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Efficiency of Electrochemical Sensors Based on Nanomaterials

D.B. Konarbay[1*], Y. Bakytkarim[1], Zh.S. Mukataeva[1], N.A. Shadin[1], Zh.M. Assirbayeva[1], Ye. Tileuberdi[1], L.A. Zhusupova[2]

[1]Abai Kazakh National Pedagogical University, 13, Dostyk ave., Almaty, Kazakhstan
[2]Korkyt Ata Kyzylorda University, 29A, Aiteke bi, Kyzylorda, Kazakhstan

ABSTRACT

Electrochemical sensors are one of the most important technologies in modern analytical chemistry and enable high-precision analyses. In this study, the efficiency of electrochemical sensors based on nanomaterials, as well as their sensitivity, selectivity, detection limit, and stability, were analyzed. The study investigated the analytical capabilities of sensors based on carbon nanotubes (CNTs), graphene, metal nanoparticles (Au, Pt, Ag), metal oxides (ZnO, CuO, Fe_3O_4), and metal-organic frameworks (MOFs). Nanomaterials play an important role in improving the sensitivity of electrochemical sensors. The large surface area and high conductivity of carbon nanotubes improve the adsorption of analytes on the electrode surface, thus enabling the detection of their low concentrations. The two-dimensional structure of graphene amplifies electrochemical signals and helps to shorten the analysis time. Metal nanoparticles and metal oxides increase the reaction rate and activate redox processes on the electrode surface. The high porosity of MOF structures enables the effective detection of heavy metal ions and organic pollutants. Research results show that the composition of the nanomaterials used in sensor devices significantly affects their sensitivity and stability. Their chemical and structural modification improves the long-term performance of the sensors. In the future, the development of multicomponent hybrid sensors and the optimization of their industrial applications are particularly relevant.

Keywords: electrochemical sensors, nanomaterials, carbon nanotubes, graphene, metal nanoparticles, metal oxides, metal-organic frameworks, analytical reliability

1. Introduction

Electrochemical sensors are devices that can detect very low concentrations of chemical substances. In recent years, the use of nanomaterials to increase the sensitivity and selectivity of electrochemical sensors has become widespread. Due to their large specific surface area, unique electronic properties and catalytic activity, nanomaterials amplify analytical signals and accelerate the kinetics of chemical reactions [1].

Electrochemical sensors convert a chemical reaction into an electrical signal, enabling the measurement of the presence and concentration of substances [2]. They are widely used for environmental monitoring, food safety control, and medical diagnostics due to their high sensitivity and rapid response [3]. When an analyte interacts with the electrode, an oxidation-reduction reaction occurs that generates a signal proportional to its concentration.

With the growth of automation and urbanization, the demand for compact and reliable sensors has increased. Initially, sensors based on MEMS and monocrystalline silicon demonstrated high sensitivity and energy efficiency [4, 5], but they have limitations due to high cost and fragility [6]. As an alternative, flexible sensors have been developed using polymers [7, 8] and nanomaterials [9, 10], expanding their applications in wearable and consumer devices.

The emergence and rapid development of nanotechnology in the scientific and technological process is a new step in the development of electrochemical sensors. Nanomaterials are materials with dimensions in the nanoscale (approximately 1–100 nm) and unique physicochemical properties. Nanoscale properties are characterized by their high surface energy, large specific surface area

**Ответственный автор*
E-mail: konarbay98@bk.ru

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and quantum confinement effect [11]. Thus, nanomaterials make a huge contribution to various industries, including sensor technology (Fig. 1).

Among nanomaterials, the most common are carbon (carbon) nanostructures, metal and non-metal nanoparticles, bimetallic or hybrid nanostructures. They perform catalytic, adsorption and electron-carrying functions in electrochemical analysis mechanisms. For example, carbon-based materials such as carbon nanotubes (CNTs) or graphene have high electrical conductivity, are chemically inert and have a wide thermodynamic stability. Meanwhile, metal nanoparticles (gold, platinum, silver, etc.) enhance the sensitivity of sensors and allow for lower detection limits [12].

This article discusses the theoretical foundations and development paths of these systems, as well as their current results. The aim of the article is to comprehensively review electrochemical sensors based on nanomaterials, and to demonstrate their main properties, achievements and future prospects.

2. Literature review

The application of nanomaterials in electrochemical sensors has been extensively studied in recent years. One of the primary advantages of such sensors is their high sensitivity, low detection limits, and rapid measurement capabilities. As the size of nanoparticles decreases, their surface area increases, leading to an enhancement of the analytical signal. In this context, nanomaterials act as catalysts, accelerating reactions on the electrode surface and facilitating electron transfer.

In electrochemical sensors, the electrochemical element (cell) is sensitive. Primary information signals about the phenomenon or object under study arise in the form of a change in the properties of this element: potential difference or electrical conductivity, electric current or volt-ampere characteristic, the dynamics of their change. The physical form of the information signal is the basis for the classification. Accordingly, electrochemical sensors are divided into conductometric, potentiometric, amperometric, voltammetric and chronoamperometric.

Nanorods, nanowires, and nanocomposites (such as metal/metal oxide combined with graphene or carbon nanotubes) are widely utilized in the development of electrochemical sensors. In his research, John B. [13] discusses the analytical potential of electrochemical and biosensors based on polymer nanocomposites. A crucial factor in such materials is the uniform distribution of nanoparticles and their chemical compatibility with the matrix.

Shahamirifard et al. describe in their study a novel sensor system that enables the simultaneous detection of arbutin and vitamin C using carbon paste electrodes (CPE) modified with CNTs. This modification enhances the catalytic activity of the electrode, significantly facilitating the oxidation-reduction reactions of the target compounds. Similarly, Shahamirifard and Ghaedi demonstrate the advantages of composite nanoparticles, such as ZnO-Pd. Oxides of molybdenum, zinc, iron, nickel, and cobalt are also extensively used in sensor applications. Graphene and its derivatives, such as graphene oxide and reduced graphene oxide, are also

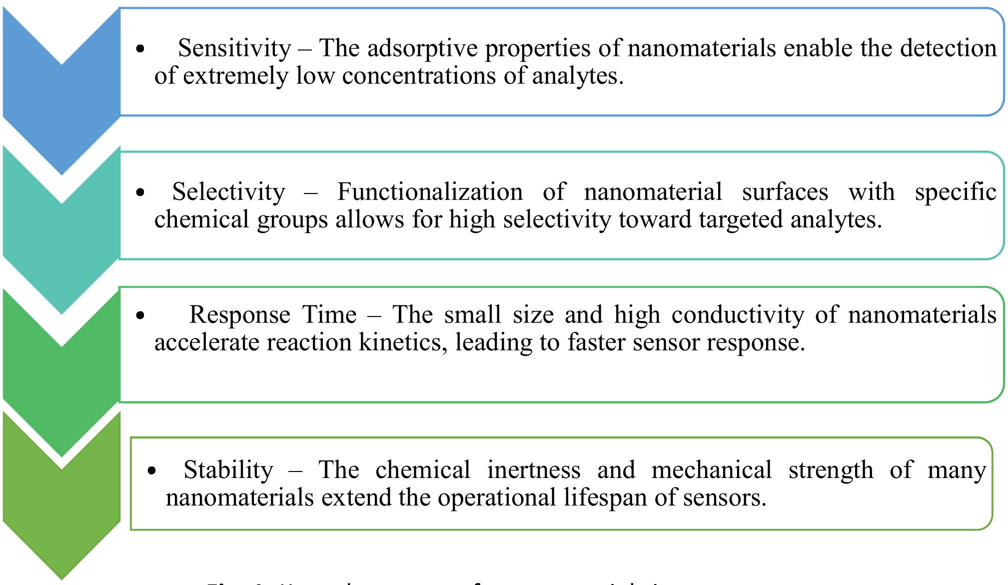

Fig. 1. Key advantages of nanomaterials in sensor systems.

recognized as effective platforms for electrochemical sensors [14]. Yuan F. and colleagues, in their latest work [15], propose new approaches for integrating inorganic functional nanomaterials with graphene to create flexible sensor elements. Their findings highlight that graphene's large specific surface area and high conductivity contribute to increased analytical sensitivity. Bimetallic nanoparticles (e.g., Pt–Au, Ag–Au, Pd–Au) exhibit greater catalytic activity compared to monometallic counterparts, thereby enhancing electrochemical reactions [15].

Carbon nanotubes (CNTs) are distinguished by their high electrical conductivity, exceptional mechanical strength, and electrochemical inertness, making them a preferred medium in sensor electronics. In the studies conducted by Shambilova G.K. and Baktygalieva T.T., the synergistic effect of carbon nanomaterials and metal nanoparticles is analyzed [16], underscoring the potential of nanocomposite-based sensors.

Zhumnazar N.N. et al. describe a track-membrane sensor designed for cadmium ion detection [17]. This sensor employs metal oxide nanofilms for electrochemical detection. Baranwal and colleagues explore the applications of various electrochemical sensors in liquid media, food samples, and biological systems [18]. Metal nanoparticles, including gold, platinum, and palladium, serve as intermediate electron carriers or direct catalytic centers in electrochemical sensors. Meti M.D. and colleagues [19] demonstrate that modified electrodes based on gold-graphene hybrids enable the sensitive detection of certain organic compounds. Meti M.D. et al. [19] and Wen X. [20] investigate gold-graphene hybrids and N-doped Cu–MOF-based sensors, which exhibit high accuracy in detecting various organic pollutants. These sensors have potential applications in pharmaceutical manufacturing, environmental monitoring, and the agro-industrial sector. In biosensor applications, bioreagents such as enzymes or antibodies are immobilized on nanomaterial surfaces using specialized techniques. In biosensors, biological macromolecules such as proteins, enzymes, or DNA are immobilized onto the surface of nanomaterials, enabling selective binding of target analytes. For instance, Nikiforova A.A. [21] focuses on improving pharmaceutical compound detection methods using sensors modified with carbon-based nanomaterials. Such an approach is particularly advantageous for the precise and rapid quantification of drug concentrations. Metal-organic frameworks (MOFs) are highly porous structures formed by metal ions and organic ligands, capable of capturing molecules and catalyzing chemical reactions. From a chemical perspective, metal oxides such as those of Al, Ti, Zr, Cu, and Ce exhibit high activity in oxidation-reduction processes [22]. Zhumasheva N.Z. and colleagues provide insights into molybdenum-based sensors, such as MoO_3 and MoO_4^{2-} [23]. MOF materials share similar functional capabilities, making them suitable for a wide range of applications.

Cho G. et al. [24] highlight the potential of MOF-based materials for monitoring hazardous chemicals in water, in addition to carbon nanotube applications. The large specific surface area and porosity of MOFs contribute to enhanced sensor sensitivity.

In Kazakhstan, notable research on sensor development using nanomaterials has been conducted by Aimashova Zh. and Ismailov D., Shambilova G. K. and Baktygalieva T.T., as well as Zhumnazar N.N. and colleagues. These studies focus on the synthesis of carbon-based nanostructures, their physicochemical properties, and their integration into analytical systems. Aimashova Zh. and Ismailov D. particularly investigate the synthesis and purification of fullerenes in dispersed media, which could expand the operational range of electrochemical sensors.

Shambilova G.K. and Baktygalieva T.T. analyze the fabrication methods of carbon nanomaterials, emphasizing their significance in catalysis and adsorption processes. Additionally, Zhumnazar N.N. et al. provide evidence of the effectiveness of track-membrane sensors for environmental monitoring, suggesting their potential for industrial-scale application. Assirbayeva Zh.M. et al. introduced the method of making portable electrochemical sensors for on-site detection of pesticide residues in fruits and vegetables, namely the achievements in recent years in the fields of cyclic voltammetry, square wave voltammetry, differential pulse voltammetry and electrochemical impedance spectroscopy [25], also Bakytkarim Yu. and others. He analyzed the application and progress in research of immune, enzymatic, nano- and molecular imprinting electrochemical sensors for the detection of pesticide residues and analyzed the future application of electrochemical sensors for the detection of pesticide residues [26]. Bakytkarim Y. et al. detected chlorogenic acid by using Pt@r-GO@MWCNTs ternary nanocomposite modified electrode [27].

In Russia, notable contributions to the application of nanomaterials in sensors come from researchers such as Buzanovsky V.A. and Ziyatdinova G.K. The works of Budnikov G.K., Zhupanova A.S., Nikiforova A.A., and Khamzina E.I. are also widely recognized. Their studies explore the use of electrodes made from carbon nanotubes and their advantages in simultaneously detecting phenolic antioxidants. For instance, Ziyatdinova G.K. et al. investigate the role of nanomaterials in enhancing the sensitivity of electrochemical methods for phenolic antioxidant analysis. The addition of carbon-based modifiers such as nanotubes or graphene accelerates electrode surface reactions, leading to increased current signals and improved detection limits. Nikiforova A.A. proposes methodologies for assessing the concentrations of potential pharmaceutical compounds using carbon-nanomaterial-based sensors, highlighting their importance for pharmaceutical applications. Khamzina E.I. describes electrochemical sensors based on carbon fiber platforms for detecting synthetic dyes in the food industry. These sensors, characterized by high precision, are well-suited for food quality control.

On a global scale, studies by Shahamirifard S.A. and Ghaedi M., Yuan F. et al., Baranwal et al., Meti M.D. et al., Cho G. et al., and John B. provide valuable insights into the advantages of nanomaterials in electrochemical sensors. Shahamirifard and Ghaedi describe the synthesis of ZnO-Pd nanoparticles and their integration into carbon paste electrodes, demonstrating their effectiveness in the simultaneous detection of arbutin and vitamin C. Yuan F. et al. explore the structural features of flexible sensors based on inorganic functional nanomaterials, noting their applicability in healthcare and wearable devices. Baranwal et al. review recent advances in bioanalytical compound detection, emphasizing the versatility of electrochemical sensors. Agnihotri A.S. et al. examine the contributions of transition metal oxides to electrochemical and biosensing devices. Their findings indicate that the activity of enzymes or antibodies in such systems enables highly sensitive nano-level detection.

In some studies, the speed of enzymatic reactions increases and the detection limit decreases somewhat in the combined system of enzymes and nanomaterials. Such biosensors can be an effective tool, especially in medicine (detection of markers in the blood), food safety (detection of antibiotic residues) and ecology (monitoring of pesticides and heavy metal ions).

Summarizing these works, the directions of using nanomaterials in electrochemical sensors are different: in some studies, modification with carbon nanotubes is carried out, in others, metal oxides or hybrid nanocomposites are used. As a result, the sensitivity, analysis speed and selectivity of sensors are significantly improved. These achievements will be of great importance in the future in the industrial, environmental and medical fields.

The main elements of the sensor are an electrode and an active layer interacting with the detected substance (analyte). Methods of introducing nanomaterials: surface modification, coating in the form of a film, a mixture in the form of a paste, etc. Many studies suggest applying nano powders to the electrode surface by methods such as ultrasonic dispersion, chemical precipitation, electrophoresis, and spin-coating. In addition, the selectivity of the sensor can be increased by functionalizing the materials (with special reagents, proteins, DNA probes, etc.). For example, when ZnO nanoparticles are coupled with enzymes, the efficiency of detecting biomolecules (glucose, lactate) increases.

Reviewing the literature, several advantages of electrochemical sensors based on nanomaterials are obvious. First, the sensitivity and selectivity are significantly higher compared to traditional methods. Second, the speed and accuracy of analysis are suitable for industrial and clinical use. Third, nanomaterials are an indispensable platform for creating sensors aimed at specific tasks through various modification strategies. In addition, from a commercial point of view, if such sensors have the ability to use available reagents and work with simple equipment, their mass production will be facilitated. Electrochemical sensors based on nanomaterials will play an important role in solving the problems of improving environmental protection, food quality control and early detection of diseases. As we can see from the literature, electrochemical sensors based on nanomaterials play a key role in modern analytical systems. Their catalytic activity and adsorption properties are in great demand both in the scientific community and in the industrial sector. The rapid development of nanotechnology not only improves the methods of sensor production, but also opens up new, branched fields of application.

3. Overall comparative characteristics of electrochemical sensors based on single nanomaterials

The following is a list of several well-known research techniques for improving the efficiency of electrochemical sensors based on nanomaterials:

1. Theoretical analysis method – used to study

Table 1. Comparative characteristics of electrochemical sensors based on nanoscale materials

#	Type of Nanomaterial (Single)	Target Analyte	Detection Limit (LOD)	Brief Description
1	Carbon Nanotubes (CNTs)	Glucose, lactate, heavy metal ions (Pb, Cd)	0.01–0.1 μM	CNTs grant detection of extremely low concentrations through high electrical conductivity and an extensive surface area. Bioanalysis is common. Carbon nanotubes (CNTs) and graphene exhibit extensive surface areas and conductivity, enabling detection of extremely low analyte concentrations.
2	Graphene (Gr)	Ascorbic acid, dopamine, hazardous organics	0.005–0.05 μM	Single-layer, planar geometry accelerates reaction kinetics, less interference from extraneous species, higher selectivity in complex matrices.
3	Metal Oxides (ZnO, CuO, Fe_3O_4)	Nitrophenol, pesticides, H_2O_2	0.01–0.2 μM	ZnO, CuO, Fe_3O_4 serve as catalysts. ZnO tolerates a wide pH range, CuO lowers redox potential, Fe_3O_4 has magnetic attributes. Metal nanoparticles (Au, Pt, Ag) and metal oxide nanomaterials (ZnO, CuO) catalyze redox processes and lower potential thresholds.
4	Metal-Organic Framework (MOF)	Cd^{2+}, Pb^{2+}, organic toxicants	0.001–0.01 μM	MOF systems with high porosity adsorb heavy metals or large molecules. LOD can drop to 0.001 μM. MOF structures detect heavy metals or organic molecules in complex environments because of a network of pores.

the physicochemical foundations of electrochemical sensors. The properties of sensor materials, their role in electrochemical systems, and the effectiveness of nanostructures were analyzed.

2. Comparative-analytical method – data obtained in various studies were compared and modern achievements of electrochemical sensors were analyzed.

3. Systematic analysis method – used to fully study the working mechanisms of sensors based on nanomaterials.

4. Mathematical modeling – allowed to predict the operating parameters of electrochemical sensors based on nanomaterials and to quantitatively evaluate their sensitivity indicators.

In the Table 1 is presenting the comparative characteristics of electrochemical sensors obtained from nanoscale materials [28, 29].

As shown in Table 1, the detection limit of graphene sometimes reaches 0.005 μM, which is due to the efficiency of its single-layer two-dimensional structure in electron transport. CNTs also give high sensitivity, used frequently with pharmaceuticals and biomarkers. Metal oxide nanoparticles (ZnO, CuO, Fe_3O_4) handle diverse tasks. ZnO remains stable over a broad pH range, CuO selectively shifts oxidation potential, Fe_3O_4 offers magnetic capabilities [28]. MOF handles heavy metals by adsorbing analyte ions in high-porosity frameworks, with detection limits near 0.001 μM.

Graphene (Gr) is a one-atom-thick flat sheet of sp^2-bonded carbon atoms arranged in a honeycomb (hexagonal) lattice, exhibiting high electrical conductivity at room temperature, flexibility, and tensile strength surpassing that of diamond [30]. Its unique structure provides exceptional mechanical, electrical, and thermal properties, a large surface area, ease of processing, and safety [31, 32]. Graphene nanosheets are individual nanoscale units used in energy devices, composites, and sensors [33].

Graphene oxide (GO) contains functional groups (carboxyls, hydroxyls, epoxides) that act as active sites for immobilizing sensitive molecules, thereby enhancing sensor sensitivity. Reduced graphene oxide (rGO), derived from GO, partially restores graphene's sp^2 structure and is utilized in electronics, energy storage devices, and composites while retaining many of graphene's properties [34].

4. Application fields and analytical parameters of hybrid nanomaterial-based sensors

In the Table 2 is presenting the application fields and analytical parameters of hybrid nanomaterial-based sensors. Au-graphene hybrids are crucial for

Table 2. Application fields and analytical parameters of hybrid nanomaterial-based sensors

#	Hybrid Material (Combination)	Analyte of Interest	LOD (µM)	Linear Range (µM)	Explanation
1	Graphene + Au Nanoparticles	Biomarkers (blood glucose, immunoglobulin)	0.005–0.02	0.1–1000	Au offers catalytic functionality, graphene supports rapid conductivity, beneficial for long-term stability in biological analysis. Graphene combined with gold nanoparticles forms an innovative hybrid material that leverages graphene's excellent electrical conductivity and extensive surface area alongside gold's catalytic and biocompatible attributes.
2	Carbon Nanotubes + ZnO	Pesticides (carbamates, organophosphates)	0.01–0.15	0.5–200	ZnO provides catalytic capacity, CNTs facilitate electron transport, oxidation peaks for pesticides become distinct. Carbon Nanotubes + ZnO represent a promising hybrid for developing highly sensitive sensors. They can be used for environmental pollution monitoring, food quality control, and integration into IoT systems.
3	MOF (Cu) + Graphene	Heavy metal ions (Cd^{2+}, Pb^{2+})	0.001–0.005	0.01–50	MOF cavities capture ions, graphene speeds electron flow. Detection limit decreases markedly. The MOF (Cu) + Graphene hybrid can be applied for the detection and control of heavy metals, such as Cd^{2+} and Pb^{2+}, in water and industrial environments. Thanks to the highly porous structure of MOF, which efficiently captures ions, and the rapid electron transfer through graphene, such sensors can achieve an ultra-low detection limit and a wide linear range.
4	Carbon Nanotubes + Pd	Organic toxicants (nitrophenol, phenol derivatives)	0.02–0.08	1–500	Pd accelerates redox reactions, CNTs reduce interference in solution. The carbon nanotubes + Pd hybrid promises high sensitivity and selectivity in detecting organic toxicants such as nitrophenol. Thanks to the catalytic activity of Pd and the high conductivity of CNTs, these sensors offer a low detection limit and rapid response.
5	Graphene + Fe_3O_4 (magnetic)	Food quality (dyes, preservatives)	0.01–0.05	0.2–150	Fe_3O_4 magnetically pre-concentrates samples, graphene yields higher sensitivity of recorded signal. The graphene and iron oxide (Fe_3O_4) hybrid combines magnetic properties with high conductivity, making it suitable for food quality control, environmental monitoring, and biomedical analysis. It is expected to lower detection limits, enhance sensitivity, and provide a rapid response, leading to the development of compact and integrable sensor systems.

biomedical analysis due to Au's biocompatibility and graphene's large surface area. Carbon nanotubes + ZnO can detect pesticides at 0.01 µM, where ZnO catalyzes their oxidation, CNTs suppress background currents. Carbon nanotubes + Pd accelerate oxidation of nitrophenol, lowering LOD to 0.02 µM. Graphene + Fe_3O_4 measures dyes in food products after magnetic separation [35].

The analysis of the data presented in the table highlights the high efficiency of hybrid nanomaterials in the development of modern electrochemical sensors. Each material combination – graphene with gold nanoparticles, carbon nanotubes with ZnO or Pd, MOF with graphene, and graphene with Fe_3O_4 – offers unique advantages, providing high sensitivity, wide linear detection ranges, and low limits of detection. Notably, MOF (Cu) + graphene and graphene + Au demonstrate ultra-low detection limits (down to 0.001 µM) for the analysis of heavy metals and biomarkers, making them highly promising for biomedical diagnostics, environmental monitoring, and food safety control. The magnetic properties of Fe_3O_4, when combined with graphene, enable effective sample pre-concentration, which is especially valuable in food quality analysis. Overall, hybrid nanomaterials open up new possibilities for the development of multifunctional, compact, and energy-efficient sensors with high selectivity and stability. Future research should focus on scaling up these solutions, enhancing long-term durability, and integrating them into smart analytical systems (Table 3).

This table shows how hybrid nanomaterials are applied across various fields, both in the present and in the future. By comparing current and potential uses, we can observe the development dynamics of technologies based on these materials and their strategic importance for science and industry. At present, hybrid nanomaterials are already being used in areas such as biomedicine, environmental protection, energy, electronics, and the food industry. For example, in medicine, they are used as highly sensitive components in biosensors and drug delivery systems. In environmental applications, they assist in detecting pollutants and purifying water. In the energy sector, they help improve the performance of batteries and fuel cells [38].

However, in the future, a significant expansion of their applications is expected. Hybrid nanomaterials are projected to form the foundation for next-generation smart devices, such as self-learning sensors, electronic skin, intelligent packaging,

Table 3. Applications of Hybrid Nanomaterials: Present and Future [36, 37]

#	Application Area	Current Uses	Potential Future Uses
1	Biomedicine	Biosensors for glucose, cholesterol, cancer markers	Smart nanodevices for combined diagnostics and therapy (theranostics)
		Contrast agents for MRI and CT	Neuroimplants
		Drug delivery systems	Personalized medicine based on real-time sensing
2	Environment & Ecology	Detection of heavy metals, organic pollutants	Autonomous sensor networks in air, water, and soil
		Water purification using nanosorbents	Self-cleaning surfaces that adapt to pollution levels
3	Energy	Nanomaterials in batteries and supercapacitors	Smart energy storage systems
		Catalysts in fuel cells	Self-healing nanomaterials for long-term performance
4	Electronics & Sensors	Flexible sensors and transistors	Electronic skin, wearable electronics
		Electrochemical sensors	AI-powered and self-learning sensor systems
5	Food Industry	Sensors for monitoring product freshness	Smart packaging that changes color when food spoils
		Antibacterial packaging materials	Nanostructures to enhance flavor and shelf life
6	Agrotechnology	Detection of pesticides and nitrates	Nano-devices embedded in plants
		Sensors for soil moisture and nutrient content	Precision agriculture with continuous monitoring

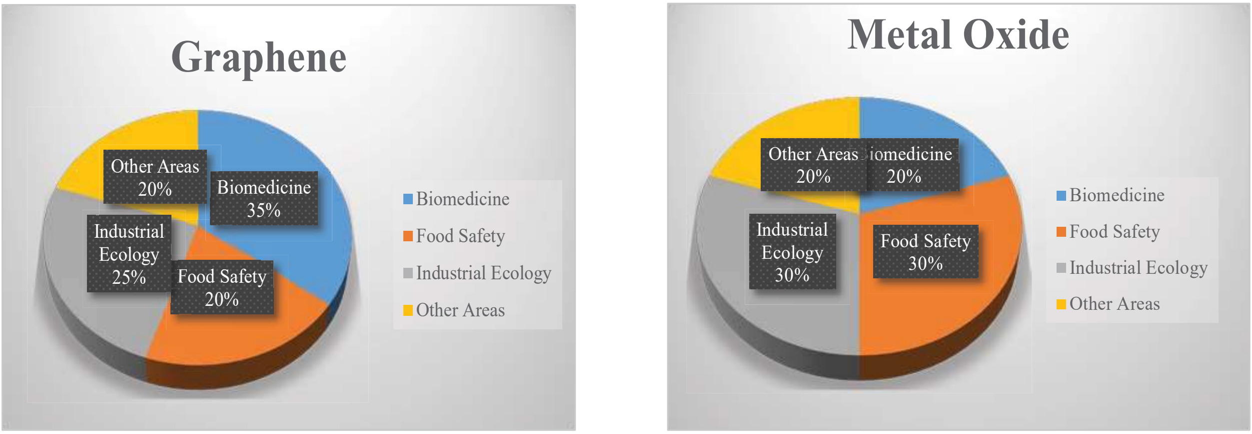

Fig. 2. Conditional usage frequency of carbon-based nanomaterial sensors.

and nanoplatforms that combine diagnostics and therapy. Particularly promising is their potential use in personalized medicine, precision agriculture, and neuro technology [39]. Thus, the table highlights the shift from laboratory-scale use to real-world, multifunctional solutions that are likely to play a key role in the advancement of future technologies.

Fig. 2 shows the conditional percentage data on the frequency of use in each field. In biomedicine, carbon nanotubes (~40%) and graphene (~35%) are widely used, since high conductivity is required for the detection of markers in biological fluids.

Metal oxides (~30%) play an important role in food safety, facilitating the oxidation of compounds such as pesticides and dyes. In industrial ecology, MOFs reach up to 25%, since they can selectively trap heavy metal ions (Fig. 3). By visually displaying this data in the diagram, it is clear which nanomaterial is most widely used in which field [40].

The efficiency of electrochemical sensors is directly related to the properties of the nanomaterials used in them. Studies have shown that nanomaterials play an important role in increasing the sensitivity and selectivity of sensors. Carbon nanotubes (CNTs) have high conductivity and a large specific surface area, which makes them very effective for use in electrochemical sensors.

The effectiveness of electrochemical sensors depends directly on the physicochemical properties of the nanomaterials they contain. Studies have shown that carbon nanotubes play an important role in biosensor tests due to their high conductivity and large surface area. The presence of functional groups on their surface improves the interaction of the electrode with the molecules to be analyzed and enhances the electrochemical reaction. The two-dimensional structure of graphene accelerates reaction kinetics and facilitates current transfer, which increases the sensitivity of electroanalytical methods. Metal nanoparticles, including gold (Au) and platinum (Pt), increase the catalytic activity on the electrode surface and increase the rate of redox processes. Metal oxides (ZnO, CuO) are chemically stable and are advantageous for use in enzymatic sensors. In particular, MOF structures enable the selective detection of heavy metals and organic

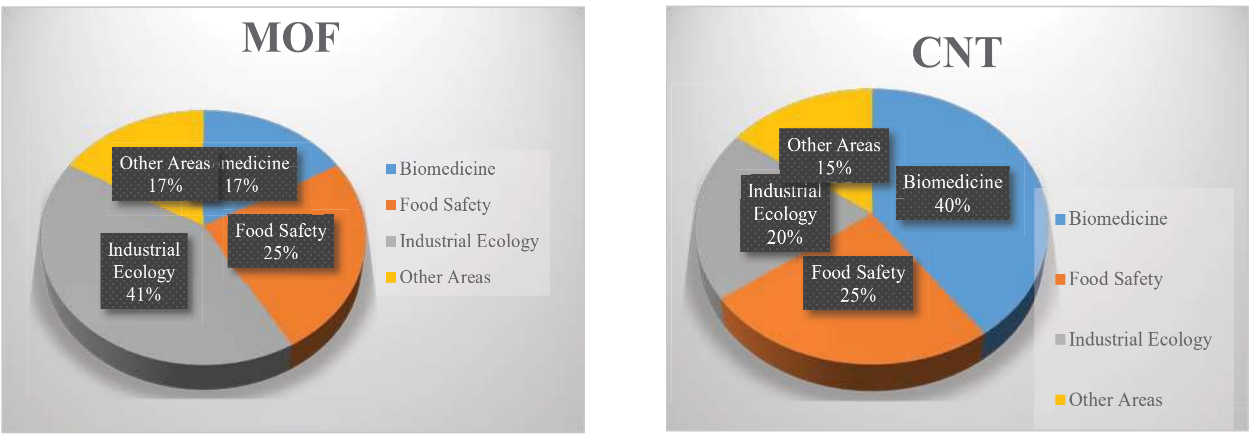

Fig. 3. Conditional usage frequency of metal-based nanomaterial sensors.

pollutants due to their high porosity. However, the stability of sensors also depends on the long-term stability of the nanomaterials used in them. Studies have shown that some nanomaterials can clump together over time, reducing the efficiency of sensors. Therefore, it is important to increase the stability of sensors through polymer coatings or special surface modification techniques. Hybrid structures, such as combinations of graphene + metal nanoparticles or carbon nanotubes + metal oxides, can improve the sensitivity and durability of electrochemical sensors. The results show that multi-component sensors have higher efficiency than devices based on individual nanomaterials, improving their functionality in different chemical and biological environments. In addition, research has shown that the manufacturing technology of sensors must be optimized for their use on an industrial scale. Nanomaterial-based electrochemical sensors have great potential for use in medical diagnostics, food safety, environmental monitoring and pharmaceutical analysis. In order to increase the efficiency of electrochemical sensors, it is necessary in the future to investigate new material combinations and develop methods to improve their stability.

5. Conclusion

This study demonstrates that the application of nanomaterials in electrochemical sensors significantly expands their analytical capabilities by enhancing sensitivity, selectivity, and lowering detection limits. The use of materials such as carbon nanotubes, graphene, metal nanoparticles, metal oxides, and metal-organic frameworks not only accelerates electrochemical reactions but also ensures the stable performance of sensors under various analytical conditions. A comprehensive approach that includes the chemical and structural modification of nanomaterials, as well as the optimization of their deposition on electrode surfaces, is of paramount importance.

The achievements outlined in the review open up new prospects for the industrial application of electrochemical sensors in medicine, environmental protection, the food industry, and pharmaceuticals. The development of hybrid systems that combine the advantages of different nanomaterials is a key direction for future research, as it will enable the creation of highly efficient and versatile analytical devices. Consequently, further research in this area will not only deepen the understanding of sensor mechanisms but also lay the foundation for developing new, more accurate, and reliable methods of analysis for both industrial production and everyday life.

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Наноматериалдарға негізделген электрохимиялық сенсорлардың тиімділігі

Д.Б. Қонарбай[1*], Ы. Бақыткәрім[1], Ж.С. Мұқатаева[1], Н.А. Шадин, Ж.М. Асирбаева[1], Е. Тілеуберді[1], Л.А. Жусупова[2]

[1]Абай атындағы Қазақ ұлттық педагогикалық университеті, Достық даңғылы, 13, Алматы, Қазақстан
[2]Қорқыт ата атындағы Қызылорда университеті, Әйтеке би к-сі, 29А, Қызылорда, Қазақстан

АҢДАТПА

Электрохимиялық сенсорлар – қазіргі заманғы аналитикалық химиядағы ең маңызды технологиялардың бірі болып табылады және жоғары дәлдіктегі талдаулар жүргізуге мүмкіндік береді. Бұл зерттеуде наноматериалдарға негізделген электрохимиялық сенсорлардың тиімділігі, сондай-ақ олардың сезімталдығы, селективтілігі, анықтау шегі мен тұрақтылығы талданды. Зерттеу көміртекті нанотүтіктерге (CNTs), графенге, металл нанобөлшектеріне (Au, Pt, Ag), металл оксидтеріне (ZnO, CuO, Fe_3O_4) және металл-органикалық қаңқаларға (MOFs) негізделген сенсорлардың аналитикалық мүмкіндіктерін қарастырды.

Наноматериалдар электрохимиялық сенсорлардың сезімталдығын арттыруда маңызды рөл атқарады. Көміртекті нанотүтіктердің беттік ауданының үлкендігі мен жоғары өткізгіштігі электрод бетіндегі талданатын заттардың адсорбциясын жақсартады, осылайша олардың төмен концентрацияларын анықтауға мүмкіндік береді. Графеннің екі өлшемді құрылымы электрохимиялық сигналдарды күшейтіп, талдау уақытын қысқартады. Металл нанобөлшектері мен металл оксидтері реакция жылдамдығын арттырып, электрод бетіндегі тотығу-тотықсыздану процестерін активтендіреді. Металл оксидті қаңқалы құрылымдарының жоғары кеуектілігі ауыр металл иондары мен органикалық ластаушы заттарды тиімді анықтауға мүмкіндік береді.

Зерттеу нәтижелері сенсор құрылғыларында қолданылатын наноматериалдардың құрамы олардың сезімталдығы мен тұрақтылығына айтарлықтай әсер ететінін көрсетеді. Олардың химиялық және құрылымдық модификациясы сенсорлардың ұзақ мерзімді жұмысын жақсартады. Болашақта көпкомпонентті гибридті сенсорларды жасау және олардың өнеркәсіпте қолданылуын оңтайландыру ерекше өзекті болады.

Түйін сөздер: электрохимиялық сенсорлар, наноматериалдар, көміртекті нанотүтіктер, графен, металл нанобөлшектері, металл оксидтері, металл-органикалық қаңқалар, аналитикалық сенімділік.

Эффективность электрохимических сенсоров на основе наноматериалов

Д.Б. Қонарбай[1*], Ы. Бақыткәрім[1], Ж.С. Мұқатаева[1], Н.А. Шадин, Ж.М. Асирбаева[1], Е. Тілеуберді[1], Л.А. Жусупова[2]

[1]Казахский национальный педагогический университет им. Абая, пр. Достык, 13, Алматы, Казахстан
[2]Кызылординский университет им. Коркыт ата, ул. Айтеке би, 29А, Қызылорда, Казахстан

АННОТАЦИЯ

Электрохимические сенсоры являются одним из важнейших направлений в современной аналитической химии, позволяющим проводить высокоточный анализ. В данном исследовании были проанализированы характеристики электрохимических сенсоров на основе наноматериалов: чувствительность, селективность, предел обнаружения и стабильность. В исследовании изучены аналитические возможности сенсоров на основе углеродных нанотрубок (УНТ), графена, металлических наночастиц (Au, Pt, Ag), оксидов металлов (ZnO, CuO, Fe_3O_4) и металлорганических каркасов (MOF). Наноматериалы играют важную роль в повышении чувствительности электрохимических сенсоров. Большая площадь поверхности и высокая проводимость углеродных нанотрубок улучшают адсорбцию аналитов на поверхности электрода, что позволяет обнаруживать их низкие концентрации. Двумерная структура графена усиливает электрохимические сигналы и помогает сократить время анализа. Металлические наночастицы и оксиды металлов увеличивают скорость реакции и активируют окислительно-восстановительные процессы на поверхности электрода. Высокая пористость структур MOF позволяет эффективно обнаруживать ионы тяжелых металлов и органические загрязнители. Результаты исследования показывают, что состав наноматериалов, используемых в сенсорных устройствах, существенно влияет на их чувствительность и стабильность. Их химическая и структурная модификации улучшают долгосрочную работу сенсоров. В перспективе особенно актуальны разработка многокомпонентных гибридных сенсоров и оптимизация их промышленного применения.

Ключевые слова: электрохимические сенсоры, наноматериалы, углеродные нанотрубки, графен, металлические наночастицы, оксиды металлов, металлорганические каркасы, аналитическая надежность.