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REVIEW OF ELECTROCHEMICAL BIOSENSORS BASED ON CARBON NANOMATERIALS FOR EARLY CANCER DIAGNOSIS

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Abstract. Cancer is one of the leading causes of mortality worldwide. Early diagnosis of tumors is considered a key and at the same time challenging task in the effective treatment of oncology patients. In recent years, nanomaterial-based biosensors have been rapidly developing as modern and highly sensitive tools for cancer diagnostics. In particular, carbon nanomaterials significantly enhance the analytical performance of electrochemical and optical sensing systems.

The aim of this review is to systematize the capabilities of electrochemical and optical biosensors based on carbon nanomaterials for early cancer detection. The main objectives include analyzing the properties of the applied carbon nanostructures (graphene, graphene oxide, carbon nanotubes, and carbon quantum dots) and evaluating their efficiency in the determination of tumor markers. A comprehensive analysis of the scientific literature was conducted, and methods such as voltammetry, amperometry, electrochemical impedance spectroscopy, electrochemiluminescence, and surface plasmon resonance were considered. Special attention is paid to strategies for bioreceptor immobilization and nanocomposite functionalization. Carbon nanomaterials exhibit high electrical conductivity, large specific surface area, and good biocompatibility. These properties enable the detection of tumor markers (CEA, AFP, miRNA, and proteins) at low concentrations. The sensors are characterized by portability, rapid response, and low limits of detection. Biosensors based on carbon nanomaterials have high practical significance in the field of early diagnosis and demonstrate strong potential for clinical application.

Keywords: biomarkers, cancer, electrochemical biosensors, carbon nanomaterials, graphene, carbon nanotubes, optical biosensors.

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1. Introduction

Globally, cancer remains one of the leading causes of human mortality. According to Siegel et al., approximately 2,001,140 new cancer cases and 611,720 cancer-related deaths were projected in the United States, corresponding to a mortality rate of about 30% [1].

In Kazakhstan, according to data reported in 2025, the number of patients diagnosed with cancer in 2024 increased by 5.9% compared to 2023 [2]. Cancer remains the second leading cause of death worldwide after cardiovascular diseases, and early detection significantly improves survival outcomes and reduces mortality [3].

Life expectancy largely depends on the stage at which cancer is diagnosed. If cancer biomarkers are detected at an early stage, the prognosis is more favorable, leading to improved therapeutic outcomes and reduced burden on patients [4]. However, conventional cancer diagnostic methods, including non-invasive imaging techniques such as Computed Tomography, Magnetic Resonance Imaging, Ultrasound Imaging, Positron Emission Tomography, And Single-Photon Emission Computed Tomography, as well as Invasive Biopsy and Histopathological Examinations used to identify cancer types and stages, are considered highly specific. Nevertheless, these methods are relatively expensive, require complex instrumentation, and may face limitations in point-of-care applications [5].

Molecular biomarkers such as proteins, nucleic acids, metabolites, and exosomes are considered promising indicators for the early diagnosis, prognosis, and monitoring of therapeutic response in cancer. The National Cancer Institute defines a biomarker as a biological molecule found in body fluids or tissues that indicates a normal or abnormal process, or a condition or disease [6]. Cancer biomarkers can generally be classified into two main groups:

1. Genetic biomarkers: BRCA1, BRCA2, COX2, EGFR, DAPK, KRAS, GSTP1, circulating tumor DNA (ctDNA), microRNA, tRNA, rRNA, miR-21, miR-122, miR-16, miR-155, P53, and others.

2. Protein biomarkers: AFP, CEA, PSA, VEGF, CA-15-3, CA-19-9, CA-125, CA-242, EPCAM, NSE, PAM-4, PAP, HER-2, Mucin-1, CYFRA-21-1, and others.

In many types of cancer, biomarkers such as Carcinoembryonic Antigen (CEA), Prostate-Specific Antigen (PSA), Interleukins (IL-6, IL-8), Circulating Tumor DNA (ctDNA), microRNA, and exosomes have been well established as indicators closely associated with tumor genesis and prognosis. However, the concentrations of these biomarkers may be extremely low during the early stages of the disease. Therefore, highly sensitive and selective detection methods, as well as efficient electrochemical biosensors, are required. Systems based on carbon nanomaterials fully meet these requirements. The high electrical conductivity and large specific surface area of graphene and carbon nanotubes enable the detection of cancer-related biomarkers at extremely low concentrations

[7]. In addition, their excellent capability for functionalization with biomolecules ensures accurate and rapid electrochemical signal transduction and detection.

Electrochemical Biosensors. An electrochemical sensor is an analytical device that converts chemical substances and their analytical properties into electrical signals [8]. The structure of an electrochemical sensor typically consists of three main components:

1) Electrode system or analyzer (Transducer) – the core component that converts a chemical or biochemical signal into an electrical signal (current, potential, or impedance). Most commonly, a three-electrode system is used:

a) Working electrode (WE): The primary surface where the electrochemical reaction of the analyte occurs and where the signal is measured. Common materials include gold (Au), carbon (C), glassy carbon, and modified electrodes.

b) Reference electrode (RE): Maintains a stable and well-defined potential for accurate measurement of the working electrode potential. Common examples include Ag/AgCl and saturated calomel electrodes (SCE).

c) Counter electrode (CE): Completes the electrical circuit and allows current to flow. The electrochemical reaction occurs at this electrode, but it is not used for signal measurement. Typical materials include platinum wire and carbon.

2) Recognition layer (Biorecognition layer) – the selective component responsible for recognizing the target analyte and facilitating its interaction with or binding to the electrode surface. This layer determines the selectivity of the sensor. Its composition includes:

a) For chemical sensors: simple chemical compounds, ionophores, and polymer membranes.

b) For biosensors: biological materials (bioreceptors), such as enzymes, antibodies, DNA, or cells, which are immobilized on the electrode surface.

3) Electrode (Electrode platform) – a solid conductive material that supports the biorecognition layer and enables the measurement of electrical signals. Common types include:

a) Screen-printed electrodes (SPE): Widely used in modern portable sensor systems.

b) Glassy carbon electrodes (GCE)

c) Gold and platinum electrodes

The fundamental components and operating principle of the proposed electrochemical biosensor are illustrated in Figure 1, comprising three sequential stages: biological recognition, signal transduction, and data processing. Initially, the electrode surface is functionalized with specific biorecognition elements, such as antibodies, which selectively bind target cancer biomarkers through high-affinity interactions. This binding event is subsequently converted by the transducer into a measurable electrical or optical signal using electrochemical (e.g., potentiostatic) or optical (e.g., SPR or fluorescence) techniques. The resulting signal is then processed by the signal processing unit, where it undergoes amplification, filtering, and analysis to yield a precise quantitative output. Such an integrated system enables real-time monitoring and accurate

determination of biomarker concentrations, supporting its potential application in clinical diagnostics [5, 9].

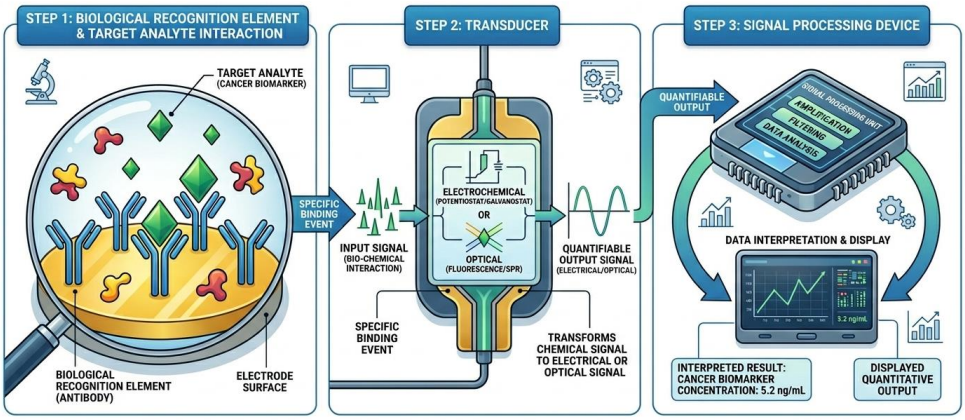

Figure 1 - Fundamental components and workflow of a biosensor

Early cancer detection remains a critical challenge that requires highly sensitive, selective, and rapid analytical tools, as conventional diagnostic methods are often limited by cost, complexity, and restricted applicability in point-of-care settings [1,3]. In this context, this review critically examines recent advances in carbon nanomaterial-based biosensors, with particular emphasis on electrochemical and optical platforms, and evaluates how key nanostructures such as graphene, carbon nanotubes and carbon quantum dots enhance sensivity, selectivity and detection limits. By comparatively analyzing different sensing strategies and biomarker types, including proteins and nucleic acids. This work highlights the relationships between nanomaterial properties, sensor design and analytical performance, while identifying current limitations and promising future directions for the development of next-generation biosensing systems suitable for early cancer diagnostics and clinical applications.

2. Discussion and Analysis

The analytical performance characteristics of sensors, such as sensitivity, selectivity, and limit of detection, primarily depend on the material of the working electrode and its surface structure [10]. Therefore, the electrode material plays a crucial role in the development and improvement of electrochemical sensors. In recent years, carbon based nanomaterials (CNMs), such as graphene, carbon nanotubes, carbon quantum dots, and graphitic nanostructures, have been increasingly explored to improve the performance of electrochemical sensors.

The incorporation of CNMs onto the surface of the working electrode accelerates the electron transfer process at the electrode-analyte interface. As a result, the kinetics of electrochemical reactions are improved, and the current

response of the sensor is enhanced. This increases the sensitivity of the sensor and enables the detection of analytes at very low concentrations. Since the surface of CNMs can be easily modified with various functional groups, they provide an ideal platform for the immobilization of biomolecules, enzymes, or selective recognition elements. This property makes CNMs particularly effective for the fabrication of electrochemical biosensors and significantly improves sensor selectivity [11]. The main nanomaterials commonly used for the modification and enhancement of electrochemical sensors, as well as their functional roles, are presented in Table 1.

Table 1 - Types of nanomaterials and their roles in electrochemical sensors

Type of Nanomaterial	Material	Structural Features and Properties	Effect on Sensor
Carbon based nanomaterials	Graphene	A single-atom-thick, two-dimensional (2D) sp^2-hybridized carbon lattice with exceptional electrical conductivity and high surface area [12]	Enhances electron transfer and provides a large interface for bioreceptor immobilization, improving sensitivity and signal amplification
	Carbon nanotubes (SWCNTs, MWCNTs)	One-dimensional (1D) cylindrical nanostructures formed by rolled graphene sheets with high conductivity and mechanical strength [13]	Increases active surface area and facilitates efficient electron transport pathways
Metal-based nanomaterials	Gold nanoparticles (AuNPs)	Nanoscale metallic particles with high surface-to-volume ratio, excellent conductivity, and strong affinity to biomolecules [14]	Enable efficient biomolecule immobilization and accelerate electron transfer, enhancing ECL/SERS signals
Other nanomaterials	MXenes	Two-dimensional transition metal carbides/nitrides with metallic conductivity and hydrophilic functional groups (-OH, -O, -F) [15]	Improve charge transfer kinetics and enable stable immobilization of biomolecules
	Metal–organic frameworks (MOFs)	Three-dimensional porous crystalline materials composed of metal nodes and organic ligands with tunable pore size and large surface area [16]	Improve selectivity via selective adsorption and increase sensitivity through analyte preconcentration
	Nanostructured polymers (e.g., chitosan, polyaniline)	Three-dimensional crosslinked or network-like polymer structures composed of repeating monomer units, often forming porous and flexible architectures [17]	Provide a biocompatible matrix for immobilization, enhance stability, and improve adhesion to electrode surfaces

Carbon Nanomaterial-Based Electrochemical Biosensors for Cancer Diagnosis. Among the various types of biosensors, electrochemical biosensors are widely used in disease diagnosis, environmental monitoring and food safety control [18]. These sensors consist of a biological recognition element and an electronic detection system. The operating principle of a biosensor is based on specific electrochemical interactions between the surface of the working electrode

and the target analyte. When the analyte interacts with the electrode surface, electrochemical responses such as current, impedance, or potential are generated and recorded. For practical applications, it is essential to maintain a linear relationship between the analyte concentration and the sensor signal. Various approaches are employed for the detection of target molecules. For example, electroactive analytes such as dopamine and glucose can be directly detected at the electrode surface, either in the presence or absence of a catalyst. In contrast, the detection of non-electroactive compounds requires the use of additional electroactive species, such as hexacyanoferrate or hydrogen peroxide. In sandwich-type structures, the binding of the analyte triggers redox reactions of electroactive species, thereby enhancing the sensitivity of the electrode.

Two key performance characteristics of biosensor electrodes are selectivity and sensitivity. Selectivity refers to the ability of the electrode to specifically recognize a particular analyte, while sensitivity depends on the efficiency of electron transfer between the analyte and the electrode. The signal amplitude can be increased by enlarging the electrode surface area, modifying it with highly conductive materials, or promoting redox reactions. Generally, electrodes with larger surface areas provide more active sites for electrochemical reactions, resulting in higher current responses [19].

One of the important quantitative parameters of a sensor is the limit of detection (LOD), which represents the lowest concentration of the analyte that can be reliably detected by the sensor. This is typically defined by a signal-to-noise ratio greater than 3 [20]. The LOD is a critical parameter for evaluating sensor performance. Selectivity also plays a decisive role in biosensors; therefore, biorecognition elements specific to the target analyte are immobilized on the electrode surface. In cancer biosensors, the primary objective is the proper selection of the target antigen and the accurate determination of its concentration in the human body. Once the antigen is selected, the corresponding antibodies are immobilized on the electrode surface. DNA biosensors are typically fabricated by immobilizing single-stranded oligonucleotides on the sensing surface, which hybridize with complementary DNA sequences [21]. This hybridization process is converted into a measurable electrical signal by the transducer. After immobilization, it is necessary to block the remaining free binding sites on the electrode surface to prevent nonspecific interactions. For this purpose, bovine serum albumin (BSA) or thiol-containing molecules on gold surfaces are commonly used [22].

Carbon nanoparticles are highly suitable materials for biosensor platforms due to their excellent electrical conductivity and large specific surface area. Currently, electrochemical techniques such as amperometry, voltammetric methods including Cyclic Voltammetry (CV), Stripping Voltammetry, Square-Wave Voltammetry (SWV), Differential Pulse Voltammetry (DPV), And Linear Sweep Voltammetry (LSV), as well as impedimetric methods, are widely used for the detection of cancer biomarkers. Voltammetric methods typically employ an electrochemical cell consisting of two or three electrodes and a potentiostat. This system operates by applying a controlled potential and measuring the resulting

current. In contrast, the working principle of amperometric biosensors is based on the use of antibodies conjugated with electroactive nanoparticles or enzymes to capture the target analyte, and determining its concentration by measuring the current generated under an applied potential. The performance of such biosensors is directly influenced by the properties of the electrode, as the signal is generated in close proximity to the electrode surface [22, 23].

Biomarkers are important indicators for the diagnosis of various diseases. Biomarkers found in biological fluids include DNA, RNA, proteins, polysaccharides, and small molecules such as dopamine, uric acid, and glucose. In cancer biosensors, the accurate determination of antigen concentration is of critical importance. Carbon nanomaterials are used in sensors as biorecognition elements for biomarker binding, as transducers that convert molecular interactions into electrochemical signals such as current or impedance, and as labeling elements for signal amplification. Functionalization of carbon nanomaterials with organic polymers or metal oxide nanoparticles increases the electrode surface area and facilitates the immobilization of biorecognition elements. The development of functionalized carbon nanomaterials has significantly improved the analytical performance of electrochemical sensors [22,23].

In recent years, there has been growing in the development of carbon nanomaterial based biosensors for the detection of cancer biomarkers. This interest is driven by the potential of these biosensors to enable rapid, simple, and reliable detection of biomarkers, with strong prospects for clinical application. Carbon nanomaterial-based biosensors offer advantages such as high sensitivity, rapid response time, and ease of use, making them promising tools for early cancer diagnosis. In this field, the recent achievements of international researchers in detecting cancer biomarkers are summarized in Table 2, which presents selected cancer biomarkers, the carbon nanomaterials and composite materials used, the detection methods employed, the associated cancer types, the analytical performance (including detection limits and linear ranges), and references to the corresponding scientific publications.

Table 2 - Various carbon-based nanomaterials used for biomarker detection

Biomarker	Carbon material	Detection method	Detection level	Associated cancer type	Reference
TP53	rGO-CMC	Amperometry	2.9-3.4 nM	All types of cancer	[25]
miR-21	GME	DPV and EIS	2.09 μg mL^{-1}	Breast, lung, prostate cancers	[26]
VEGFR2	Chitosan-functionalized rGO	CV, DPV	0.28 pM	Leukemia, breast and ovarian cancers	[27]
LRG1	rGO nanosheets	CV, EIS, SWV	75 pg mL	Colorectal cancer	[28]
PSMA	Magnetic graphene oxide-$PSMA_{ab}$	DPV	10 pg mL^{-1}	Prostate cancer	[29]
CYFRA-21-1	APTES-modified rGO-ZrO_2 nanocomposite	DPV	0.122 ng mL^{-1}	Oral cancer	[30]
p53 protein	GO@CdS NCs/Au NPs	ECL	4fg mL^{-1}	p53 related cancers	[31]
miR-223	GO@Au-NS	CV, DPV and EIS	0.012 aM	colorectal cancer	[32]

Biomarker	Carbon material	Detection method	Detection level	Associated cancer type	Reference
CEA	Pb^{2+}@Au@MWCNTs-Fe_3O_4)	Amperometry and CV	1.7 fg mL^{-1}	Colon cancer	[38]
CEA	GO/MWCNT-COOH/Au@CeO_2 nanocomposite	ECL	0.02 ng mL^{-1}	Breast tumor, Ovarian and cervical carcinomas	[38]
CEA	Ag NPs-MWCNTs/MnO_2	Amperometry	0.03 pg mL^{-1}	Ovarian carcinoma, colon cancer, breast and lung cancers	[39]
PSA	rGO-MWCNT/AuNPs	Rct and DPV	1 pg mL^{-1}	Prostate cancer	[40]
AFP	PLL-functionalized SWCNTs	DPV and EIS	0.011 ng mL^{-1}	Liver and ovarian cancers, hepatic carcinoma, nasopharyn geal cancer	[41]
miRNA-24	MWCNT-modified GCE	DPV	1 pM mL^{-1}	Multiple cancer types (miR-24-associated, not specified in this study)	[42]
miR-21	FTO-SWCNTs-denAu	DPV	0.01 fmol L^{-1}	Prostate cancer	[43]
CEA	SWCNTs@GQDs / rGO-AuNPs	CV and EIS	5.3 pg mL^{-1}	Ovarian, colon, breast, pancreatic and lung cancers	[44]
CEACAM 5	VA-MWCNTs	CV and EIS	0.92 μM	Gastric, colorectal, lung, breast, and pancreatic cancers	[45]
MALAT1	AuNCs/MWCNT-NH_2	DPV	42.8 fM	lung cancer (NSCLC)	[46]
PSA	Au/Ag-rGO/aminated-GQDs/carboxyl-GQDs	ECL	0.29 pg mL^{-1}	Prostate cancer	[48]
CEA	GQDs/Au@Pt	ECL	0.6 pg mL^{-1}	Colon cancer	[49]
CA-19-9	GQD-functionalized pPtPd nanochains	ECL	0.96 mU mL^{-1}	Pancreatic cancer	[50]
miRNA-155	GQDs	Amperometry	0.14 fM	Not specified (miR-155 is a cancer-related biomarker)	[51]
IL-13Rα2	GQD-functionalized MWCNTs	Amperometry	0.8 ng mL^{-1}	Colorectal cancer, glioma, squamous cell carcinoma of head and neck	[52]
α-L-Fucosidase (AFU)	Au-functionalized carbon dots	Fluorescence emission spectroscopy	3.4 nM	Hepatocellular carcinoma	[53]
ANXA2	CNDs derived from Aloe vera	CV	1 fg mL^{-1}	Liver cancer	[54]
PSA	rGO/g-C3N4/Au NPs	CV, SWV, EIS	0.44 fM	Prostate cancer	[55]
miRNA-141	GO-AuNPs	SPR	1 fM	Prostate cancer	[58]
BRCA1	GCOF	SPR	1-100 nM	Breast and ovarian cancers	[59]
BRCA2	GCOF	SPR	1-100 nM	Breast and ovarian cancers	[59]
CK-19	GO-COOH	SPR	1fg mL^{-1}	Lung cancer	[60]
FAP	Au/rGO	SPR	5 fM	Early detection of cancer	[61]
PPi	PDI-HIS-Cu-GO nanocomposite	Fluorescence spectroscopy	$0.60 \cdot 10^{-7}$ M	Although not a direct cancer biomarker, (monitored as a byproduct of enzymatic reactions)	[63]
uPA	ssDNA-SWCNTs	Fluorescence spectroscopy	50 nM	Prostate cancer	[64]
CA-125	3DNCNTs	Fluorescence spectroscopy	20 μg mL^{-1}	Ovarian cancer	[65]
miR-19 and miR-23 RNA	SWCNTs	Photoluminescence	0.02 mg mL^{-1}	Breast cancer, lung cancer, lymphoma	[66]

Biomarker	Carbon material	Detection method	Detection level	Associated cancer type	Reference
Leukemia K562 cells	CNTs functionalized with GPMS	Photoconductivity	27 cell/ml	Leukemia	[67]
PSMA	Functionalized MWCNTs	ECL	0.88 ng mL^{-1}	Prostate cancer	[68]
CD63	sSWCNTs	UV-Vis spectroscopy	$5.2 \cdot 10^5$ particles/μL	breast cancer	[69]
uPA	Peptide-MWCNT nanoprobes	Fluorescence spectroscopy	500 pg mL^{-1}	general cancer-related proteases	[70]
MMP-7	Peptide-functionalized MWCNT nanoprobes	Fluorescence spectroscopy	0.5 pg mL^{-1}	general cancer-related proteases	[70]
MMP-2	Peptide-functionalized MWCNT nanoprobes	Fluorescence spectroscopy	4.8 pg mL^{-1}	general cancer-related proteases	[70]
miRNA-155	C-dot-MnO_2 nanosheets	FRET	0.1×10^{-18} M	Cancer cells	[71]
CA-15-3	GO-PEI-CQD-Au nanohybrid	ECL	0.0017 U mL^{-1}	Specific to breast cancer (for metastasis monitoring)	[72]
β-Glucuronidase (GLU)	Nitrogen-doped carbon quantum dots (N-CQDs)	Photoluminescence	0.3 U L^{-1}	Colorectal, pancreatic, breast, bladder, liver cancers	[73]
AFP	CNF/AuNPs	CV, SWV and EIS	0.50 pg mL^{-1} (SWV) 0.48 pg mL^{-1} (EIS)	Liver cancer	[74]
miR-31	PEI-Ru@Ti_3C_2@AuNPs	ECL	1.67 aM	Lung cancer	[75]

Graphene-Based Electrochemical Biosensors. Two-dimensional (2D) nanomaterials such as graphene, graphene oxide (GO), and reduced graphene oxide (rGO) have been extensively studied to improve the analytical performance of electrochemical biosensors for the early detection of cancer biomarkers. Graphene-based biosensors exhibit high affinity toward biomarkers such as microRNAs (miRNAs), p53 gene mutations, carcinoembryonic antigen (CEA), alpha-fetoprotein (AFP), and cancer antigens (CA-125, CA15-3), enabling their efficient capture and detection. Electrochemical sensors based on graphene and graphene-like nanomaterials are characterized by rapid response times and high selectivity for the detection of nucleic acid biomarkers. Wu et al. developed a paper-based microfluidic electrochemical platform incorporating rGO for the quantitative analysis of cancer biomarkers [24]. Esteban et al. fabricated a screen-printed carbon electrode functionalized with o-carboxymethylcellulose and rGO for the detection of the tumor suppressor gene TP53, and covalently immobilized two different selective hairpin-forming capture probes onto its surface [25].

In addition, graphene-modified electrodes were used for the voltammetric detection of miR-21 in lysates obtained from breast cancer cells. First, an inosine-substituted anti-miR-21 probe was passively adsorbed onto the surface of a graphene-modified pencil graphite electrode (GME). Subsequently, solid-phase hybridization occurred between the inosine substituted probe and the target miR-21. This process was monitored using DPV and electrochemical impedance spectroscopy (EIS), achieving a detection limit of 2.09 mg mL^{-1}. The proposed method successfully distinguished miR-21-positive breast cancer cells (MCF-7)

from miR-21-negative hepatoma cells (HUH-7) [26]. To detect vascular endothelial growth factor receptor 2 (VEGFR2), the surface of a glassy carbon electrode was modified with chitosan-functionalized rGO to fabricate an electrochemical biosensor. The hybridization process was monitored using voltammetric techniques, and an increase in peak current was observed as the protein concentration increased from 0.4 to 86 pM. This biosensor demonstrated a detection limit of 0.28 pM for VEGFR2 and was described as a simple and effective method for detecting small changes in protein concentration at the electrode surface [27].

Yu et al. developed an advanced electrochemical biosensor for the detection of the colorectal cancer (CRC) biomarker leucine-rich alpha-2 glycoprotein-1 (LRG1), based on graphene-peptide conjugates integrating rationally designed synthetic peptides with rGO nanosheets. The peptides were engineered with dual graphene-anchoring motifs to ensure optimal orientation and high binding affinity toward LRG1 when immobilized on rGO-modified gold electrodes. Benefiting from the high conductivity, large surface area, and stability of rGO, together with the specificity, small size, and facile modification of synthetic peptides compared to conventional antibodies, the sensor exhibited enhanced analytical performance. Electrochemical detection using SWV demonstrated high sensitivity (22.3 $\mu A/(ng/mL \cdot cm^2)$), a low limit of detection of 75 pg/mL in serum, and a wide linear range from 100 pg/mL to 100 ng/mL. The biosensor also showed excellent selectivity, precision (RSD<6-7%), and high accuracy (recovery ~97-104%). Importantly, analysis of colonoscopy-classified patient serum samples enabled clear discrimination between normal, precancerous adenomatous polyps, and malignant CRC stages, with LRG1 levels increasing by approximately 24% in adenomas and 103% in CRC cases. Compared to traditional antibody-based assays, the proposed platform demonstrated superior sensitivity, broader linear range, improved reproducibility, and faster response time. This work highlights the significant potential of combining computational peptide design with graphene-based nanomaterials to develop highly efficient electrochemical biosensors for quantitative detection and staging of colorectal cancer biomarkers [28].

Graphene-based electrochemical immunosensors have also been applied for the detection of tumor-associated biomarkers such as prostate-specific antigen (PSA), carcinoembryonic antigen (CEA), and squamous cell carcinoma antigen (SCCA). Yang et al. proposed an immunomagnetic sensor composed of magnetic GO and anti-PSMA antibodies for the efficient capture and rapid detection of prostate-specific membrane antigen (PSMA) and PSMA-positive prostate cancer cells in blood samples [29]. To detect the CYFRA-21-1 biomarker associated with oral cancer, indium tin oxide (ITO) electrodes were modified with an rGO-zirconium dioxide (ZrO_2) nanocomposite functionalized with APTES (aminopropyltriethoxysilane) [30]. Furthermore, Heidari et al. developed an immunosensor for the detection of the p53 biomarker using a sandwich-type configuration based on GCE/CdS/p53-Ab1 and p53-Ab2-tGO-AuNP. The

incorporation of graphene oxide and gold nanoparticles significantly enhanced the electrochemiluminescence (ECL) signal. This immunosensor exhibited a linear detection range of 20-1000 fg mL^{-1} and an ultralow detection limit of 4 fg mL^{-1} [31].

Akbari et al. developed a novel label-free electrochemical biosensor based on a nanostructured platform composed of graphene oxide (GO) nanosheets decorated with gold nanoflowers (GO@Au-NS) for the sensitive detection of miR-223, a microRNA biomarker associated with colorectal cancer. The sensor utilizes a thiolated single-stranded DNA probe (Cap-223) immobilized covalently on the GO@Au-NS surface through thiol-gold interactions to capture the target miR-223 via hybridization. The biosensor demonstrated excellent electrochemical activity and a remarkably low detection limit of 0.012 aM, with high selectivity against mismatched sequences. Importantly, it showed reliable performance in detecting miR-223 in human serum samples, indicating its clinical applicability. This nanostructured electrochemical immunosensor exhibits high sensitivity, specificity, and antifouling properties due to the hydrophilic nature of the platform, making it a promising tool for early, non-invasive diagnosis of colorectal cancer [32].

Carbon Nanotube (CNT)-Based Electrochemical Biosensors. CEA is a highly glycosylated complex macromolecule belonging to the family of cell surface glycoproteins [33]. These glycoproteins are produced in gastrointestinal tract cells during embryonic development. In healthy adults, the normal concentration of CEA in blood should be below 2.5 μg mL^{-1} [34]. Elevated CEA levels are closely associated with ovarian, lung, and breast cancers [35], and particularly with colorectal carcinoma [36].

Li et al. proposed a label-free electrochemical immunosensor for CEA detection based on the catalytic reduction of hydrogen peroxide. In this system, a glassy carbon electrode modified with magnetic multi-walled carbon nanotubes functionalized with gold nanoparticles (AuNPs) and Pb(II) ions was used to immobilize primary antibodies (Ab1). The sensor exhibited a linear relationship between analyte concentration and catalytic hydrogen peroxide reduction, achieving a detection limit of 1.7 fg mL^{-1} [37]. Pang and et al. developed a notable label-free immunosensor for CEA detection based on ECL characteristics. They proposed a bioanalytical GCE modified with GO, carboxylated MWCNTs, and AuNPs that were functionalized with CeO_2NPs, all dispersed within a chitosan matrix. The biorecognition event was monitored through a decrease in ECL intensity upon interaction with CEA, achieving a detection limit of approximately 0.02 ng mL^{-1}. The proposed immunosensor demonstrated excellent stability and selectivity, showing negligible interference from other biomarkers such as PSA, BSA and AFP. Furthermore, it exhibited reliable performance in serum samples, with recovery values ranging from 98.9% to 102.6% [38].

In an enzyme-free sandwich-type electrochemical biosensor, primary antibodies (Ab1) specific to CEA were immobilized on β-cyclodextrin/multi-walled carbon nanotubes (β-CD/MWCNTs), which enhanced the electrode

surface area and electrical conductivity. Further signal amplification was achieved by immobilizing secondary antibodies (Ab2) on an AgNPs-MWCNTs/MnO_2 nanocomposite, enabling catalytic hydrogen peroxide reduction. This sensor achieved a detection limit of 0.03 pg mL^{-1} for CEA [39]. Heydari-Bafrooei and Shemszadeh prepared an ultrasensitive label-free electrochemical aptasensor based on a modified rGO-MWCNT with densely packed gold nanoparticle (rGO-MWCNT/AuNP) platform to detect the biomarker PSA in serum. The detection was carried out on the variation of electron transfer resistance (Rct) and DPV. As compared to other platforms, the rGO-MWCNT/AuNP nanocomposite modified electrode is the most sensitive aptasensing proposal for the determination of PSA with a detection limit of 1 pg mL^{-1} [40]. The detection of alpha-fetoprotein (AFP) is important for liver cancer diagnosis. Wang et al. fabricated a glassy carbon electrode modified with a Prussian blue (PB) layer and coated with poly-L-lysine-functionalized single-walled carbon nanotubes (PLL-SWCNTs), onto which HRP-labeled anti-AFP antibodies were immobilized. Voltammetric and impedimetric measurements demonstrated a detection limit of 0.011 ng mL^{-1} for AFP [41]. Li et al. developed a biosensor for miRNA-24 detection by covalently immobilizing synthetic DNA probes onto an MWCNT-modified glassy carbon electrode. Hybridization with complementary miRNA-24 was evaluated based on changes in guanine oxidation signals using DPV [42].

Sabahi et al. developed an Fluorine-doped Tin Oxide-based biosensor for detecting the miR-21 biomarker associated with prostate cancer. The fluorine-doped tin oxide (FTO) electrode was functionalized with dendritic gold nanostructures (den-Au) and thiolated receptor probes immobilized on a single-walled carbon nanotube platform. The detection limit obtained using DPV was 0.01 fmol L^{-1} [43]. Luo et al. developed an enzyme-free electrochemical CEA immunosensor using an SWCNT@GQD composite platform modified with an rGO-AuNP system. This immunosensor exhibited a dual signal amplification effect, providing a linear detection range of 50-650 pg mL^{-1} and a low detection limit of 5.3 pg mL^{-1} [44]. Genosensors have demonstrated high cost-effectiveness in detecting the colorectal cancer biomarker CEACAM5. In this system, vertically aligned multi-walled carbon nanotubes were fabricated on a flexible PET substrate using a hot-pressing method and used as a sensing electrode. Target DNA was captured through immobilized DNA probes and characterized using EIS and CV. The hybridization process was studied within the concentration range of 50-250 μM, and the detection limit was determined to be 0.92 μM [45].

Currently, non-small cell lung cancer (NSCLC) is recognized as the most common type of lung cancer. Mei et al. developed an ultrasensitive electrochemical biosensor for detecting the MALAT1 biomarker for NSCLC diagnosis. The biosensor was based on a screen-printed electrode modified with gold nanocages and aminated MWCNTs (AuNC/MWCNT-NH_2). DPV measurements demonstrated an ultralow detection limit of 42.8 fM [46].

Carbon Quantum Dot-Based Electrochemical Biosensors. Carbon quantum dots (QDs) are currently in the early stages of development for the fabrication of

biosensors aimed at biomarker detection [47]. In general, graphene quantum dots (GQDs) have emerged as promising candidates for the construction of ECL and fluorescent biosensors. Wu and co-workers designed a label-free electrochemiluminescent (ECL) immunosensor for PSA detection. The sensor was fabricated by coating a glassy carbon electrode (GCE) with Au/Ag-rGO modified using aminated GR-QDs and GO-QDs, followed by immobilization of anti-PSA on the electrode surface. The developed immunosensor exhibited a detection limit of 0.29 pg·mL^{-1} [48]. Li et al. developed a highly sensitive paper-based ECL immunobiosensor for CEA detection using nanoporous gold-chitosan hybrids and Au@Pt functionalized with graphene quantum dots. In addition, a simple one-pot synthesis strategy for graphene quantum dots was shown to enhance their quantum yield and biocompatibility [49].

The one-pot synthesis of graphene quantum dots provides high quantum yield and excellent biocompatibility. Owing to their good electrical conductivity, Yang et al. developed an ECL-based immunosensor for the detection of carbohydrate antigen 19-9 (CA19-9). In this system, a GCE was modified with a hybrid nanomaterial composed of reduced rGO doped with Au and Ag nanoparticles (GN-Ag-Au) to increase the electrode surface area and improve electron transfer, enabling immobilization of primary antibodies (Ab1). After the specific binding of CA19-9, signal amplification was performed using a secondary antibodies (Ab2) labeled with GQDs functionalized porous PtPd nanochainstructures (pPtPd@GQDs). Under optimal conditions, the immunosensor exhibited a wide detection range of 0.002-70 U mL^{-1} and a low detection limit of 0.96 mU mL^{-1} [50]. A sensitive and accurate method for detecting miRNA-155 was developed based on an electrochemical biosensor fabricated by immobilizing activated carboxyl groups of graphene quantum dots onto aminated DNA structures on the electrode surface. A specific amount of horseradish peroxidase (HRP) immobilized on graphene quantum dots effectively catalyzed the oxidation of 3,3′,5,5′-tetramethylbenzidine (TMB) in the presence of hydrogen peroxide (H_2O_2), resulting in enhanced electrochemical signals. The proposed sensor operated over a concentration range from 1 fM to 100 pM and achieved a detection limit of 0.14 fM [51].

Serafin et al. developed the first integrated electrochemical immunosensor for detecting interleukin-13 receptor alpha-2 (IL-13Rα2). The operating principle of this sensor was based on two main components: 1) MWCNTs functionalized with graphene quantum dots, serving as carriers for multiple detector antibodies and HRP molecules, and 2) biotinylated capture antibodies specific to IL-13Rα2 immobilized on streptavidin-modified screen-printed electrodes. The calibration curve obtained using the amperometric H_2O_2/hydroquinone (HQ) system showed a linear concentration range from 2.7 to 100 ng mL^{-1} and a detection limit of 0.8 ng·mL^{-1} [52].

Mintz and co-workers designed an assay combining AuNPs and CDs for the detection of the α-L-fucosidase (AFU) biomarker, aimed at monitoring hepatocellular carcinoma (HCC). The approach is based on the selective binding

between AFU and its specific antibody (IgG anti-FUCA2). In the presence of AFU, the close proximity of these components enables energy transfer to the surface plasmon band of the AuNPs, leading to fluorescence quenching of the CDs. This method achieved a detection limit of 3.4 nM and exhibited a wide linear detection range from 11.3 to 200 nM [53].

Kulkarni et al. reported a highly efficient electrochemical biosensing platform for the detection of the liver cancer biomarker Annexin A2 (ANXA2), employing CNDs derived from Aloe vera. In this system, anti-ANXA2 antibodies were immobilized onto a thin CND layer electrophoretically deposited on ITO electrodes, while BSA was used to block nonspecific adsorption sites. The sensing mechanism relies on the specific antigen-antibody interaction between ANXA2 and its corresponding antibody, enabling highly sensitive detection using CV. The developed platform exhibited an ultralow detection limit of 1 fg mL^{-1} and a broad linear range from 1 fg mL^{-1} to 500 ng mL^{-1}, along with a rapid response time of 20 minutes, high selectivity, and good reproducibility. This biosensor demonstrates a cost-effective, environmentally benign, and highly sensitive electrochemical immunosensing approach for early-stage liver cancer diagnosis [54].

Saeidi Tabar et al. developed a highly sensitive electrochemical aptasensor for the detection of PSA) a biomarker for prostate cancer diagnosis, based on a novel two-dimensional (2D):2D rGO/graphitic carbon nitride (g-C_3N_4) nanocomposite decorated with AuNPs. The sensing platform was constructed by modifying a GCE with the rGO/g-C_3N_4/AuNPs composite, followed by immobilization of PSA-specific aptamer strands. The successful synthesis of the nanocomposite and electrode modification were confirmed using XRD, FTIR, and TEM. Electrochemical characterization using CV, SWV, and EIS demonstrated enhanced electron transfer properties and effective surface functionalization. The aptasensor exhibited excellent selectivity toward PSA over potential interfering species, including CA 15-3, BSA, fetal bovine serum (FBS), and glucose. Under optimized conditions, the sensor achieved rapid detection within 30 minutes, with an ultralow LOD of 0.44 fM and a limit of quantification of 2.5 fM using methylene blue as a redox mediator. Furthermore, the practical applicability of the developed platform was validated through analysis of real serum samples, highlighting its strong potential for clinical diagnostics [55].

Optical Biosensors. The operating mechanism of optical biosensors is based on changes in light emission resulting from interactions between the target analyte and the recognition element. The generated optical signal is proportional to the concentration of the target analyte in the solution. Carbon nanomaterials, particularly graphene derivatives, are known to be highly efficient fluorescence quenchers. In GO- or rGO-based fluorescent sensors, fluorophores are typically covalently linked to probes designed to capture target analytes. These probe-fluorophore complexes are non-covalently adsorbed onto the GO surface, resulting in fluorescence quenching. Upon binding of the target analyte to the probe, the fluorophore detaches from the GO surface, restoring fluorescence. Due

to their high sensitivity, signal enhancement capability, simplicity of operation, and potential for multiplex detection, optical biosensors based on surface-enhanced Raman scattering (SERS) and localized surface plasmon resonance (LSPR) have attracted significant attention in modern analytical applications [56].

Graphene-Based Optical Biosensors. In SPR-based sensors, biorecognition elements are immobilized on a metal surface, and molecular interactions with the target analyte or biomarker result in changes in the surface mass and refractive index. These changes are converted by the transducer into an SPR signal proportional to the analyte concentration [57]. A highly sensitive and simple SPR biosensor for the detection of miRNA-141 was developed using GO-AuNP hybrids. In this system, a thiolated complementary DNA probe was first immobilized on the gold film surface, and subsequently, the second segment of miRNA-141 was captured using GO-AuNP hybrids conjugated with auxiliary DNA. As a result, an ultralow detection limit of 1 fM was achieved [58]. In addition, quantitative analysis using a graphene-coated fiber-optic SPR biosensor was performed to detect BRCA1 and BRCA2 gene mutations for early breast cancer diagnosis. The 916delTT and 6174delT mutations in the BRCA1 and BRCA2 genes were monitored using the attenuated total reflection (ATR) method [59]. When carboxyl-functionalized graphene oxide (GO-COOH) was incorporated onto a gold film surface, the sensitivity of the SPR sensor for detecting CK19 protein, a biomarker associated with NSCLC, was significantly enhanced, achieving a detection limit of 1 fg mL^{-1} [60]. Li et al. also developed a selective and sensitive label-free graphene-based SPR biosensor for detecting folic acid protein (FAP) in human serum at fM concentrations [61]. By exploiting the polarization and absorption properties of graphene under attenuated total reflection conditions, Fei et al. developed a high-resolution optical sensor capable of detecting refractive index changes with a precision of $1.7 \cdot 10^{-8}$ and a sensitivity of $4.3 \cdot 10^{7}$ mV/RIU. This sensor enables label-free detection of living cells at the single-cell level [62].

Another important optical approach related to cancer detection involves the measurement of pyrophosphate (PPi). A sensor platform based on a self-assembled nanocomposite composed of perylene diimide-histidine (PDI-HIS), Cu^{2+} ions, and graphene oxide demonstrated a detection limit of $0.60 \cdot 10^{-7}$ M for PPi detection [63].

Carbon Nanotube-Based Optical Biosensors. Single-walled carbon nanotubes exhibit near-infrared (NIR) photoluminescence properties in the wavelength range of 900-1600 nm, making them highly suitable for optical biosensing applications. Ryan M. Williams et al. developed a sensitive fluorescent biosensor for detecting urokinase plasminogen activator (uPA), a biomarker associated with metastatic prostate cancer, by utilizing the optical properties of SWCNTs [64]. The DNA/aptamer-CNT platform demonstrated enhanced performance in detecting the cancer biomarker CA125. A fluorescence-based biosensor has also been developed for CA125 detection, employing anti-CA125 antibodies immobilized on three-dimensional carbon nanotubes (3D CNTs) [65].

The near-infrared emission, photostability, and high sensitivity of SWCNTs enable real-time monitoring of the hybridization of microRNAs and other oligonucleotides. A DNA - nanotube-based photoluminescent sensor employing a $(GT)_{15}$ single-stranded oligonucleotide demonstrated a detection range of 10-100 pM for miR-19 and miR-23 RNA targets [66]. For the early diagnosis of chronic myeloid leukemia (CML), a light-induced optoelectronic sensor based on CNTs functionalized with GPMS molecules was developed, achieving a detection limit of 27 cells mL^{-1} for K562 leukemia cells [67].

An ECL-based ELISA-type immunosensor using carbon nanotubes was developed for detecting prostate-specific membrane antigen (PSMA), achieving a detection limit of 0.88 ng mL^{-1} in complex biological samples [68]. To detect exosomes, a visible and colorimetric aptasensor based on DNA-functionalized SWCNTs was proposed. Exosomes bound to the transmembrane protein CD63 catalyzed the oxidation of tetramethylbenzidine (TMB), resulting in a measurable color change. This system demonstrated a detection limit of $5.2 \cdot 10^2$ particles μL^{-1} [69]. Yong et al. developed multicolor fluorescent peptide-CNT nanoprobes capable of simultaneously detecting three cancer-related proteases, including MMP-7, uPA, and MMP-2. Based on fluorescence quenching and recovery mechanisms, protease activity was quantitatively evaluated, achieving detection limits in the range of 0.5-500 $pg \cdot mL^{-1}$ [70]. Mohammadi and co-workers developed a FRET-based sensing platform for the quantification of miRNA-155 using carbon dots (CDs) and MnO_2 nanosheets as donor-acceptor pairs. The system exhibited high specificity, enabling clear discrimination between perfectly complementary miRNA-155 and sequences with a single-base mismatch. Moreover, this approach was successfully applied to the detection of miRNA-155 in spiked serum samples as well as in breast cancer cells, such as MCF-7 [71]. Under the synergistic action of polydopamine, AuNPs, PEI-GO and AgNPs, the ECL signal of CQDs was significantly enhanced and considered as an excellent conductive material to speed up the electron transfer rate and electrochemical detection capability as well. Under optimal conditions, the constructed immunosensor presented a linear concentration in the range from 0.005 to 500 U mL^{-1}, with a detection limit of 0.0017 U mL^{-1} [72]. Early diagnosis is of great practical importance for improving the survival rate and effectiveness of cancer treatment. Shuaimin Lu and colleagues developed a highly sensitive fluorescent biosensor based on the inner-filter effect (IFE) for detecting the tumor-related biomarker β-glucuronidase (GLU). N-CQDs were used as fluorophores, while p-nitrophenol (pNP), generated from the GLU-catalyzed reaction of PNPG, acted as an absorber that quenched fluorescence due to spectral overlap. The sensor enabled monitoring of GLU activity with a low detection limit of 0.3 U L^{-1} [73]. Olorundare et al. developed a highly sensitive electrochemical immunosensor for the detection of AFP, a key cancer biomarker, using a hybrid nanomaterial platform composed of functionalized CNFs and electrodeposited AuNPs on a GCE. The CNF/AuNPs composite significantly enhanced the electrochemical

response, enabling AFP detection over a wide linear range of 0.005 to 500 ng mL^{-1} with a low limit of detection of 0.50 pg mL^{-1} from SWV and 0.48 pg mL^{-1} from EIS measurements. The immunosensor demonstrated excellent sensitivity, selectivity, repeatability, and stability, and was successfully applied to AFP detection in human serum samples, highlighting its potential for clinical cancer diagnostics [74]. Ji et al. developed an ultrasensitive signal-on electrochemiluminescence (ECL) biosensor based on CRISPR/Cas12a and MXene nanocomposites for the detection of miR-31. The platform combined a PEI-Ru@Ti_3C_2@AuNPs-modified electrode with a ferrocene-labeled DNA probe and employed a cascade amplification mechanism involving isothermal strand displacement amplification and Cas12a-mediated trans-cleavage, leading to efficient ECL signal restoration. The biosensor exhibited a wide linear range from 10 aM to 100 pM with an ultralow detection limit of 1.67 aM, along with high specificity and good performance in serum samples, demonstrating its potential for early cancer diagnosis [75].

Overall, the comparative analysis of the reviewed studies clearly demonstrates that hybrid nanocomposite platforms, particularly those combining carbon nanomaterials with metal nanoparticles (e.g., rGO/AuNPs, CNT/AuNPs, CNF/AuNPs), provide the highest analytical performance in electrochemical biosensing of cancer biomarkers. These systems exhibit significantly lower limits of detection (down to fg-aM levels) compared to single-component materials, due to synergistic effects such as enhanced electron transfer kinetics, increased surface area, and improved immobilization efficiency of biorecognition elements. Among detection techniques, electrochemical methods such as DPV, SWV, and EIS demonstrate superior sensitivity and reliability, particularly for nucleic acid biomarkers (e.g., miRNAs), while ECL-based systems show excellent performance for protein biomarkers due to their low background signal and high amplification capability. In contrast, purely optical or single-material systems generally exhibit higher detection limits and lower stability. Therefore, the most effective strategy for the detection of cancer biomarkers involves the use of multifunctional nanocomposite platforms combined with highly sensitive electrochemical techniques, enabling ultrasensitive, selective, and reproducible detection.

3. Conclusion

The theoretical foundations of electrochemical sensors are closely related to the properties of CNMs. The use of CNMs as electrode materials represents a promising approach for improving the analytical performance of electrochemical sensors, thereby making a significant contribution to the advancement of modern sensing technologies.

Nanomaterials are commonly used to modify the surface of working electrodes. In addition to increasing the effective surface area of the electrode, they significantly enhance its analytical performance. Surface modification with

nanomaterials accelerates electron transfer at the electrode/electrolyte interface, resulting in amplified output signals from biosensors. The unique properties of CNMs have contributed substantially to the development and evolution of biosensors for cancer diagnosis. Compared with conventional sensing methods, next-generation biosensors based on CNMs demonstrate superior analytical performance. The distinctive characteristics of graphene, CNTs, and carbon quantum dots have facilitated the development of various nanostructured biosensors and promoted diverse scientific approaches in biosensor design.

In recent years, considerable research efforts have been devoted to improving immunosensors and DNA-based biosensors for the detection of major cancer biomarkers. Considering their cost-effectiveness, high sensitivity, stability, simplicity, and selectivity, biosensors based on carbon nanostructures represent promising tools for the development of advanced diagnostic technologies. With the rapid progress of nanotechnology, particularly in the synthesis and fabrication of carbon nanomaterials, their contribution to biosensing applications continues to expand. Biosensor electrodes modified with nanostructures not only enhance electrochemical and optical properties but also provide a favorable and biocompatible environment for the immobilization of recognition elements. This represents a critical step in the development of immunosensors and DNA biosensors.

In this review, various types of carbon nanomaterial-based biosensors developed for clinical cancer diagnosis over recent decades were analyzed, highlighting the advantages of incorporating carbon nanostructures at different stages of biosensor fabrication. The biosensors discussed in this article enable highly selective, sensitive, and cost-effective detection of cancer biomarkers through the use of carbon nanomaterials as functional components. Therefore, such biosensors have strong potential for widespread application in automated diagnostic systems. However, further improvements in key parameters such as reproducibility, long-term stability, and biocompatibility are required to facilitate their practical implementation. These advancements will enable the use of CNM-based biosensors as affordable and efficient diagnostic tools in clinical laboratories and healthcare settings.

Despite the significant progress achieved in the development of carbon nanomaterial-based biosensors, several critical challenges remain that limit their widespread clinical application. One of the major issues is the lack of reproducibility and standardization in nanomaterial synthesis and electrode fabrication, which leads to variability in sensor performance. In addition, long-term stability and biofouling effects in complex biological samples remain insufficiently addressed. Another important limitation is the gap between laboratory-scale studies and real clinical validation, as many reported sensors are tested only in controlled conditions or spiked samples. Current research trends indicate a shift toward the development of multifunctional, miniaturized, and portable sensing platforms, including lab-on-a-chip and wearable biosensors, as

well as the integration of artificial intelligence for signal processing and data analysis. Future research should focus on improving the scalability, stability, and real-sample applicability of these systems, as well as developing multiplexed biosensors capable of simultaneous detection of multiple biomarkers. Addressing these challenges will be essential for translating carbon nanomaterial-based biosensors from laboratory research into practical clinical diagnostic tools.

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ОБЗОР ЭЛЕКТРОХИМИЧЕСКИХ БИОСЕНСОРОВ НА ОСНОВЕ УГЛЕРОДНЫХ НАНОМАТЕРИАЛОВ ДЛЯ РАННЕЙ ДИАГНОСТИКИ РАКА

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Резюме. Рак является одной из основных причин смертности во всём мире. Ранняя диагностика опухолей рассматривается как ключевая и одновременно сложная задача в эффективном лечении онкологических пациентов. В последние годы биосенсоры на основе наноматериалов активно развиваются как современные и высокочувствительные инструменты диагностики рака. В частности, углеродные наноматериалы значительно улучшают аналитические характеристики электрохимических и оптических сенсорных систем. Целью данного обзора является систематизация возможностей электрохимических и оптических биосенсоров на основе углеродных наноматериалов для раннего выявления рака. К основным задачам относится анализ свойств применяемых углеродных наноструктур (графен, оксид графена, углеродные нанотрубки, углеродные квантовые точки) и оценка их эффективности при определении опухолевых маркеров. Проведён анализ научной литературы, рассмотрены методы вольтамперометрии, амперометрии, электрохимической импедансной спектроскопии, электрохемилюминесценции и поверхностного плазмонного резонанса. Особое внимание уделено стратегиям иммобилизации биорецепторов и функционализации нанокомпозитов. Углеродные наноматериалы обладают высокой электропроводностью, большой удельной поверхностью и биосовместимостью. Эти свойства обеспечивают возможность определения опухолевых маркеров (CEA, AFP, miRNA и белков) в низких концентрациях. Сенсоры характеризуются портативностью, быстрым откликом и низким пределом обнаружения. Биосенсоры на основе углеродных наноматериалов имеют высокую практическую значимость в области ранней диагностики и демонстрируют большой потенциал для клинического применения.

Ключевые слова: биомаркеры, рак, электрохимические биосенсоры, углеродные наноматериалы, графен, углеродные нанотрубки, оптические биосенсоры.

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ҚАТЕРЛІ ІСІКТІ ЕРТЕ ДИАГНОСТИКАЛАУҒА АРНАЛҒАН КӨМІРТЕКТІ НАНОМАТЕРИАЛДАР НЕГІЗІНДЕГІ ЭЛЕКТРОХИМИЯЛЫҚ БИОСЕНСОРЛАРҒА ШОЛУ

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Түйіндеме. Қатерлі ісік әлем бойынша адам өлімінің негізгі себептерінің бірі болып табылады. Ісіктерді ерте кезеңде анықтау онкологиялық науқастарды тиімді емдеудің шешуші әрі күрделі міндеті саналады. Соңғы жылдары наноматериалдарға негізделген биосенсорлар қатерлі ісікті диагностикалаудың заманауи әрі жоғары сезімтал құралы ретінде қарқынды дамып келеді. Әсіресе көміртекті наноматериалдар электрохимиялық және оптикалық сенсорлық жүйелердің аналитикалық сипаттамаларын едәуір жақсартады. Бұл шолудың мақсаты – көміртекті наноматериалдарға негізделген электрохимиялық және оптикалық биосенсорлардың қатерлі ісікті ерте анықтаудағы мүмкіндіктерін жүйелеу. Негізгі міндеттерге қолданылатын көміртекті нанокұрылымдардың (графен, графен оксиді, көміртекті нанотүтіктер, көміртекті кванттық нүктелер) қасиеттерін талдау және олардың ісік маркерлерін анықтаудағы тиімділігін бағалау жатады. Ғылыми әдебиеттерге талдау жүргізіліп, вольтамперометрия, амперометрия, электрохимиялық импеданстық спектроскопия, электрохемилюминесценция және беттік плазмондық резонанс сияқты әдістер қарастырылды. Биорецепторларды иммобилизациялау және нанокомпозиттерді функционализациялау стратегияларына ерекше назар аударылды. Көміртекті наноматериалдар жоғары электрөткізгіштікке, үлкен меншікті бетке және биосәйкестілікке ие. Бұл қасиеттер ісік маркерлерін (CEA, AFP, miRNA және ақуыздар) төмен концентрацияларда анықтауға мүмкіндік береді. Сенсорлар портативтілігімен, жылдам жауап беруімен және төмен анықтау шегімен ерекшеленеді. Көміртекті наноматериалдарға негізделген биосенсорлар ерте диагностика саласында жоғары практикалық маңызға ие және клиникалық қолдануға үлкен әлеует көрсетеді.

Түйін сөздер: биомаркерлер, қатерлі ісік, электрохимиялық биосенсорлар, көміртекті наноматериалдар, графен, көміртекті нанотүтікшелер, оптикалық биосенсорлар

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