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Advances in Applied Chemistry: From Electrochemical Biosensors and Gas Sensing to Sustainable Remediation and Nanofluid Engineering

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Abstract

Applied chemistry acts as a crucial link between fundamental molecular science and practical technological innovation. It transforms theoretical knowledge into real-world applications that address challenges in healthcare, environment, and industry. This review highlights recent advancements in electrochemical biosensors, which offer rapid and sensitive diagnostic capabilities, along with modern gas detection technologies designed for improved safety and environmental monitoring. Significant attention is given to environmental remediation, particularly the use of activated carbon for efficient removal of pollutants from air and water.

In addition, the integration of data science—especially big data analytics and cognitive computing—is revolutionizing drug discovery and enabling more precise personalized medicine. These tools enhance predictive modeling, reduce development timelines, and improve therapeutic outcomes. The review also discusses the thermophysical properties of nanofluids, which demonstrate improved heat transfer efficiency and have potential applications in energy systems and industrial processes. Lastly, the kinetics of heavy metal adsorption using biomass-derived materials is examined, emphasizing sustainable and cost-effective approaches to pollution control.

Together, these developments underscore the interdisciplinary nature of applied chemistry and its vital role in shaping a more sustainable and technologically advanced future.

Introduction

Applied chemistry has emerged as a dynamic and interdisciplinary field, driving innovation across healthcare, environmental science, and advanced materials engineering. In recent years, significant progress has been made in translating fundamental chemical principles into practical technologies that address real-world challenges. Among these developments, electrochemical biosensors and gas sensing systems have gained considerable attention due to their high sensitivity, rapid response, and potential for miniaturization. These technologies are revolutionizing diagnostics, environmental monitoring, and industrial safety by enabling precise detection of biological markers and hazardous gases at trace levels. Simultaneously, the growing concern over environmental pollution has accelerated research in sustainable remediation strategies. Applied chemistry plays a crucial role in designing eco-friendly approaches for the removal of contaminants from air, water, and soil. Techniques such as photocatalysis, adsorption using advanced materials, and green chemical processes are being developed to ensure effective and energy-efficient pollutant degradation. These methods not only minimize environmental impact but also align with global sustainability goals.[1]

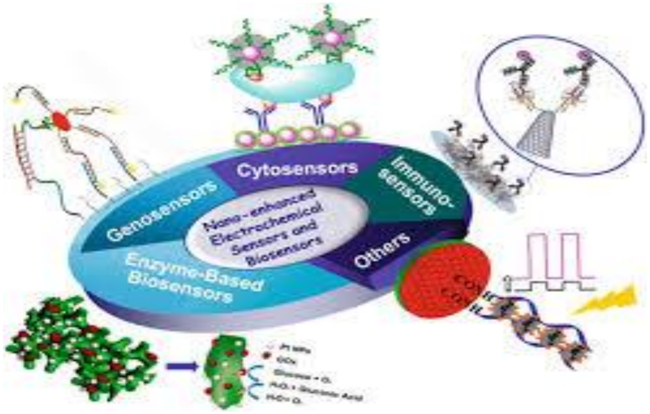

Fig 1: Figure: Schematic representation of different types of biosensors, including genosensors, cytosensors, immunosensors, enzyme-based biosensors, and other non-enzymatic electrochemical biosensing platforms.

Another promising area is nanofluid engineering, which involves the dispersion of nanoparticles in base fluids to enhance thermal and transport properties. Nanofluids have shown remarkable potential in applications such as heat transfer systems, energy storage, and cooling technologies shown in fig 1. Their tunable properties allow for improved efficiency in industrial processes and renewable energy systems. Together, these advancements highlight the transformative impact of applied chemistry in bridging the gap between scientific discovery and technological application. By integrating innovations in sensing technologies, sustainable remediation, and nanofluid engineering, researchers are paving the way for smarter, cleaner, and more efficient solutions to contemporary global challenges.[2]

1. Electrochemical Biosensors: The Frontier of Diagnostics

An electrochemical biosensor is a compact analytical device designed to detect and measure specific substances by combining biological recognition with electrochemical signal conversion. It consists of a biological element—such as enzymes, antibodies, nucleic acids, or cells—that selectively interacts with a target analyte, and an electrochemical transducer that converts this interaction into a measurable electrical signal. The biological component ensures high specificity by recognizing only the intended compound, while the transducer translates the biochemical reaction into signals such as current, voltage, or impedance. These biosensors operate based on electrochemical principles like amperometry, potentiometry, or conductometry, depending on the nature of the signal generated. When the target analyte binds to or reacts with the biological receptor, it produces or alters an electrical response proportional to the analyte concentration. This allows for accurate quantitative or semi-quantitative analysis.[3]

Electrochemical biosensors are widely used due to their sensitivity, rapid response, portability, and cost-effectiveness. They play a crucial role in medical diagnostics (such as glucose monitoring), environmental monitoring, food quality control, and pharmaceutical analysis. Their ability to provide real-time and on-site detection makes them valuable tools in both clinical and industrial applications.

1.1 Single-Use Biosensors and Performance Criteria

Single-use (disposable) biosensors have revolutionized point-of-care testing. Their utility is governed by rigorous **performance criteria**:

- **Selectivity:** The ability to distinguish the analyte in a complex matrix.
- **Sensitivity:** The slope of the calibration curve.
- **Stability:** Resistance to ambient degradation.
- **Calibration Characteristics:** Defining the linear range and the Limit of Detection (LOD).[4]

1.2 Direct Electron Transfer (eT) and Surface Modification

Achieving **direct electron transfer (eT)** between the redox center of a protein and an electrode surface is a "holy grail" in biosensing. This is often achieved via:

- **Gold Colloids:** Providing high surface area and biocompatibility.

- **Self-Assembled Monolayers (SAMs):** Organizing molecules like alkanethiols to create a controlled interface for analytes like **hydrogen peroxide**.[5]

2. Data Science in Chemical Discovery

The integration of **Big Data** and **Cognitive Computing** has shifted the paradigm in **drug discovery**, **genetics**, and **personalized medicine**.

Technology	**Application in Applied Chemistry**
Big Data	Processing high-throughput screening results for molecular libraries.
Cognitive Computing	Simulating protein-ligand interactions to predict efficacy.
Data Science	Identifying genetic markers for tailored pharmaceutical dosages.

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Aptamer affinity chromatography and **directed ligand evolution** utilize these computational tools to refine the selection of high-affinity binders for diagnostic and therapeutic targets.[6]

3. Gas Sensing Mechanisms and Alcohol Detection

Gas sensors operate on the fundamental principle that certain materials undergo measurable changes in their electrical properties when exposed to specific gases. Most commonly, these sensors use metal oxide semiconductors such as tin oxide or zinc oxide as the sensing element. When the sensor is exposed to air, oxygen molecules adsorb onto the surface of the material and capture free electrons from its conduction band, forming negatively charged oxygen ions. This process increases the resistance of the sensor.[7]

When a target gas—such as carbon monoxide, methane, or hydrogen—is introduced, it reacts with the adsorbed oxygen ions. This reaction releases the trapped electrons back into the conduction band, thereby decreasing the resistance of the material. The magnitude of this change in electrical conductivity is proportional to the concentration of the gas present. By measuring this variation, the sensor can detect and quantify the target gas. These sensors are widely used due to their high sensitivity, relatively low cost, and simple design. However, they may have limitations such as cross-sensitivity to multiple gases and dependence on environmental factors like temperature and humidity, which can affect their accuracy and stability.[8]

3.1 Catalytic Oxidation

Alcohol detection in many sensors is primarily based on a catalytic oxidation mechanism occurring at the surface of the sensing material. Typically, these sensors operate at elevated temperatures, which facilitate the interaction between alcohol molecules and adsorbed oxygen species present on the sensor surface, such as O^-, O_2^-, or O^{2-}. In clean air conditions, oxygen molecules are adsorbed onto the sensor surface and capture free electrons from the conduction band, forming negatively charged oxygen ions. This process creates a depletion layer and increases the electrical resistance of the sensor.

When alcohol vapor comes into contact with the heated sensor, it reacts with these adsorbed oxygen ions in an oxidation reaction. As a result, the trapped electrons are released back into the conduction band. This release of electrons reduces the width of the depletion layer and significantly decreases the sensor's electrical resistance. The magnitude of this resistance change is proportional to the concentration of alcohol present in the environment. Thus, by continuously monitoring the resistance variation, the sensor can effectively detect and quantify alcohol levels. This mechanism forms the basis of many semiconductor-based gas sensors widely used in breath analyzers and industrial safety applications.[9]

3.2 Material Fabrication: Magnetron Sputtering

Magnetron sputtering is a widely used physical vapor deposition (PVD) technique for fabricating thin, highly uniform films of sensing materials. In this process, a target material is bombarded with high-energy ions—typically generated from a plasma—causing atoms to be ejected from the target surface. These atoms then travel through a vacuum chamber and deposit onto a substrate, forming a thin film with controlled thickness and composition. The use of a magnetic field in magnetron sputtering enhances plasma density and improves deposition efficiency, enabling better film adhesion and uniformity compared to conventional sputtering methods.

One of the key advantages of magnetron sputtering is its ability to produce films with excellent structural and chemical stability. This is particularly important in gas sensing applications, where consistent sensor performance over time is critical. The technique allows precise control over parameters such as deposition rate, film thickness, and microstructure, which directly influence the sensitivity and selectivity of gas sensors. Additionally, it supports the deposition of a wide range of materials, including metals, metal oxides, and composite films, making it highly versatile for developing advanced sensing layers.[10]

Furthermore, magnetron sputtering ensures high reproducibility, which is essential for large-scale industrial production of gas sensors. The uniformity of the deposited films leads to consistent device performance across multiple batches, reducing variability and improving reliability. Its compatibility with various substrates, including silicon, glass, and flexible materials, further enhances its applicability in modern sensor technologies. Overall, magnetron sputtering plays a crucial role in advancing the development of high-performance, durable, and reliable gas sensing devices for industrial monitoring and environmental applications.[11]

4. Nanofluid Engineering and Stability

Nanofluids are engineered colloidal suspensions of **nanoparticles** in a base fluid. Their performance in heat transfer applications is highly dependent on their dispersion stability.

4.1 Synthesis and Dispersion

- **High-Pressure Homogenizer:** A mechanical method to break up nanoparticle clusters.
- **Zeta Potential:** A critical measure of electrokinetic potential. A zeta potential magnitude generally indicates a stable suspension due to electrostatic repulsion.[12]

5. Environmental Remediation: Adsorption Studies

Sustainable chemistry focuses on minimizing environmental impact while maximizing resource efficiency, and one promising approach is the use of agricultural waste to produce value-added materials. Residues such as peanut shells and date pits, which are often discarded or underutilized, can be converted into activated carbon through controlled thermal and chemical processes. This transformation not only reduces the burden of agricultural waste disposal but also provides an eco-friendly alternative to conventional raw materials like coal or wood.

Activated carbon derived from these biomass sources exhibits high surface area and porosity, making it highly effective for applications in water purification, air filtration, and even energy storage. By repurposing organic waste, this method supports a circular economy, where waste materials are reintegrated into productive use rather than contributing to environmental pollution. Additionally, the process typically requires lower energy input and produces fewer greenhouse gas emissions compared to traditional methods.

Overall, utilizing peanut shells and date pits for activated carbon production exemplifies how sustainable chemistry can address both waste management and material demand, offering a cost-effective and environmentally responsible solution for modern industrial and environmental challenges.[13]

5.1 Adsorption of Cr(VI) and Methylene Blue

Activated carbon is highly effective for the removal of **Cr(VI)** (hexavalent chromium) and organic dyes like **methylene blue**.[14]

5.2 Kinetic and Isotherm Modeling

The efficiency of these adsorbents is validated through mathematical models:

- **Lagergren Model (Pseudo-first order):** Describes the rate of adsorption based on adsorption capacity.
- **Adsorption Isotherms:** Langmuir and Freundlich models determine the maximum monolayer capacity and the heterogeneity of the surface.

- **Thermodynamics:** Calculating Gibbs free energy (), enthalpy (), and entropy () to determine the spontaneity of the process.[15]

Conclusion

The convergence of nanomaterials, electrochemical interfaces, and computational data science is reshaping the modern landscape of applied chemistry. These interconnected domains enable the design of highly efficient, selective, and scalable solutions to complex scientific and industrial challenges. Nanomaterials, with their tunable surface properties and high surface-area-to-volume ratios, play a crucial role in enhancing reaction kinetics, adsorption efficiency, and sensing capabilities. When integrated with electrochemical interfaces, they facilitate precise control over charge transfer processes, leading to improved performance in energy storage, biosensing, and catalysis. At the same time, computational data science accelerates discovery by enabling predictive modeling, optimization, and real-time analysis of chemical systems. Techniques such as aptamer affinity chromatography demonstrate remarkable specificity in molecular separation, supporting advancements in biotechnology and diagnostics. Similarly, nanofluids offer enhanced thermal conductivity, making them valuable in industrial heat transfer applications. Environmental applications, particularly the adsorption of toxic Cr(VI) ions, highlight the critical role of these innovations in addressing pollution and sustainability concerns. Together, these technologies not only improve efficiency and functionality but also contribute to the development of greener, more sustainable chemical processes, aligning scientific progress with global environmental priorities.

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