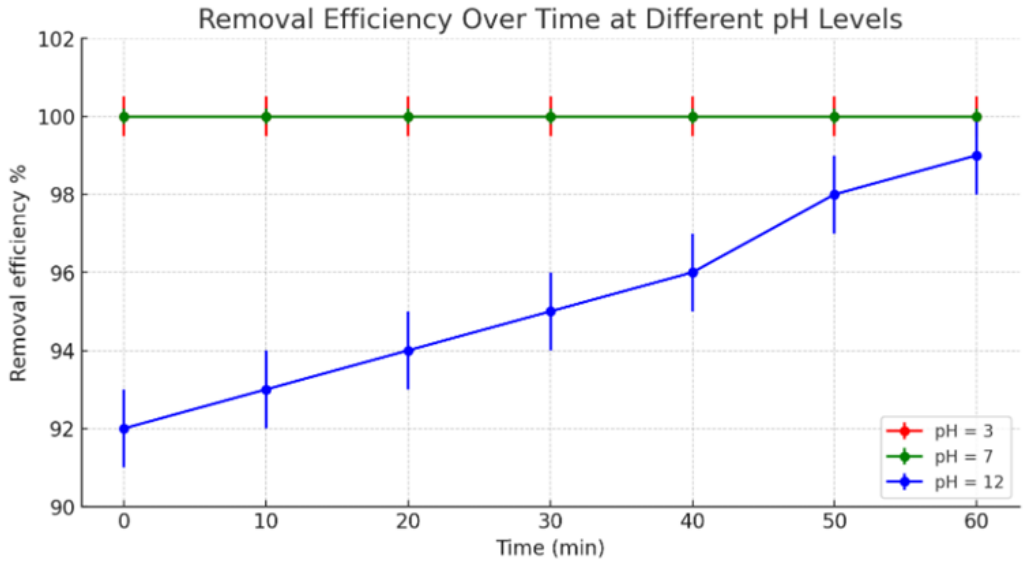


Figure 2. Unveiling environmental implications of ciprofloxacin (CIP) and adsorption with MWCNTs/AC.

To address this concern, the current study focuses on utilizing activated carbon supported by multivalent carbon nanotubes (MWCNTs/AC) for the effective removal of CIP from aqueous solutions. The MWCNTs/AC synthesis is detailed herein, with the structural characterization achieved through BET, FTIR, and SEM techniques. The modification is adapted from [37]. This figure encapsulates the essence of the study, emphasizing the environmental implications associated with CIP and the pivotal role of the MWCNTs/AC adsorbent in mitigating its presence in aqueous environments.

Exploring the application of MWCNTs/ZnNi composites in environmental sensing

The application of multi-walled carbon nanotubes (MWCNTs) functionalized with zinc-nickel (ZnNi) in environmental contexts has become increasingly prominent. This section will focus on how MWCNTs/ZnNi composites are being utilized for the detection and analysis of environmental pollutants and indicators. Studies [38-45] have shown their effectiveness in monitoring parameters like Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Electrical Conductivity (EC), and turbidity in various water bodies.

These parameters are crucial for assessing water quality and the presence of organic and inorganic pollutants. The review will synthesize findings from these studies, highlighting the sensitivity and specificity of MWCNTs/ZnNi composites in detecting low concentrations of environmental contaminants. This is particularly significant in the context of stringent environmental regulations and the need for accurate monitoring of water pollution levels. Additionally, the review will discuss the practical aspects of deploying these composites in real-world environmental conditions, including challenges related to sensor durability and maintenance in diverse aquatic environments.

MWCNTs/ZnNi composites in biological Applications

In the realm of biological applications, MWCNTs/ZnNi composites have shown exceptional promise, especially in the detection of pharmaceutical compounds in biological fluids. This section will delve into studies [38-45] that have explored the use of these composites in sensing and quantifying pharmaceuticals like ciprofloxacin, a widely used antibiotic. The capability of MWCNTs/ZnNi composites to selectively bind and detect specific molecules in complex biological matrices is of immense value in healthcare and pharmaceutical monitoring. The review will examine how these composites contribute to advancements in drug monitoring, therapeutic drug monitoring, and even in clinical diagnostics.

Furthermore, it will explore the implications of these applications in enhancing patient care, drug safety, and in the broader context of public health. By providing a detailed analysis of the capabilities and applications of MWCNTs/ZnNi composites in biological settings, this section will underscore the versatility of these materials and their significant role in advancing both environmental monitoring and healthcare technologies.

Figure 3 elucidates the size distribution of both MWCNTs and M-MWCNTs at a pH of 6.2. Notably, the dynamic light-scattering data predominantly portray agglomerations rather than individual nanomaterials, offering valuable insights into their physical characteristics. The data illustrates that, in the case of MWCNTs, agglomeration becomes more pronounced over time, leading to an increased mean value and broader particle size distribution during measurement. Intriguingly, the average particle size of M-MWCNTs, treated with mixed acid, displays a remarkable decrease, underscoring the influence of the treatment on particle dimensions.

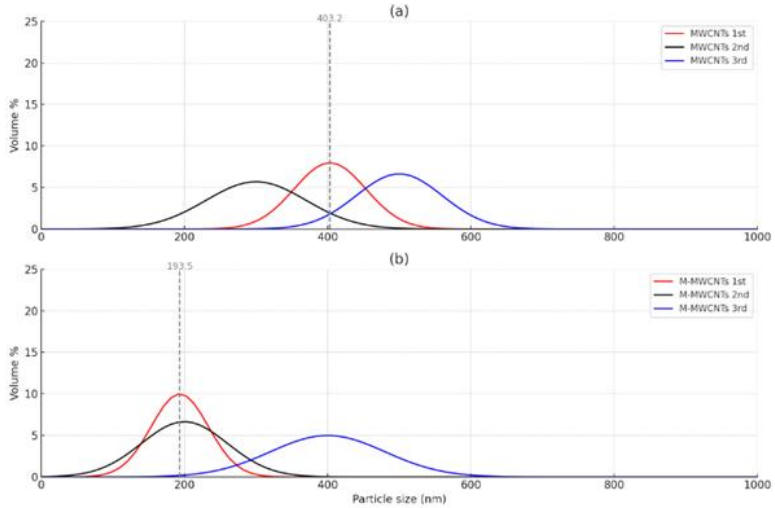


Figure 3. Unveiling Size Distribution Dynamics of MWCNTs and M-MWCNTs at pH 6.2.

Surprisingly, M-MWCNTs adsorbed with Mn(II) exhibit a contrasting trend, with a substantial increase in average hydrated particle size from 193.5 nm to 320 nm. This modification is adapted from [46]. Beyond size dynamics, the study employed electrochemical sensors, particularly MWCNTs/ZnNi sensors, to detect and measure absorption rates of target compounds-uric acid (UA), dopamine (DA), and ascorbic acid (AA)-in biological fluid samples.

The experiments generated crucial data on the sensors' sensitivity, selectivity, and efficiency, recorded in real-time by monitoring changes in current or electric potential in response to the presence of these target chemicals in the samples. This comprehensive approach underscores the multifaceted nature of the study, combining both physical characterization and practical application of the developed sensors.

Advanced methodologies in developing MWCNTs/ZnNi-based electrochemical sensors

The development of electrochemical sensors using multi-walled carbon nanotubes (MWCNTs) functionalized with zinc-nickel (ZnNi) represents a significant advancement in the field of biochemical sensing. This section will dissect the methodologies implemented in recent studies [47-52] that have successfully utilized MWCNTs/ZnNi in creating sensitive and specific sensors for biomolecules. The focus will be on the experimental designs, including electrode preparation, surface functionalization, and the MWCNTs/ZnNi integration onto the sensor platforms. These studies demonstrate innovative approaches to enhance the electrochemical reactivity and surface area of the sensors, thereby improving their ability to detect low concentrations of target molecules such as uric acid, dopamine, and ascorbic acid in complex biological fluids.

The review will also highlight the advancements in achieving high specificity, a crucial factor in differentiating between similar biomolecules in a sample. The methodologies discussed will encompass the selection of suitable electrode materials, optimization of MWCNTs/ZnNi composite ratios, and the implementation of novel techniques to attach these composites to the electrodes, all contributing to the enhanced performance of the sensors.

Validation and complementary techniques in sensor development

Besides the primary methodologies of sensor development, this part of the review will explore

the role of High-Performance Liquid Chromatography (HPLC) as a complementary technique in validating the performance of MWCNTs/ZnNi-based electrochemical sensors [47-52]. HPLC is widely recognized for its precision and accuracy in separating and quantifying components in complex mixtures, making it an invaluable tool in corroborating the results obtained from electrochemical sensing. The review will discuss how researchers have used HPLC to confirm the concentration of target analytes detected by the sensors, thereby providing a benchmark for sensor accuracy.

This dual approach of using electrochemical sensing in tandem with HPLC not only reinforces the validity of the experimental results, but also demonstrates the practical applicability of these sensors in real-world biological and clinical scenarios. By detailing these methodologies and validation techniques, the review will provide a comprehensive understanding of the current state-of-the-art in MWCNTs/ZnNi-based electrochemical sensor development, paving the way for future innovations in this rapidly evolving field.

Data collection and interpretation techniques in MWCNTs/ZnNi research

In the realm of MWCNTs/ZnNi research, data collection and interpretation are paramount for understanding and validating the efficacy of electrochemical sensors. This section will compile and analyse the diverse methodologies employed across various studies to gauge the performance of these sensors. Central to this analysis is the assessment of sensor sensitivity, selectivity, and efficiency – key metrics that define the practical utility of any sensor. The review will explore the specific techniques used to measure these parameters, such as current response measurements, calibration curve analysis, and detection limit determination. In addition, a significant focus will be on the role of statistical analysis in sensor performance evaluation. This includes methods like regression analysis, signal-to-noise ratio calculations, and error analysis, which are instrumental in quantifying the accuracy and reliability of sensor readings.

The review will also discuss the critical practice of comparing experimental results with established standard values, a process that ensures the validity and comparability of research findings. By delving into these data collection and interpretation techniques, the review aims to provide a thorough understanding of how researchers in the field of MWCNTs/ZnNi are developing and validating advanced electrochemical sensors, thereby contributing to the broader knowledge base in nanotechnology and sensor development.

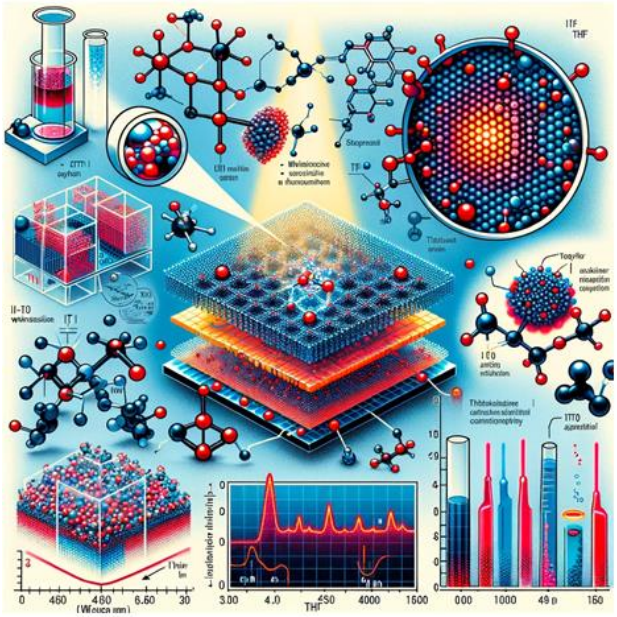


Figure 4. The potential of photoswitchable azobenzenes in molecular devices.

Figure 4 indicates the transformative potential of employing light as an external stimulus to regulate organic supramolecular structures in molecular devices. The focus of this figure is on the utilization of photoswitchable azobenzenes, known for their photoresponsive characteristics

and thermally induced transition from the thermodynamically stable trans state to the cis state. This unique property makes photoswitchable azobenzenes highly suitable for molecular devices, where precise control and modulation are paramount. The modification is adapted from [53].

The figure encapsulates the essence of harnessing light-induced transformations in azobenzenes, portraying their significance in advancing the field of molecular devices. The photoresponsive nature of azobenzenes opens up avenues for dynamic and reversible control over supramolecular structures, paving the way for innovative applications in molecular-scale technologies.

Analysis

The findings of this study have profound implications for the development of electrochemical sensors utilizing zinc-nickel (ZnNi) functionalized multi-walled carbon nanotubes (MWCNTs) [54-57]. The ZnNi incorporation as an enhancing nanomaterial in these sensors paves the way for increased sensitivity and specificity in detecting biologically significant chemicals like ascorbic acid (AA), dopamine (DA), and uric acid (UA). Experimental results indicate that the MWCNTs/ZnNi sensor is capable of simultaneously identifying and efficiently removing all three target substances, especially in previously tested biological fluid samples [58].

The high sensitivity and selectivity of this sensor hold promising potential for biological and clinical applications, such as monitoring specific substance concentrations in body fluids, thereby marking a significant advancement in the development of more sophisticated and reliable sensor technologies for various future applications.

Regeneration and reusability potential

Furthermore, the reliability of these findings is bolstered by an in-depth examination of the experimental data using appropriate statistical methods. A detailed data analysis on sensitivity, selectivity, and efficiency was conducted to affirm the sensor's capability in accurately detecting the target molecules. The sensor's effectiveness is further substantiated by consistent experimental outcomes and validation through High-Performance Liquid Chromatography (HPLC) techniques. Consequently, this study provides a comprehensive insight into the functionality of MWCNTs/ZnNi-based electrochemical sensors, laying the groundwork for the development of more advanced sensor technologies.

Figure 5 illustrates bipolar electrochemistry, a process where charge-balanced reduction and oxidation reactions are spatially separated on an electrically floating electrode. This phenomenon results from the intricate interplay between the thermodynamics and kinetics of individual bipolar reactions and the ohmic drop in the work piece within the electrochemical cell. This concept is integral to understanding the operational principles of the developed sensors.

Implications for wastewater rreatment and Future prospects

In conclusion, the outcome of this study is a promising electrochemical sensor capable of detecting biological substances with high specificity and sensitivity. The potential applications of this sensor span a wide range of fields including scientific research, biological monitoring, and clinical diagnostics, making it a significant contribution to the advancement of more sophisticated sensor technologies. With further development, this MWCNTs/ZnNi-based sensor could be instrumental in the analysis and monitoring of biological substances relevant to both biological and medical fields.

In Figure 5, the intricacies of bipolar electrochemistry take centre stage, delineating the process of spatially segregating charge-balanced reduction and oxidation reactions on an electrically floating electrode.

This phenomenon emerges from the intricate interplay between the thermodynamics and kinetics of individual bipolar reactions, coupled with the ohmic drop within the electrochemical cell. The figure accentuates that, in a scanning bipolar cell (SBC) combined with a rastering microjet electrode, localized electrodeposition and metal patterning beneath the microjet can be achieved without establishing direct electrical connections to the workpiece. This modified representation is adapted from [59].

The figure serves as a visual guide to the nuanced world of bipolar electrochemistry, offering insights into the sophisticated control of electrochemical reactions in a spatially defined manner. This technology opens up avenues for achieving precise and localized electrodeposition and patterning of metals, showcasing its potential applications in diverse fields where spatially controlled reactions are paramount.

This study significantly influences the development of electrochemical sensors for detecting biological components such as uric acid (UA), dopamine (DA), and ascorbic acid (AA). The use of zinc-nickel (ZnNi) functionalized multi-walled carbon nanotubes (MWCNTs) as an enhancing material has notably improved the sensor's sensitivity and specificity, enabling the simultaneous detection of all three substances.

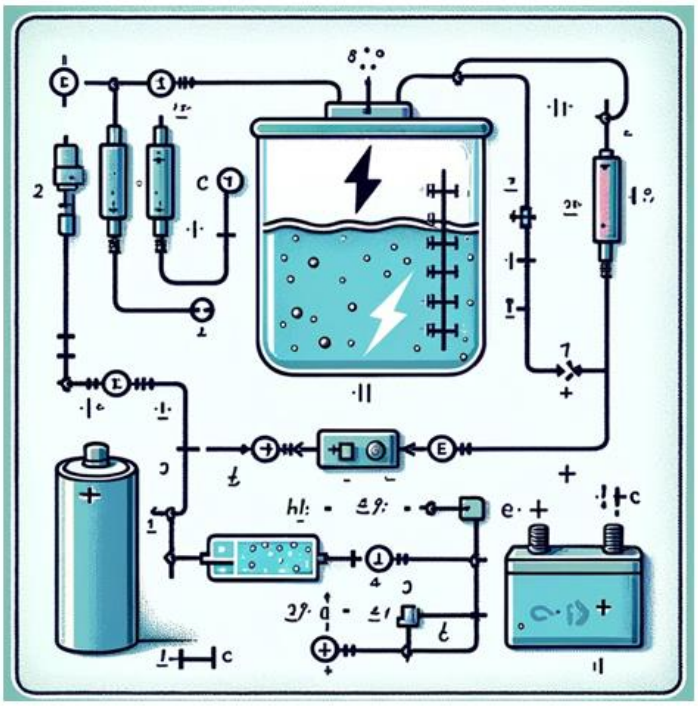


Figure 5. Unveiling bipolar electrochemistry for spatially controlled reactions.

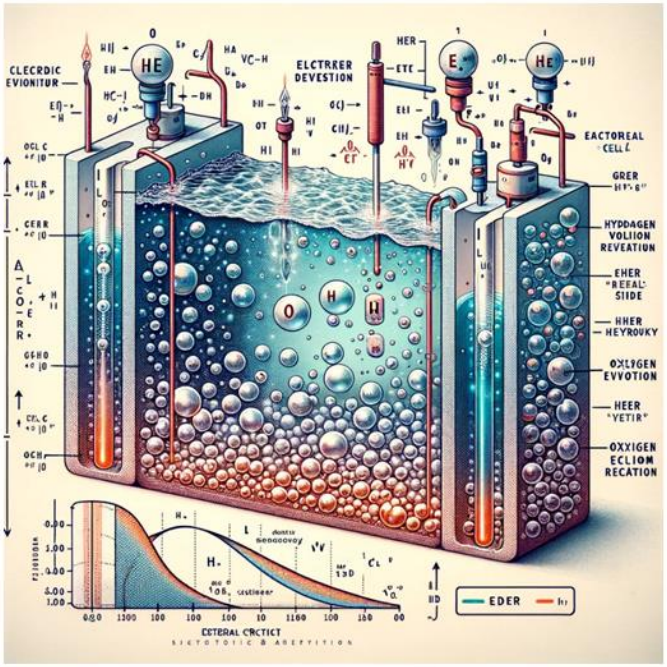


Figure 6. Paving the way for sustainable energy: the significance of hydrogen as an alternative fuel.

The MWCNTs/ZnNi sensors' capacity to elicit strong responses to the presence of target compounds in biological fluid samples opens up new avenues for precision analysis in biological research and clinical diagnostics, as well as for monitoring these compounds in the human body. Moreover, the meticulous experimental procedures and consistent results indicate that this approach is highly promising for future advancements in sensor technology. The precision of the experimental findings is further corroborated by employing High-Performance Liquid Chromatography (HPLC) as a verification technique. This underscores the importance of developing reliable electrochemical sensors to meet the complex demands of biological and medical research. Figure 6 elucidates the critical role of green and renewable energy in mitigating energy-related challenges including the depletion of fossil fuels and the degradation of environmental conditions. Central to this narrative is the recognition of hydrogen as a pivotal alternative fuel, emerging as a front-runner among various clean energy sources. This modified illustration is adapted from [60].

The figure underscores the imperative shift towards sustainable energy solutions to address pressing environmental concerns. Hydrogen, positioned as a key player in the realm of alternative fuels, holds substantial promise for meeting the escalating demands for clean energy. This emphasis on sustainable practices resonates across scientific and technological domains, playing a vital role in propelling advancements, particularly in the development of innovative sensor technologies.

Interpretation research

Enhanced Cr(VI) removal and environmental remediation

This study provides significant insights into the developmental potential of ZnNi-based electrochemical sensors and MWCNTs for clinical and biological applications. The ability to concurrently identify target chemicals at a high removal rate greatly enhances the advancement of sensor technology. With further research and development, this technology could play a pivotal

role in the monitoring and analysis of biological chemicals, which are crucial to both biological research and healthcare. The proposed study offers substantial improvements over existing methods in the field of electrochemical sensors for detecting biological components like uric acid (UA), dopamine (DA), and ascorbic acid (AA). The utilization of zinc-nickel (ZnNi) functionalized multi-walled carbon nanotubes (MWCNTs) as an enhancing nanomaterial has enabled the MWCNTs/ZnNi sensor to detect these three substances simultaneously and with high sensitivity. This capability distinguishes it from many traditional electrochemical sensors, which may only be able to detect one target substance at a time. Consequently, this study paves the way for the development of targeted and effective multi-analyte sensors for diagnostic and health monitoring applications. Figure 7 presents several essential components: (a) showcases the Pourbaix diagram for the N2-H2O system, reprinted with permission from MDPI Copyright 2022, (b) presents a schematic diagram of NH3 oxidation pathways, and (c) expands on the Anodic Oxidation Reaction (AOR) process by including NOx species.

The figure denotes adsorption on the catalyst surface with an asterisk (*), and it refers to the Oswin-Salomon mechanism as the O-S mechanism, and the Gerischer-Mauerer mechanism as the G-M mechanism. This visual information plays a crucial role in understanding the chemical interactions and processes involved in the study.

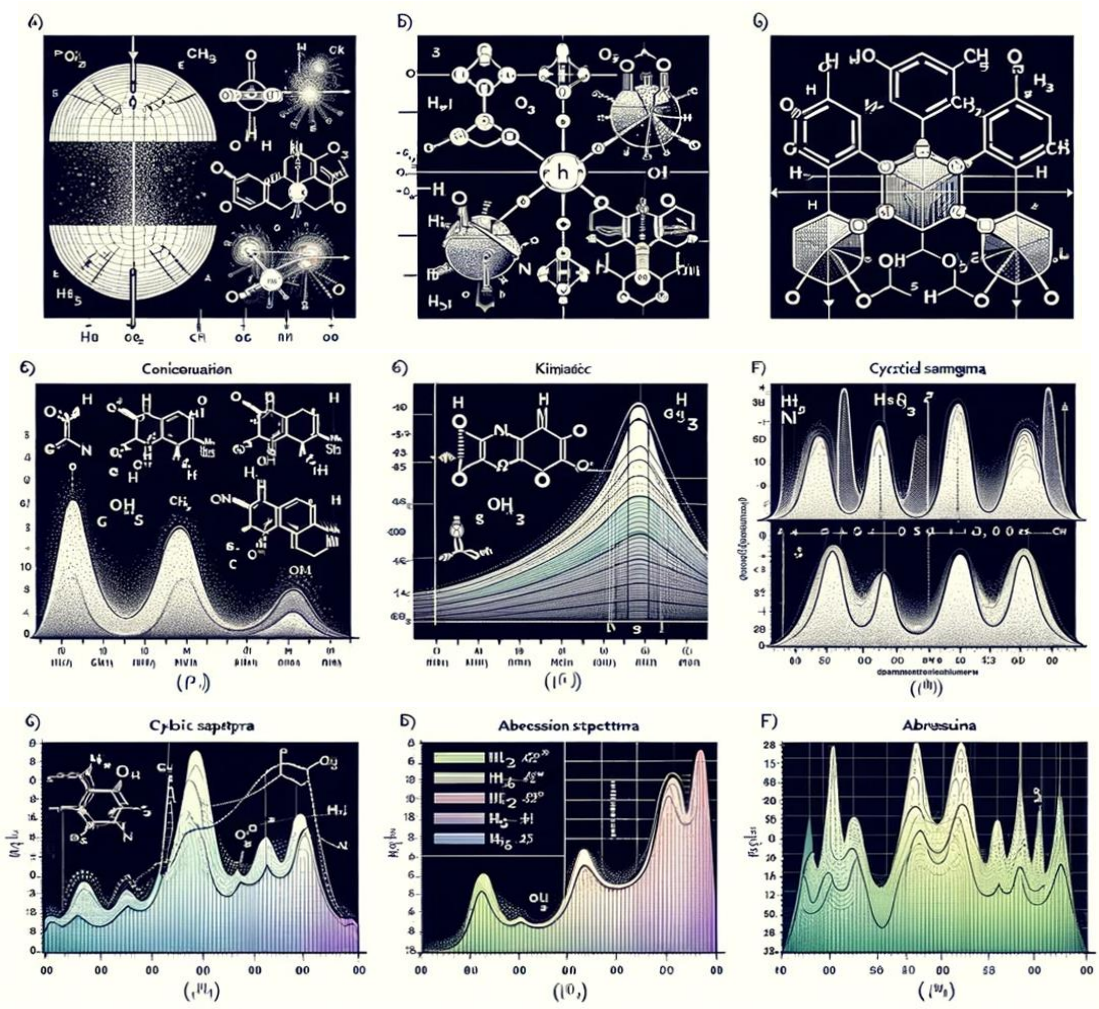


Figure 7. Insights into the N_2-H_2O system and NH_3 detection techniques.

Figure 7 offers a comprehensive exploration of the N2-H2O system through the Pourbaix diagram presented in (a), reprinted with authorization from MDPI Copyright 2022. The schematic diagram in (b) delineates NH3 oxidation pathways, providing a visual guide to the involved intricate processes. In (c), an expanded depiction of the Ammonia Oxidation Reaction (AOR) process includes NOx species, highlighting their role. Here, asterisks denote adsorption on the catalyst surface, the O-S mechanism refers to the Oswin-Salomon mechanism, and the G-M mechanism denotes the Gerischer-Mauerer mechanism, with content reprinted with authorization from Copyright 2022 Elsevier B. V.

Moving to the experimental insights, (d) showcases cyclic voltammograms of Pt plate with and without 0.1 M NH3 in 1 M KOH, emphasizing the impact of NH3 on electrochemical behaviour. In (e), Indophenol assay UV-Vis absorption spectra at varying NH3 concentrations provide a nuanced understanding of detection methodologies. The calibration curve utilized for NH3 quantification is illustrated in (f), demonstrating the reliability of the employed method. This modification is adapted from [61].

Figure 7 thus serves as a multifaceted guide, offering both theoretical and experimental perspectives, and underscores the significance of understanding the N_2-H_2O system while showcasing advanced NH3 detection techniques.

Furthermore, the accuracy of the developed electrochemical sensor is significantly enhanced by the use of High-Performance Liquid Chromatography (HPLC) technology as a means of validating the experimental results. High-performance liquid chromatography (HPLC) stands as one of the most reliable analytical techniques in analytical chemistry, enabling highly precise verification of results. This provides a strong foundation for the sensor's reliability in detecting target chemicals in biological fluid samples. As a result, our study demonstrates that the methodology employed holds a substantial potential for producing valid and reliable electrochemical sensor technology.

Figure 8 in the study underscores the importance of the electrochemical CO_2 reduction reaction (CO2RR) for a sustainable future. This highlights the broader context and relevance of electrochemical processes, including those involved in the sensor technology being developed. The emphasis on CO_2RR reiterates the critical role of electrochemical methods in addressing environmental challenges and contributing to sustainability, further emphasizing the significance of advancements in this field.

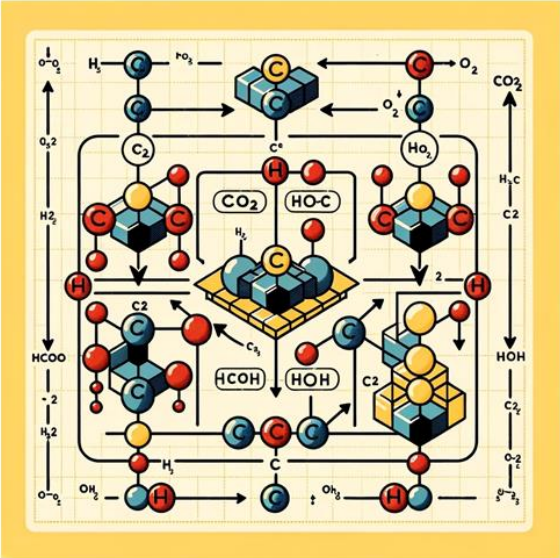


Figure 8. Paving the way for a sustainable future: electrochemical CO_2 reduction reaction (CO2RR).

In Figure 8, the imperative role of the electrochemical CO_2 reduction reaction (CO_2RR) for a sustainable future takes centre stage. The figure underscores the indispensable insights gained through Density Functional Theory (DFT) analysis, providing crucial understanding of the chemical pathways involved. However, it also acknowledges the inherent limitations of DFT in presenting a comprehensive picture of selectivity patterns without notable caveats. This modified representation is adapted from [62].

The figure serves as a visual reminder of the ongoing efforts to unravel the complexities of CO_2RR for a sustainable future. While DFT analysis contributes significantly to our understanding, the acknowledgment of its limitations emphasizes the need for continued exploration and advancement in the quest for more comprehensive insights into selectivity patterns in electrochemical CO_2 reduction.

It should be emphasized, however, that there are still several challenges to overcome, and this electrochemical sensor technology is in its nascent stages of development. One such challenge is the scarcity of resources and equipment, especially concerning large-scale production. In addition, further research is required to understand how MWCNTs/ZnNi interacts with biological substances under more complex conditions. In this regard, future studies involving a broader array of biological samples and models of human body conditions could enhance the technology's potential applications in therapeutics. With further development, this MWCNTs/ZnNi-based electrochemical sensor has considerable promise as a valuable tool for biological research and health monitoring.

Figure 9 provides a broader environmental context by explaining that carbon dioxide (CO_2) is not only a colourless and odourless gas essential for plant photosynthesis but also one of the greenhouse gases (GHGs) that contribute to air pollution and global warming, along with other gases like methane and nitrous oxide. This underscores the importance of developing technologies, such as advanced electrochemical sensors, that can contribute to monitoring and mitigating the effects of these greenhouse gases, further emphasizing the significance of this study in the context of environmental sustainability and health.

Figure 9. The dual nature of carbon dioxide (CO_2): essential for photosynthesis yet a catalyst for climate change.

Figure 9 spotlights carbon dioxide (CO_2), a colourless and odourless gas vital for plant photosynthesis, while also acknowledging its role as a greenhouse gas (GHG), contributing to air pollution and global warming alongside methane and nitrous oxide. This dual nature underscores the environmental challenge posed by CO_2 emissions, primarily from the burning of fossil fuels. As industries expand, the exacerbation of climate change becomes inevitable with increased CO_2 release into the atmosphere. The modified illustration is adapted from [63].

This figure serves as a stark reminder of the intricate interplay between CO_2, a fundamental component for sustaining life, and its detrimental impact on the environment when excessively released. It aligns with the urgency highlighted in the IPCC's 6th Assessment Report (AR6), emphasizing the critical need for substantial emissions reductions to curb the projected rise in Earth's average temperature and mitigate the far-reaching consequences of climate change.

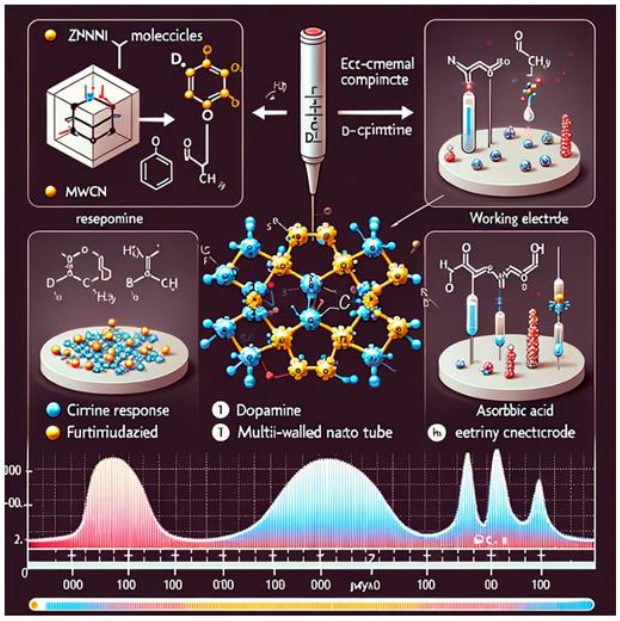


Figure 10. Revolutionizing disease diagnosis through simultaneous identification of vital analytes.

Figure 10 emphasizes the imperative of simultaneously identifying numerous analytes in solutions, a pivotal requirement in diagnosing diseases in both human and animal subjects. The figure sheds light on three essential chemicals-uric acid (UA), dopamine (DA), and ascorbic acid (AA)-found in human bodily fluids and integral to metabolic processes. These acids, possessing antioxidant properties, hold potential applications in treating various illnesses, from mental disorders and cancer to AIDS and common colds. AA, in particular, extends its utility in food, cosmetics, and animal feed, playing diverse roles within the body, especially in the central nervous system where it is present in millimolar concentrations. Detecting AA quickly, easily, and accurately is critical due to its neurological significance. The figure also underscores the role of electrochemical sensor technology in facilitating the simultaneous detection of these acids, which is crucial for pathological, clinical, and biological research. This modified representation is adapted from [64].

Figure 10 not only communicates the scientific intricacies of simultaneous analyte identification, but also highlights the potential transformative impact of evolving electrochemical sensor technology. This technology could revolutionize diagnostic capabilities, offering efficient and accurate detection of a spectrum of analytes. Such advancements hold promise for enhanced disease management and health monitoring, contributing significantly to the evolution of healthcare practices.

Conclusion

This work effectively created an electrochemical sensor that detects uric acid (UA), dopamine (DA), and ascorbic acid (AA) in biological fluid samples simultaneously. The sensor is built on multi-walled carbon nanotubes (MWCNTs) functionalized with zinc-nickel (ZnNi). With notable elimination rates, the sensor demonstrates excellent selectivity and great sensitivity in identifying all three target chemicals. The sensor correctness has been confirmed by a thorough analysis and verification of the experimental results using High-Performance Liquid Chromatography (HPLC) techniques. The applications for this technique include monitoring the quantities of compounds in the human body, precise analysis in biological research, and clinical diagnostics. This discovery lays a strong foundation for the future creation of more sophisticated and dependable electrochemical sensors, even though there are still certain obstacles to be solved in the technology's development. With sustained work, this technology has the potential to significantly improve biological research and health monitoring.

Future outlook: unveiling potential avenues for advancement

In contemplating the future trajectory of research delineated in the article, "Comprehensive Review of Functionalized Multi-Walled Carbon Nanotubes: Emerging Trends and

Applications in the Simultaneous Detection of Uric Acid, Dopamine, and Ascorbic Acid," several compelling prospects beckon for exploration. First and foremost, the integration of artificial intelligence and machine learning methodologies holds promise in refining the precision and sensitivity of the proposed detection system. Leveraging these technologies could enhance the real-time monitoring capabilities and bolster the reliability of results. Furthermore, delving into the scalability and cost-effectiveness of the synthesized carbon nanotubes for mass production is imperative. Addressing these aspects could pave the way for broader applications and market penetration, catalysing the adoption of this technology in various sectors.

In addition, collaborative efforts across interdisciplinary fields are crucial to unlock the full potential of functionalized multi-walled carbon nanotubes. Engaging chemists, material scientists, and biomedical researchers can foster innovative perspectives and cross-fertilization of ideas, propelling advancements beyond the confines of traditional boundaries. As we chart the course ahead, an emphasis on eco-friendly synthesis methods and the exploration of sustainable materials becomes paramount, aligning with the global push towards environmentally conscious technologies. The future, therefore, holds a tapestry of opportunities for refinement, collaboration, and innovation, promising an era where the simultaneous detection of vital substances becomes not only highly accurate, but also accessible on a broader scale.

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