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Cutting-Edge Applications of Carbon nanotubes in Biosensors

Biyosensörlerde Karbon Nanotüplerin Son Teknoloji Uygulamaları

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ABSTRACT

Carbon nanotubes (CNTs) have emerged as powerful nanomaterials for enhancing the performance of biosensors due to their exceptional electrical conductivity, high surface area, and compatibility with biological molecules. Their unique structure supports efficient electron transfer and robust immobilization of biomolecules, enabling high sensitivity and selectivity in detecting a wide range of analytes. This review reviews the integration of single-walled and multi-walled CNTs into various biosensing platforms, including electrochemical, optical, and field-effect transistor-based sensors. We highlight how functionalization strategies involving carboxyl, amine, and hydroxyl groups improve biocompatibility and target binding, and how CNT-based nanohybrids with metal nanoparticles enable multiplexed and dual-mode detection. The versatility of CNTs has also facilitated the development of flexible, wearable biosensors for real-time health monitoring. Despite challenges in large-scale synthesis and consistent functionalization, recent technological advances continue to drive innovation in this field. This review aims to provide an overview of the latest progress in CNT-based biosensors and their growing impact in clinical diagnostics, environmental monitoring, and food safety applications.

Key Words
Biosensor carbon nanotubes, electrochemical, nanomaterials.

ÖZ

Karbon nanotüpler (CNT'ler), olağanüstü elektriksel iletkenlikleri, yüksek yüzey alanları ve biyolojik moleküllerle uyumlulukları sayesinde biyosensörlerin performansını artırmak için güçlü nanomalzemeler olarak öne çıkmıştır. Bu benzersiz yapıları, verimli elektron transferini ve biyomoleküllerin sağlam bir şekilde immobilizasyonunu destekleyerek, çok çeşitli analizlerin tespitinde yüksek hassasiyet ve seçicilik sağlar. Bu derleme, tek duvarlı (SWCNT) ve çok duvarlı (MWCNT) karbon nanotüplerin elektrokimyasal, optik ve alan etkili transistör (FET) tabanlı sensörler dahil olmak üzere çeşitli biyosensör platformlarına entegrasyonunu ele almaktadır. Karboksil, amin ve hidroksil gruplarını içeren fonksiyonelleştirme stratejilerinin biyouyumluluğu ve hedef bağlanmayı nasıl artırdığını, ayrıca metal nanoparçacıklarla oluşturulan CNT tabanlı nanohibritlerin çoklu ve çift modlu tespiti nasıl mümkün kıldığını vurgulamaktayız. CNT'lerin çok yönlülüğü, gerçek zamanlı sağlık takibi için esnek ve giyilebilir biyosensörlerin geliştirilmesini de kolaylaştırmıştır. Büyük ölçekli sentez ve tutarlı fonksiyonelleştirme konusundaki zorluklara rağmen, son teknolojik gelişmeler bu alandaki yenilikleri sürdürmektedir. Bu derleme, CNT tabanlı biyosensörlerdeki en son gelişmeleri ve bunların klinik tanı, çevresel izleme ve gıda güvenliği uygulamalarındaki artan etkisini kapsamlı bir şekilde sunmayı amaçlamaktadır.

Anahtar Kelimeler
Biyosensör, karbon nanotüpler, elektrokimya nanomalzemeler.

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INTRODUCTION

Biosensors, which combine a biological recognition element with a transducer, have become indispensable tools in fields such as clinical diagnostics, environmental monitoring, and food safety [1]. CNTs are highly valued in biosensors due to their outstanding qualities, like high electrical conductivity, large surface area, and compatibility with biological materials [2]. These features make CNTs ideal for boosting biosensor performance by allowing fast electron transfer and increasing sensitivity [3]. The long, thin structure of CNTs also supports the efficient attachment of biomolecules, which enables accurate and selective detection of targets [4]. Additionally, CNT-based biosensors are very stable and durable, making them suitable for long-term monitoring [5]. The ability of CNTs to be chemically modified allows further control over their interaction with biological elements, which improves selectivity and signal stability. These modifications are essential for enhancing biocompatibility and minimizing background interference [6]. Functional groups such as carboxyl, amine, and hydroxyl can be introduced onto CNT surfaces to provide binding sites for enzymes [7], antibodies [8], DNA [9], or aptamers [10]. Researchers have demonstrated that both single-walled and multi-walled CNTs can be incorporated into electrochemical biosensors to enhance current response and detection accuracy. These biosensors convert biochemical reactions into electrical signals, and the high conductivity of CNTs significantly enhances this conversion efficiency [11]. In amperometric glucose biosensors, for example, CNTs have provided a large and conductive surface for enzyme immobilization, resulting in lower detection limits and improved response times [12]. In addition to electrochemical platforms, CNTs have also been integrated into optical biosensors, where they have been used to enhance fluorescence and Raman signals [13]. These sensors benefit from the photoluminescence and quenching properties of CNTs, which allow highly sensitive and label-free detection [14]. Their utility has been demonstrated in surface-enhanced Raman scattering (SERS) [15] and fluorescence resonance energy transfer (FRET)-based assays [16]. Hybrid biosensor systems that combine CNTs with nanoparticles have shown synergistic effects that improve sensitivity, stability, and signal amplification. These nanohybrids can be used to build multi-functional biosensors capable of simultaneous detection of multiple targets. For instance, CNT–Au nanocomposites have been successfully used for dual-mode electrochemical and optical sensing [17]. Recent advancements also include CNT-based field-effect transistor (FET) biosensors, which enable real-time and label-free detection with ultra-low limits of detection [18]. These devices are especially promising for the detection of cancer biomarkers, viruses, and toxins. The semiconducting properties of CNTs are ideal for modulating current in FET channels upon biomolecular interaction [19]. The flexibility, miniaturization potential, and reproducibility of CNT-based biosensors make them suitable for wearable devices and point-of-care testing kits [20]. Researchers are exploring printed and stretchable biosensor designs using CNT inks and flexible substrates [21]. These systems have been used in continuous glucose monitoring and wearable sweat sensors [22]. Despite significant progress, some challenges still need to be addressed. These include large-scale production of CNTs with consistent quality, removal of metallic impurities, and reliable functionalization strategies for reproducible sensor responses [23]. Nevertheless, the rapid evolution of nanotechnology and surface chemistry is expected to overcome these obstacles. Altogether, adding CNTs to biosensor systems shows great potential for advancing health diagnostics, environmental checks, and food safety monitoring. This review aims to provide a comprehensive overview of the current state of CNTs-based biosensors. We will discuss the recent advancements that have been made in this field.

Recent Advances in CNTs-Based Biosensors

Carbon nanotubes (CNTs) have emerged as a powerful material in biosensing due to their exceptional electrical conductivity, high surface-to-volume ratio, and strong interaction with biomolecules. Their unique structure allows for fast electron transfer and efficient molecular recognition, making them ideal for electrochemical and field-effect transistor (FET)-based biosensors. CNT-based biosensors have been applied in various fields, including medical diagnostics, environmental monitoring, and food safety. Recent advancements have focused on functionalizing CNTs with biomolecules, integrating them into flexible and wearable sensor platforms, and enhancing their selectivity and stability. These advancements have enabled highly sensitive, real-time detection of biomarkers, pathogens, and toxins, setting the foundation for next-generation biosensing technologies (Table 1). In this context, Shi et al. developed an electrochemical biosensor by modifying screen-printed electrodes (SPEs) with a composite of Au and manganese (IV) nanomaterials on MWCNTs, denoted

Table 1. Overview of recent advancements in carbon nanotube-based biosensor Technologies.

Detection Type	Detector Type	Target	Nanocomposite	LOD	Linear Range	Sensitivity	Key Advantage / Note	Ref
Electrochemical	SPEs	Homocysteine	Au@MnO_2/MW NTs	0.6173 µmol·L^{-1}	5–125 µmol·L^{-1}	0.01110 µA·(µmol·L^{-1})$^{-1}$	Good sensitivity in physiological range	[24]
Electrochemical (FET)	CNTs FET	Endotoxin	CNTs with cGQDs via PLL & PMB	4.6 fg/mL (PBS), 30.3 fg/mL (Serum)	N/A	AUC = 0.99	Ultra-sensitive for clinical use	[25]
Electrochemical (FET)	CNT-array TFT	SARS-CoV-2 RBDs	CNT-array + DNA nanostructures + aptamers	10 aM (WT), 6 aM (Omicron)	8 orders of magnitude	High	Distinguishes viral variants	[26]
Electrochemical	MWCNT-GCE	Catechol, Hydroquinone	Laccase on MWCNTs	0.028 µM (CT), 0.15 µM (HQ)	0.1–57 µM (CT), 0.5–57 µM (HQ)	0.56 µA/µM (CT), 0.54 µA/µM (HQ)	Simultaneous phenol detection	[27]
Electrochemical (FET)	Aptamer-CNT-FET	S. aureus, S. enterica	CNT mesh + Y_2O_3 + AuNPs	1–3 CFU	62.5–6.4×10^4 CFU/mL	High	Real-time foodborne pathogen detection	[28]
Electrochemical (FET)	Floating Gate CNT-FET	SARS-CoV-2 antigen & RNA	Aptamer-functionalized FG CNT-FET	0.05 copies/µL	N/A	Near 100% OPA	Rapid (<1 min) viral detection	[29]
Electrochemical	3D SACNT array	Uric acid	GA/Uricase/SACNT/Pt	1 µM	100–1000 µM	518.8 µA/(mM·cm^2)	High catalytic activity	[30]
Optical (SPR)	SPR biosensor	AML	CCNT + Chitosan + Au	10 nM	0.01–150 µM	134°·RIU^{-1}	High refractive index sensitivity	[31]
Electrochemical (FET)	FET biosensor	Aβ42, Aβ40	CNT	60 aM	N/A	N/A	Detects Alzheimer's biomarkers in serum	[32]
Electrochemical (FET)	FG-CNT FET	Patau DNA, MVs	Semiconducting CNTs + Y_2O_3	45–55 aM	N/A	High	Multiplexed genetic & vesicle detection	[33]
Electrochemical	SPE	Cadaverine	DAO-MWCNT	0.8 µg/mL	3–150 µg/mL	N/A	Rapid amine detection	[35]
Electrochemical	MIP-PGE	Uric acid	MWCNTs + PPy	0.76 mM	0.22–3.5 mM	97.459 µA·$µM^{-1}$·cm^{-2}	Stable molecular imprinting	[36]
Electrochemical (FET)	SWNT-FET	SDE1 biomarker	SWNTs + antibodies	5 nM	Low nM–µM	N/A	Agricultural pathogen detection	[37]

Table 1. Continued

Detection Type	Detector Type	Target	Nanocomposite	LOD	Linear Range	Sensitivity	Key Advantage / Note	Ref
Electrochemical	f-MWCNT/AgNP	Dopamine	MWCNT/AgNP hybrid	0.2778 µM	1–8 µM	0.0058 $mA \cdot cm^{-2} \cdot \mu M^{-1}$	Metal-enhanced CNT performance	[38]
Optical	SWCNT-peptide sensor	Acidic vinegar	Peptides + SWCNTs	0.05% v/v	N/A	High	Food quality monitoring	[39]
FET	FG-CNT FET	miRNA21	CNT-AuNP-Y_2O_3	0.87 aM	N/A	N/A	Detects exosomal miRNAs	[14]
Electrochemical	Flexible PET biosensor	Uric acid	Uricase-MWCNTs	N/A	Full saliva UA range	N/A	Wearable biochemical monitoring	[40]
Electrochemical	BioCNT-FET	β-Lactamases	CNT + BLIP2	N/A	N/A	Differentiates TEM-1 & KPC-2	N/A	[41]
Electrochemical	CNT nanofilm	Alzheimer's biomarkers	CNT upheaved nanofilm	0.023 fM	N/A	High	High-fluorescence sensitivity	[42]
SPR	Ag/Se/CNT sensor	Human sperm	Ag/Se-CNT	N/A	N/A	FoM = 34.075 RIU^{-1}	Fertility diagnostics	[44]
Optical	3DN-CNT fluorescent immunosensor	OSCC biomarkers	3D CNT network + Al_2O_3	0.5 ng/mL	0.1–10,000 ng/mL	20× ELISA	Early oral cancer detection	[47]
Wearable	PAM/CNTs-Au hydrogel sensor	Physiological/motion	PAM + CNTs + Au	N/A	Strain ≤1200%	GF=54.89	Flexible strain sensing	[49]
Electrochemical	CNT-$NiSe_2$	Dopamine	$NiSe_2$-filled MWCNTs	5 nM	5 nM–640 µM	19.62 $\mu A \cdot \mu M^{-1} \cdot cm^{-2}$	High electrocatalysis	[51]

as Au@MnO2/MWCNTs. They found that due to the excellent electrochemical activity and catalytic capability of Au@MnO2/MWCNTs, the biosensor exhibited a wide linear range (5–125 µmol L^{-1}), high sensitivity (0.01110 µA (µmol L^{-1})$^{-1}$), and a low detection limit (0.6173 µmol L^{-1}) for homocysteine, completing detection in just 400 seconds. Shi et al. successfully applied this biosensor to the determination of serum homocysteine, with results consistent with those obtained from an automated clinical chemistry analyzer. Moreover, they highlighted that the simple and portable electrochemical device offered a promising method for on-site analysis and home health monitoring. They constructed an electrochemical analysis system based on a mini-potentiostat (xenSTAT) by modifying functional nanocomposites (Au@MnO_2/MWCNTs) on SPEs. This system provided rapid and sensitive determination of homocysteine with a linear range from 5 to 125 µmol L^{-1} and a detection limit of 0.6173 µmol L^{-1}. Furthermore, Shi et al. concluded that the developed biosensor was suitable for the determination of homocysteine in human serum, offering an approach for clinical diagnosis and prognosis of cardiovascular and cerebrovascular disorders, as well as daily health monitoring [24]. In an alternate inquiry, Cui et al. devised a pioneering CNTs-infused field-effect transistor (CNTs FET) nanosensor for swift, tag-free, and identification of endotoxin, a pivotal element in perilous conditions like endotoxemia and bacteremia. The CNTs FET configuration is materialized by amalgamating polymer-sorted high-grade semiconductor CNT films onto the detection conduit. To enhance sensitivity, they united carboxylated graphene quantum dots (cGQDs) to the CNT facade through poly-L-lysine (PLL). They then covalently bonded Polymyxin B (PMB), exceptionally specific to endotoxin, to cGQDs for endotoxin apprehension and recognition. This methodology exhibited an exceedingly minimal detection threshold in both PBS (4.6 fg/mL) and serum (30.3 fg/mL), with exceptional resilience to interference, allowing for the scrutiny of Gram-negative bacterial infections in blood specimens within a brief period. The receiver operating characteristic curve (ROC) substantiated the methodology's superior diagnostic precision (AUC = 0.990), rendering the CNTs FET biosensor a promising apparatus for premature disease alert in clinical Gram-negative bacteremia and endotoxemia. By employing cGQDs nanoparticles to broaden the operative territory and incorporate more capture probes, the sensor showcased high-sensitivity prowess, discerning endotoxin with a detection threshold of 30.3 fg/mL in intricate matrices. Moreover, it adeptly pinpointed endotoxin in serum specimens from clinically Gram-negative bacterial infections and discriminated against them from healthy individuals with compelling precision (AUC of ROC curve = 0.99). The sensor also facilitated real-time surveillance of endotoxin levels in clinical samples and dispensed pertinent findings within 3 minutes. These extraordinary accomplishments and detection competencies propose potential clinical utilities for the sensor [25].

Additionally, Ma et al. proposed an innovative approach for the swift detection of SARS-CoV-2 antigen using CNT-array-based thin-film transistor biosensors, incorporating tetrahedral DNA nanostructures (TDNs) and triple aptamers. These biosensors exhibited superior response capabilities for detecting the SARS-CoV-2 receptor-binding domain (RBD) compared to alternative sensor technologies. They flaunted an extensive detection span spanning eight orders of magnitude and an astonishingly meager detection limit of 10 aM for wildtype SARS-CoV-2 RBD. Furthermore, the biosensors accurately discerned SARS-CoV-2 Omicron RBD with a LOD of merely 6 aM. The attained level of precision facilitated discrimination among SARS-CoV-2, SARS-CoV, and MERS-CoV antigens. By capitalizing on the merits of CNT-array-based thin-film transistor biosensors and TDNs, Ma et al. established a top-tier, swift methodology for SARS-CoV-2 detection. This tri-aptamer biosensor platform demonstrates potential for identifying emergent SARS-CoV-2 variants and other deadly viruses clinically, furnishing a prompt and high-fidelity approach for diagnosing viral infections beyond the purview of COVID-19 [26].

Malinowski et al. devised an innovative electrochemical biosensor capable of concurrently detecting catechol and hydroquinone. Their method involved applying a laccase biorecognition layer through soft plasma polymerization onto a MWCNT-modified GCE, enhancing peak separation between catechol (CT) and hydroquinone (HQ) oxidation peaks. By utilizing density functional theory (DFT) calculations, they evaluated the variations in electronic structures between dihydroxy benzene isomers and MWCNTs constituting the biosensor interlayer. Optimal performance was attained with 75 µg of MWCNTs possessing a larger internal diameter, resulting in a linear range of 0.1 to 57 µM for CT and 0.5 to 57 µM for HQ, with sensitivities of 0.56 and 0.54 µA/µM, respectively, and LOD values of 0.028 and 0.15 µM. The biosensor exhibited exceptional selectivity, stabi-

lity, and reproducibility and was effectively utilized for quantifying contaminants in natural water samples [27].

In a separate study, Feng et al. employed aptamer-functionalized CNT-FET biosensors for highly sensitive, specific, and rapid detection of Salmonella enterica and Staphylococcus aureus in food samples. Their biosensor achieved detection limits of 1 CFU for *S. enterica* and 1.2 CFUs for *S. aureus* in phosphate-buffered saline buffer, complying with international standards for non-detectability. Despite challenges in food sample analysis, the biosensor reliably detected both bacteria across six food types with detection levels below 15 CFUs, facilitated by a simple dilution preprocessing method. It showed instant recognition within 200 ticks, remarkable precision, and fortitude against disruption, guaranteeing precise outcomes without erroneous positives or negatives. The outstanding efficiency of the biosensor was credited to the extraordinary caliber of its components, encompassing the CNT mesh layer for hyper-sensitive recognition, Y_2O_3 coating to diminish disruption, and AuNPs to amplify sensitivity. This innovation holds significant potential for on-site rapid testing scenarios, offering a promising solution for efficient and reliable pathogen monitoring in various settings [28].

In another study, Liang et al. unveiled a versatile floating gate CNT FET(FG-CNT FET) biosensor for swift and delicate identification of SARS-CoV-2 virus antigen and RNA at the individual virus scale. The sensors, functionalized with aptamers, identified SARS-CoV-2 antigens from raw nasopharyngeal swab specimens in under a minute. Boosted by a multi-probe tactic, the FG-CNT FET biosensor detected extended chain RNA directly without amplification down to the single virus level within the same period. In clinical tests, the device distinguished COVID-19 patients from healthy individuals with an overall percent agreement (OPA) close to 100% for both RNA and antigen detection. Their revelation of a tag-free multiprobe and dual-sensing method employing a FG-CNT FET as the detecting element amplified keenness. The multiprobe tactic identified three disparate loci of an elongated RNA strand, boosting discernment towards genuine viral nucleic acid samples. Additionally, ensnaring long RNA nearer to the sensor's surface circumvented the Debye length boundary in the solution, thus elevating sensor keenness. The FG-CNT FET directly discerned unamplified SARS-CoV-2 nucleic acids down to a solitary virus level of 0.05 copies μL^{-1} in nasopharyngeal swab specimens. Furthermore, the sensor adjusted by the Sp-aptamer identified SARS-CoV-2 antigens (spike protein) from untreated nasopharyngeal swab samples within a single minute, outpacing qRT-PCR in swiftness. Fusing nucleic acid detection with protein detection markedly augmented precision, with the unified OPA value attaining 100% on nasopharyngeal swab test outcomes. Their system offers considerable edges over alternative testing techniques, and the advancement of a portable setup provides a universal and rapid diagnostic tool that may evolve into a swift detection aid to supplement PCR for disease screening and extensive epidemic monitoring [29].

Additionally, Yang et al. devised an innovative electrochemical biosensor founded on a 3D Super-Aligned CNT (SACNT) array for POC uric acid surveillance. The biosensor's operative electrode featured an organized 3D SACNT array immobilized with uricase through a precipitation and crosslinking process, yielding elevated enzyme density, notably larger contact area with reactants, and preserved SACNT structure with exceptional conductivity post-modification. The 3D SACNT array electrochemical biosensor showcased remarkable sensitivity (518.8 $\mu A/(mM \cdot cm^2)$), an expansive linear range (100–1000 µM), and a minimal LOD (1 µM) for uric acid. Moreover, the biosensor facilitated dynamic uric acid monitoring, yielding results in serum samples akin to those obtained using an FDA-approved electrochemical analyzer, indicating its potential for POC monitoring of diverse biomolecules to enhance prognosis, diagnosis, and treatment outcomes of metabolic disorders [30]. Yang et al. also realized continuous flow dynamic monitoring of uric acid with the biosensor, potentially aiding in the early diagnosis and prevention of gout. The biosensor's fabrication was streamlined, relying on conventional microfabrication procedures, rendering it poised for large-scale production. Future investigations could explore diverse 3D structured materials for enzyme immobilization and broaden the detection system to encompass other biomolecules. The apparatus could amalgamate supplementary components to facilitate POC instantaneous surveillance of assorted biomolecules. Their triumph in crafting a 3D SACNT array electrochemical biosensor for POC uric acid monitoring satisfies the medical exigency for regular and effortless uric acid detection. Their discoveries emphasize the biosensor's accuracy and reliability for uric acid measurement in real-world samples, bearing significant potential for future use in observing the fluctuating patterns of various

biomolecules, such as glucose and lactic acid, down the line [30].

Nasiri et al. was presented a breakthrough in bio photonic sensing technologies by developing a carboxylate-functionalized CNT (CCNT) and chitosan (CS) nanocomposite for enhanced SPR biosensors. This study leverages effective medium theory and FDTD simulations to optimize the plasmonic properties of the CCNT/CS composite, focusing on its sensitivity to variations in chitosan content. The researchers evaluated the SPR performance of this composite against a traditional Au thin layer, demonstrating that the CCNT/CS nanocomposite significantly outperformed Au layers in terms of sensitivity and detection limits. The biosensor exhibited a linear detection range from 0.01 µM to 150 µM and a detection limit of 10 nM, with an impressive sensitivity of 134° RIU^{-1}, which is 20 times higher than that of the standard Au thin layer. This biosensor was designed for detecting acute myeloid leukemia (AML) by monitoring changes in the RI upon exposure to AML biomarkers. The study is the first to demonstrate the use of CCNT in SPR biosensing for AML detection. Experimental data confirmed that the CCNT/CS-coated SPR sensor exhibited a significantly stronger interaction with AML solutions compared to unmodified Au sensors. Nasiri et al. conclude that this innovative CCNT/CS composite offers tremendous potential in biomedical diagnostics, particularly in developing highly sensitive biosensors for early cancer detection. The combination of theoretical and experimental results paves the way for further applications of CNT-based SPR biosensors in precision healthcare [31].

In a study by Liang et al., a novel approach was developed to address challenges in conventional biosensors, including poor sensitivity, unstable functionalization, and nonuniform performance. Ultrasensitive, label-free, and scalable FG-CNT-FET biosensors were constructed using polymer-sorted high-purity semiconducting CNT films with wafer-scale fabrication to ensure high uniformity and CMOS compatibility. A significant innovation involved the integration of an ultrathin 6 nm Y_2O_3 high-κ dielectric layer between the CNT channel and FG. This layer was shown to amplify the sensor response and enhance sensitivity via the chemical gate-coupling effect, which minimized ambiguous interactions between biomolecules and the CNT channel. Detection limits of 60 aM for DNA (used for Patau syndrome screening) and 6 particles/mL for microvesicles from hepatoma carcinoma cells were achieved, setting a new benchmark for FET biosensor sensitivity. High reproducibility and uniformity were demonstrated across a 4-inch wafer, and superior bias stress stability was maintained throughout the testing process. The FG-CNT-FET platform was further modified by functionalizing specific probes on Au NPs, allowing for the multiplexed detection of various biological molecules on a single chip. It was concluded that the FG-CNT-FET biosensors provided a universal platform for ultrasensitive and reliable biosensing. Due to their fabrication process being similar to that of high-performance CNT logic devices, the potential for mass production and integration with CNT-based integrated circuits (ICs) was demonstrated. This breakthrough is expected to advance the development of real-time, multibiomarker detection systems for biomedical applications [32].

Chen et al. developed aptamer-functionalized CNTFET biosensors for the highly sensitive and selective detection of Alzheimer's disease (AD) blood biomarkers, specifically β-amyloid (Aβ42 and Aβ40) peptides. These sensors utilize mass-produced, highly uniform semiconducting CNT thin films as ultrathin active channels and nucleic acid aptamers as selective receptors. The biosensors demonstrated a LOD as low as 45 aM for Aβ42 and 55 aM for Aβ40, outperforming other reported methods. To enhance selectivity, a multi-blocking step was introduced, effectively reducing nonspecific adsorption and achieving selectivity ratios of 800% for Aβ42 and 730% for Aβ40, even in the presence of structurally similar proteins like human IgG and albumin. The sensors exhibited a large dynamic range (>10^4), high accuracy with a recovery range of 88–108%, and low sensor-to-sensor variation (<10%). These robust biosensors enabled real-time detection in full human serum within minutes, making them suitable for rapid clinical diagnostics and mass screening. The platform integrates aptamer-functionalized CNT-FETs with a FG insulator design to detect Aβ peptides in both 1× PBS and undiluted serum, offering high sensitivity and reproducibility. With four decades of linear analytical range, these biosensors demonstrated long-term stability in serum and reliable performance across multiple devices. The study underscores the potential of CNT-FET-based biosensors as low-cost, scalable, and highly sensitive tools for early AD diagnosis and POC testing, bridging the gap between expensive laboratory methods and accessible clinical diagnostics [33]. Besides, Ho et al. illustrated the integration of CNTs into next-generation biosensor

chips, combining the sensitivity of CNT-FETs with antibody-based antigen targeting for a robust, multiplexed diagnostic platform. In the study demonstrated the practical application of CNT-FETs for rapid pathogen detection in biological samples by leveraging 200 mm wafer-scale and VLSI-compatible fabrication processes. The CNT-FET-based biosensor was designed to simultaneously detect and identify multiple pathogens through hundreds of functionalized CNT-FET-antibody sensors on a single chip. This multiplexing capability allowed diagnostic results to be obtained within 1 hour of sample collection, in contrast to conventional diagnostic methods such as culture-based pathogen identification, which often require several days thereby offering a scalable, fully electronic solution for real-time infectious disease diagnostics. Ho et al. also emphasize the role of VLSI integration in enabling the large-scale production and accuracy of these biosensors, making them suitable for clinical settings [34]. Amin et al. developed a novel MWCNT-based enzyme biosensor for the detection of cadaverine, a biomarker associated with periodontal disease. Current methods for cadaverine detection are inefficient, prompting the need for a rapid, cost-effective, POC diagnostic tool. In this study, the authors engineered a SPE functionalized with diamine oxidase (DAO) and MWCNTs, enabling precise detection via CV and differential pulse voltammetry (DPV). The functionalization process involved carbodiimide crosslinking using 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride (EDC) and N-Hydroxy succinimide (NHS), facilitating the covalent bonding of DAO to MWCNTs through amide linkages. The biosensor exhibited distinct redox peaks for cadaverine with the modified C-MWCNT/DAO electrode, whereas unmodified SPEs failed to display redox signals. The device demonstrated linear detection of cadaverine concentrations between 3–150 µg/mL, with a LOD of 0.8 µg/mL. Moreover, the biosensor's efficacy was validated using artificial saliva, serving as a proof-of-concept model to enhance the Technology Readiness Level (TRL). The sensor's ability to detect cadaverine in real-time and respond to slight concentration changes highlights its potential for monitoring disease progression in periodontal conditions. Amin et al. suggest that this cost-effective and scalable biosensor could be instrumental in early disease detection, offering a viable alternative to traditional diagnostic methods with superior sensitivity. This work underscores the significant potential of MWCNT-based electrochemical biosensors in advancing personalized healthcare by enabling real-time, POC monitoring of key biomarkers like cadaverine [35]. Yulianti et al. developed a non-enzymatic electrochemical sensor based on molecularly imprinted polymers (MIP) and MWCNTs for the selective detection of uric acid (UA). Uric acid is a critical biomarker for preventing hyperuricemia and related conditions, such as monosodium urate (MSU) formation and Lesch–Nyhan syndrome. Conventional detection methods are inefficient, prompting the need for a cost-effective, high-performance sensor. The researchers used a pencil graphite electrode (PGE) modified with MWCNTs and polypyrrole (PPy), creating a robust, low-cost alternative to traditional carbon electrodes. The fabrication of the sensor involved the functionalization of MWCNTs with carboxylic acid groups to improve their solubility, biocompatibility, and adsorption properties, thereby enhancing their integration into the electrode. The next step was the electropolymerization of PPy, performed using a 1:10 uric acid-to-monomer ratio, 20 polymerization cycles at 100 mV/s, and 30 template removal cycles, which optimized the formation of the molecularly imprinted polymer (MIP) layer. This process yielded a PGE/MWCNTs/MIP electrode with remarkable electrocatalytic performance. The sensor exhibited a linear detection range of 0.22–3.5 mM, a LOD of 0.76 mM, and a sensitivity of 97.459 $\mu A\ \mu M^{-1}\ cm^{-2}$. Additionally, the sensor demonstrated excellent long-term stability, retaining 71% of its performance after 19 days of use, making it a promising tool for reliable, real-time uric acid detection in clinical applications. The sensor demonstrated good selectivity even in the presence of common interfering molecules such as K^+, Na^+, sarcosine, citric acid, ascorbic acid, glucose, and dopamine (DA). Additionally, it showed high reproducibility (%RSD = 5.37) and repeatability (%RSD = 3.43), indicating potential for long-term use in clinical and POC applications. The combination of MWCNTs and PPy significantly enhanced the electrical conductivity and electron transfer efficiency, making this biosensor suitable for real-time uric acid monitoring. Yulianti et al. propose that future work should involve testing in natural sweat samples to validate the sensor's selectivity and integration into wearable devices. This would pave the way for continuous, real-time monitoring of uric acid in personalized healthcare [36].

In a separate investigation, Tran et al. unveiled a meticulously designed label-free biosensor that seamlessly integrates the physical and chemical attributes of single-walled carbon nanotubes (SWNTs) within an innovative FET/chemiresistor framework, augmented by selecti-

ve antibodies targeting Sec-delivered effector 1 (SDE1), for the precise identification of Huanglongbing (HLB) disease in citrus plants. This pioneering biosensor demonstrated exceptional proficiency in detecting SDE1 biomarkers within plant tissue extracts, showcasing a dynamic detection range spanning over three orders of magnitude, from low nanomolar to micromolar concentrations, and boasting an impressive LOD of 5 nM. By employing the standard additions assay methodology, the biosensor facilitated quantitative detection sans external calibration, effectively mitigating the challenges inherent in nucleic acid-based assays and symptom-driven diagnoses susceptible to erroneous outcomes. The successful detection and quantification of the HLB biomarker SDE1 underscore the potential of this chemiresistive biosensor, albeit further refinements are imperative for its seamless integration into field applications. Subsequent endeavors will prioritize the reduction of inter-device variability, enhancement of sensor limits of detection and stability, and the development of portable biosensor platforms tailored for field deployment. Positioned as a label-free chemiresistive biosensor, this innovative platform holds considerable promise in the detection of HLB biomarkers, offering a proactive strategy to combat the proliferation of citrus greening [37].

Furthermore, Anshori et al. engineered hybridized f-MWCNT/AgNP constructs as a biosensing substrate for DA detection. The efficacy of the hybridization process was validated through SEM, EDS, and TEM characterizations, utilizing MWCNTs as the elemental scaffold. Differential Pulse Voltammetry (DPV) assessments revealed a linear scope of 0–8 µM for the hybrid, boasting a LOD of 0.2778 µM, surpassing the requisite threshold for detecting DA in human urine (0.3–3 µM), while exhibiting robust selectivity for DA amid other biofluids of human origin. The synthesized f-MWCNT/AgNP hybrids demonstrated exceptional sensitivity for DA detection. CV analyses unveiled an augmented electrochemical response of the working electrode in the presence of the hybrids, indicative of commendable electrocatalytic prowess. The biosensor showcased an average relative error of merely 2.80% across 10 repeated measurements, underscoring its potential for repeated, highly sensitive DA detection. DPV examinations unveiled a sensitivity metric of 0.0058 mA cm^{-2} μM^{-1}, encompassing a linear range from 1 to 8 µM, alongside a coefficient correlation (R^2) value of 0.998, highlighting its exquisite selectivity for DA vis-à-vis glucose, urea, and uric acid. The inferior LOD relative to the minimum normal DA concentration in human urine underscores the auspicious prospect of this hybrid for discerning genuine human DA analytes [38].

Additionally, Shumeiko et al. pioneered a reusable, cast-and-drop, real-time optical biosensor founded on peptide-encased single-walled CNTs (SWCNTs) for discerning minute proportions of acidic vinegar in the atmosphere at ambient temperatures. Employing the (6,5) SWCNT chirality with pinnacle luminescence encompassed within the span of 970 nm to 1050 nm, they facilitated the utilization of economical and compact Si-found detectors. They illustrated that the biosensor could recognize spoilage in wine by detecting excessive airborne acidic vinegar down to 0.05% (v/v) densities. Their outcomes propose potential utilities for identifying gaseous phases utilizing NIR fluorescent SWCNT nanosensors. They unveiled a prototype of an optical biosensor for gaseous acidic vinegar, composed of dried drops of peptides enshrouding SWCNTs. The arrangement, encompassing a 532 nm laser and a CMOS camera, enabled the surveillance of the photoluminescent response of the SWCNTs to acidic vinegar at ambient temperatures. Among the scrutinized peptide-SWCNT amalgamations, merely the YK-SWCNT amalgamation could perceive minute proportions of acidic vinegar down to 0.05% (v/v). The sensor displayed complete reversibility, with UV radiation considerably diminishing the recuperation period. It also accurately identified excessive acidic vinegar in the bouquet of wine specimens, with responsiveness between 6% to 8%. Subsequent endeavors will be directed towards meticulous calibration and categorization of wine grounded on acidic vinegar concentrations, in adherence to the Code of Federal Regulations. This methodology unveils numerous potentials for remote sensing of volatile molecules using fluorescence in intricate settings [39]. Furthermore, Li et al. devised an exceptionally sensitive, label-free, and enduring FET biosensor engineered around a polymer-sorted high-purity semiconducting CNT film, tailored for the detection of exosomal miRNA. Departing from traditional CNT FET designs, this biosensor adopted a floating gate architecture featuring an ultra-thin Y_2O_3 insulating layer, with AuNPs meticulously assembled on Y_2O_3 serving as linkers to tether probe molecules. Thiolated oligonucleotide probes were immobilized onto the AuNP-coated sensing area, enabling the detection of miRNA21 through the monitoring of current fluctuations before and after hybridization between the anchored DNA probe and target miRNA. This pioneering approach achieved re-

markable sensitivity (LOD: 0.87 aM) and specificity. Clinical validation with plasma samples showcased pronounced distinctions between healthy subjects and breast cancer patients, underscoring its potential in breast cancer diagnosis. The authors underscored numerous benefits of the DNA-functionalized CNT miR-FET biosensor. The high-purity semiconductor CNT network conferred consistent performance and exceptional bias stress stability, surpassing other channel materials. The customized Y_2O_3 insulating layer mitigated interference from extraneous interactions, ensuring unparalleled sensitivity and specificity. The miR-FET biosensor adeptly discerned variations in miRNA expression levels among cancer patients and healthy individuals, heralding advancements in early cancer detection. Furthermore, the biosensor holds promise for seamless integration with microfluidic technology, enabling rapid and ultra-sensitive detection of multiple tumor biomarkers on a single chip, thereby revolutionizing accurate tumor diagnosis [14]. Furthermore, Shi et al. engineered a disposable biosensing platform for uric acid (UA) detection utilizing the screen-printing technique on a flexible PET substrate, tailored for the analysis of non-invasive biological specimens such as saliva. The functionalization of the working electrode with carbon nanotubes and uricase conferred remarkable selectivity to the biosensor, resulting in heightened sensitivity, an ultralow detection threshold and an extensive linear detection range that spans the entire spectrum of UA concentrations in human saliva. Notably, the biosensor enabled direct UA detection in human saliva, with empirical findings aligning closely with clinical assessments, underscoring its promise for non-invasive UA surveillance. The successful development of a uricase-based UA biosensor for salivary UA detection underscores the favorable electrocatalytic properties conferred by uricase-modified MWCNTs on the electrode, ensuring superior sensitivity, selectivity, and broad linear range coverage. Leveraging PET as the substrate offers advantages in terms of portability, cost-effectiveness, flexibility, and disposability, rendering it invaluable in the realm of bioanalysis. This pioneering endeavor presents a straightforward and non-invasive approach to salivary UA quantification, heralding new prospects for healthcare monitoring in diverse clinical settings [40].

Gwyther et al. demonstrated that CNT-FETs are highly promising as miniaturized biosensors, addressing key limitations such as non-specific protein attachment and heterogeneous receptor orientation. By combining advanced molecular dynamics simulations and non-canonical amino acid chemistry, they modeled electrostatic interactions between proteins and SWCNTs and developed a precise method for attaching β-lactamase binding protein 2 (BLIP2) at specific residues. This approach enabled the detection of antimicrobial resistance enzymes (TEM-1 and KPC-2) based on their unique electrostatic surface profiles, which corresponded closely with distinct conductance changes in the biosensor. The use of the non-natural amino acid azidophenylalanine (azF) ensured uniform and reliable receptor orientation, overcoming challenges in conventional setups. This group concluded that this integration of silico modeling, protein engineering, and nanofabrication can streamline the design of CNT-FET biosensors, enabling rapid, multiplexed detection of biomarkers such as β-lactamases, with significant implications for diagnosing antimicrobial resistance and guiding appropriate antibiotic treatments [41]. Withal, Jang et al. demonstrated a novel large-area fluorescent biosensor utilizing a CNT growth-upheaved rough nanofilm for the detection of Alzheimer's disease (AD) biomarkers. The biosensor was designed to identify critical AD biomarkers, including β-amyloid, Tau, and APP proteins, in both artificial cerebrospinal fluid (CSF) and monkey CSF with high sensitivity. The nanofilm was fabricated using photolithography and CVD, where CNT growth optimized the surface roughness, hardness, and area of the nanofilm, significantly enhancing biomarker adsorption. CNTs grown for 10 minutes yielded the optimal surface morphology for sensitive detection. Plasma treatment further maximized biomarker adsorption. The biosensor achieved fluorescence-based detection with detection limits (LOD) as low as 0.082 fM for β-amyloid, 0.098 fM for Tau, and 0.047 fM for APP in artificial CSF, and 0.023 fM for β-amyloid, 0.040 fM for Tau, and 0.036 fM for APP in monkey CSF. The biosensor's large sensing area (2.5 mm × 2.5 mm) and optimized nanofilm fabrication process allowed for precise and ultrasensitive detection of biomarkers. Jang et al. concluded that the CNT growth-upheaved nanofilm biosensor holds immense potential for rapid, large-scale, and early diagnosis of Alzheimer's disease in clinical settings. This innovation marks a significant advancement toward effective mass screening platforms for neurodegenerative diseases [42]. Vorobjova et al. developed a hybrid material of vertically ordered MWCNTs embedded in a porous anodic alumina (PAA) template on oxidized Si substrates for use in electrochemical impedance biosensors. The MWCNTs, synthesized via CVD using nic-

kel nanoparticles (Ni-NPs) as catalysts, had lengths of 0.6–1.5 µm and spacing of 110 ± 10 nm. The fabrication process, incorporating vacuum deposition, photolithography, and electrochemical deposition, optimized surface morphology and enhanced electron transfer kinetics. The proposed electrode structure featured exposed CNT ends, forming a functional sensing layer. EIS confirmed the system's improved electrocatalytic properties, enabling the detection of small biomolecules, nucleic acids, and high-molecular-weight compounds. Test structures were integrated with Archimedean spiral configurations, and the entire fabrication process was compatible with IC technology, allowing scalable production. They demonstrated that this approach provides a cost-effective, high-performance platform for advanced capacitive biosensors, with significant potential for the detection of biologically active molecules and complex targets in biomedical applications [43].

Uniyal et al. proposed a novel SPR biosensor for the detection of human sperm with enhanced sensitivity and precision. The sensor features a five-layered configuration consisting of a glass substrate, Ag, CNTs, selenium (Se), and a functionalized layer for sperm binding. This multilayer design optimizes surface plasmon wave excitation, enabling the detection of even low sperm concentrations. Using the TMM, the biosensor achieved an angular sensitivity of 250°/RIU, a FOM of 34.075 RIU^{-1}, and a detection accuracy (DA) of 0.1319°$^{-1}$. These values represent a significant improvement over existing SPR sensors, particularly in the detection of low sperm quantities. The integration of Se and CNTs with Ag in the sensor enhances its performance, providing strong plasmonic resonance and reliable results. Uniyal et al. concluded that this SPR biosensor offers a cost-effective and efficient tool for sperm analysis, addressing critical challenges in fertility diagnostics. With its improved sensitivity and detection accuracy, this sensor has the potential to significantly enhance diagnostic capabilities for male infertility [44]. Pathak et al. developed a fibre optic SPR sensor for the detection of sulfamethoxazole (SMX) using functionalized CNTs as the sensing layer, with a dynamic range of 0–200 µM. The probe was fabricated by immobilizing functionalized CNTs on a Ag-coated unclad fibre core, and its performance was compared to an enzyme-based fibre optic SPR sensor where CNTs were replaced by tyrosinase enzyme embedded in polyacrylamide (PAM) gel. The study found that both probes exhibited a red shift in resonance or absorbance wavelength with increasing SMX concentration. The CNT-based sensor demonstrated superior performance with a sensitivity of 0.37 nm/µM and a LOD of 0.8918 µM, compared to the enzyme-based sensor, which had a sensitivity of 0.29 nm/µM and an LOD of 1.137 µM. The CNT-based sensor was highlighted as the most effective SMX sensor reported in terms of LOD. Additional advantages of the CNT-based sensor include low cost, high sensitivity, better selectivity, repeatability, and suitability for remote sensing and real-time monitoring, owing to the use of optical fibre for probe fabrication [45]. In another study, Nagarajan et al. proposed a SPR biosensor with a novel layered design for enhanced sensitivity and performance in detecting cancer biomarkers. The sensor incorporates CNTs, ferric oxide (Fe_2O_3), and a bi-metallic layer of Ag and platinum (Pt). This configuration, combined with a PrismBK7 base, optimizes optoelectronic interactions to detect cancer cell RI changes in the range of 1.360 to 1.401, covering six types of cancerous cells. Using the angle interrogation technique, the sensor achieved the highest sensitivity (200.428°/RIU), FoM of 29.91 RIU^{-1}, and Detection Accuracy (DA) of 0.1920°$^{-1}$. The study identified MCF-7 breast cancer cells as the most sensitive to angular interrogation, making the sensor particularly effective for detecting type II breast cancer. MATLAB simulations and COMSOL Multiphysics modeling were used to optimize the Ag layer thickness and evaluate electric field enhancements for maximum performance [46]Moreover, Kil Song et al. developed a hierarchical three-dimensional network of carbon nanotubes (3DN-CNTs) on a Si pillar substrate for the detection of oral squamous cell carcinoma (OSCC) using saliva samples. The 3DN-CNTs were coated with aluminum oxide (Al_2O_3) to enhance structural stability and facilitate the immobilization of antibodies. The biomarker Cyfra 21-1, a representative OSCC marker, was detected using a fluorescence-based sandwich immunoassay. The 3DN-CNTs sensor demonstrated a LOD of 0.5 ng/mL, with a calibration range spanning 0.1 to 10,000 ng/mL and an R^2 value of 0.993. The sensor's sensitivity was approximately 20 times higher than conventional sandwich ELISA systems, attributed to the increased binding sites and hierarchical structure of the 3DN-CNTs, which improved biomolecule accessibility. The clinical applicability of the 3DN-CNTs sensor was evaluated by comparing its performance with a commercial ECL assay system for Cyfra 21-1 detection in saliva samples. The results showed a good linear correlation, with mean coefficient of variation (CV) values below 15%, confirming the sensor's reproducibility [47]. Furthermore, Zhang et al.

developed an electrochemical sensor for detecting paclitaxel (PTX), a critical breast cancer treatment drug, by fabricating a β-cyclodextrin (β-CD) and CNT nanocomposite on a GCE (β-CD/CNT/GCE). Structural and chemical characterization via FTIR, SEM, X-ray photoelectron spectroscopy (XPS), and XRD confirmed the effective grafting of β-CD onto CNTs, demonstrating enhanced sensitivity and selectivity for PTX detection. Electrochemical testing, using amperometry and CV, revealed a linear detection range of 5–1060 μM, a detection limit of 1.7 nM, and a sensitivity of 0.8418 μA/μM. The combined β-CD and CNT nanocomposite amplified electron transfer rates and sensor performance. Validation of the sensor's accuracy in urine samples showed a RSD below 4.72% and recovery values exceeding 96.00%, confirming its reliability for clinical analysis. They concluded that this innovative approach opens avenues for improving sensor selectivity and sensitivity across various applications, including cancer drug detection, food safety, and environmental monitoring [48]. In another study, Chen et al. developed a PAM/CNTs-Au hydrogel microcrack sensor, inspired by the spider slit sensilla, to address the challenges of sensitivity, detection range, and mechanical-electrical balance in flexible conductive sensors. The sensor comprises a PAM hydrogel, doped with CNTs, and coated with a highly conductive Au layer. By modulating the crosslinking density of the PAM hydrogel and the CNT content, the sensor's mechanical properties, adhesion, and sensitivity were optimized. The sensor leverages a unique "island-bridge" conductive pathway, where the interconnected CNT network ("bridge") ensures electrical conductivity and the Au microcrack structure ("island") enhances sensitivity. This architecture imparts high sensitivity (gauge factor (GF) = 54.89) over an exceptionally wide strain detection range (>1200%) and effectively suppresses crack propagation, resulting in outstanding stability and durability. The PAM/CNTs-Au hydrogel microcrack sensor successfully demonstrated its capability to detect both large-scale body motions (e.g., finger, wrist, and elbow movements) and subtle biological signals (e.g., pulses and facial expressions). Its self-adhering properties minimize detection errors caused by mismatches between sensors and human tissues, enhancing accuracy and usability. Chen et al. concluded that the PAM/CNTs-Au hydrogel microcrack sensor offers a highly sensitive, stable, and versatile platform with potential applications in wearable biosensors, medical monitoring, soft robotics, electronic skin, and artificial intelligence devices. Its innovative combination of extensibility, conductivity, and microcrack sensing mechanisms positions it as a promising tool for multiscale motion detection and advanced electronic applications [49].

Geetha et al. proposed a CNTs–CuO nanocomposite (NC) as a promising material for noninvasive acetone detection in human sweat, targeting applications such as diabetes monitoring. Acetone, a by-product of fat metabolism, is a key biomarker for ketosis and diabetes, with sweat acetone levels ranging from 0.2–1.8 ppm in healthy individuals and 1.25–2.5 ppm in diabetic patients. The CNTs-CuO NC was synthesized using the complex-precipitation method, with structural and morphological analysis confirming its properties through XRD, SEM, and FTIR. Electrochemical studies using CV and chronoamperometry demonstrated excellent sensitivity (16.1 mA cm^{-2} mM^{-1}), a detection limit of 0.05 mM, and a linear detection range of 1–50 mM. The nanocomposite showed a rapid response time (2 seconds) and high selectivity, with no cross-reactions from other biocompounds in sweat. The synergistic interaction between CNTs and CuO enhanced the electron transport properties and electrocatalytic performance of the NC. This enzyme-free acetone sensor exhibited stability and reliability in artificial sweat solutions, suggesting its potential for integration into wearable biosensors. Geetha et al. concluded that this technology could reduce the frequency of blood sugar monitoring and serve as a tool for managing diabetes and related complications, such as diabetic retinopathy, renal failure, and nerve degeneration [50]. Singh et al. developed a nonenzymatic electrochemical sensor for DA detection using CNT-encapsulated nickel selenide ($NiSe_2$) nanostructures. The composite was synthesized via a one-step, environmentally friendly CVD method, where CNTs were formed in situ from a carbon-rich metallo-organic precursor. Structural and compositional analyses using XRD, Raman spectroscopy, XPS, and HRTEM confirmed the successful formation of the hybrid $NiSe_2$@CNT nanostructures. The sensor exhibited outstanding electrocatalytic performance with a sensitivity of 19.62 μA μM^{-1} cm^{-2}, a broad linear range (5 nM–640 μM), and a low detection limit, making it suitable for accurate DA detection in human tear samples. The synergistic effects of the enhanced electrochemical activity of $NiSe_2$ and the excellent conductivity of CNTs facilitated efficient electron transfer and high selectivity for DA, even in the presence of interfering molecules. Electrochemical methods such as CV, chronoamperometry (CA), and differential pulse voltammetry (DPV)

were used to evaluate the sensor's performance. The $NiSe_2$@CNT sensor demonstrated remarkable stability, reproducibility, and reusability. Its unique properties make it a cost-effective and reliable platform for noninvasive DA detection in peripheral bodily fluids [51].

DISCUSSION

The integration of CNTs into biosensor platforms has brought considerable improvements in sensitivity, detection range, and versatility across various detection modalities. As highlighted in the table, the dominant application of CNTs has been in electrochemical biosensors, particularly those utilizing FET configurations. These CNT-FET biosensors have demonstrated ultralow detection limits, often at the attomolar (aM) or even zeptomolar (zM) level, for clinically significant biomarkers such as SARS-CoV-2 antigens [29], β-amyloid peptides [32], and exosomal miRNA [14]. The high conductivity and semiconducting behavior of CNTs allow them to act as efficient transducing elements, where even minimal changes in charge distribution due to biomolecular interactions can be translated into measurable electrical signals. Among the reviewed platforms, several hybrid nanocomposites have shown enhanced performance by leveraging the synergistic properties of CNTs with other nanomaterials. For example, gold-decorated CNTs coupled with MnO_2 exhibited improved electrochemical detection of homocysteine [24], while PAA-NiNPs-CNTs composites provided strong sensitivity for catechol and hydroquinone detection [43]. These combinations not only improve the surface area and conductivity but also facilitate better immobilization of enzymes, aptamers, or antibodies, which are critical for target recognition.

A distinct trend is the application of tetrahedral DNA nanostructures and multiple aptamer sequences in CNT-based FET biosensors, as seen in the detection of SARS-CoV-2 variants [26]. These structural strategies increase the capture efficiency of target molecules and enhance the signal-to-noise ratio. Additionally, some systems, like the CNT growth-upheaved nanofilm sensor [42], have integrated both electrochemical and fluorescent detection methods, further expanding the versatility and potential for multiplexed analysis. Beyond electrochemical detection, CNTs have also shown promise in optical biosensors, especially in surface plasmon resonance (SPR) and fluorescence-based platforms. Carboxylated CNTs combined with chitosan and gold nanoparticles have yielded notable SPR sensitivity for acute myeloid leukemia detection [31]. Similarly, peptide-functionalized SWCNTs have enabled effective optical sensing in food-related applications, such as vinegar acidity detection [39]. These results underscore CNTs' strong quenching and photoluminescence-modulating properties, making them valuable for label-free and high-sensitivity optical biosensing. In wearable and flexible biosensing applications, CNTs offer outstanding mechanical properties and electrical performance. A notable example is the PAM/CNTs-Au hydrogel microcrack sensor, which demonstrated significant strain detection capability (up to 1200%) and a high gauge factor [49]. Such innovations position CNTs as leading materials in next-generation wearable healthcare systems, especially for continuous physiological monitoring.

However, despite their impressive contributions, several limitations must be addressed to fully realize the clinical and commercial potential of CNT-based biosensors. These include the difficulty in achieving large-scale production of CNTs with consistent quality, the presence of metallic impurities in raw materials, and challenges in reproducible surface functionalization. Moreover, ensuring biocompatibility and reducing background interference remain essential for developing stable, real-world biosensing devices. In addition to these issues, concerns regarding CNT cytotoxicity and environmental safety persist, as their nanoscale dimensions, high aspect ratio, and reactive surfaces can trigger oxidative stress, inflammation, and bioaccumulation in living systems [52]. The high cost associated with complex functionalization procedures also limits large-scale adoption, particularly when advanced chemical modifications are required for enhanced selectivity or dispersibility. Batch-to-batch variability in synthesis, influenced by differences in purity, chirality, and defect density, further complicates commercialization [53]. Addressing these bottlenecks will require the adoption of biocompatible surface coatings, scalable and low-cost functionalization methods, and rigorous standardization of synthesis and purification processes. Furthermore, the integration of CNTs into flexible and miniaturized platforms must be refined through improved alignment techniques, roll-to-roll manufacturing, and hybrid material strategies. Regulatory guidelines for nanomaterial safety, coupled with interdisciplinary collaboration, will be essential to accelerate the translation of CNT-based biosensors from laboratory prototypes to clinically approved devices.

When considered together, the results from recent studies demonstrate that CNT-based biosensors especially when combined with functional nanomaterials or structured recognition elements can achieve superior detection capabilities for a broad spectrum of biological and chemical targets. Their adaptability across electrochemical, optical, and wearable formats marks them as a cornerstone in the evolution of biosensing technologies. Beyond traditional applications, CNT-based biosensors are making significant strides in emerging fields such as neurochemical sensing, implantable devices, and AI-assisted design. In neurochemical sensing, CNTs are being utilized to detect neurotransmitters like dopamine and serotonin, offering real-time monitoring capabilities essential for understanding neurological disorders. These sensors leverage the high surface area and electrical conductivity of CNTs to achieve sensitive and selective detection, facilitating early diagnosis and personalized treatment strategies.

Implantable biosensors represent another promising application. CNTs, due to their biocompatibility and mechanical flexibility, are integrated into devices designed for continuous in vivo monitoring of biomarkers such as glucose and lactate. These implantable sensors aim to provide real-time data, enabling timely medical interventions and enhancing patient care, particularly in chronic disease management. The integration of AI with CNT-based biosensors is also gaining momentum. AI algorithms are employed to analyze complex sensor data, improving the accuracy and reliability of diagnostics. This synergy allows for the development of intelligent biosensing systems capable of adaptive learning and decision-making, paving the way for advanced healthcare applications. These advancements show the versatility and potential of CNT-based biosensors in addressing complex biomedical challenges. As research progresses, further innovations are expected to enhance their functionality and applicability, solidifying their role in the future of medical diagnostics and personalized medicine [54-56].

CONLUSION

CNTs have significantly transformed the field of biosensor development due to their exceptional electrical conductivity, mechanical strength, and chemical versatility. Their high aspect ratio and excellent biocompatibility make them especially well-suited for interfacing with biological molecules, facilitating efficient electron transfer and greatly enhancing the sensitivity of biosensing systems. Integrating CNTs into biosensor platforms has led to devices with improved selectivity, faster response times, and increased operational stability. While notable progress has been achieved, several challenges still require attention—particularly in refining synthesis techniques, ensuring batch-to-batch consistency, and scaling up device fabrication for real-world applications. Moreover, the integration of CNT-based sensors into portable and user-friendly diagnostic tools remains a key area for future exploration.

Recent advancements highlight the potential of CNTs in advancing biosensing technologies across healthcare diagnostics, environmental monitoring, and food safety. Ongoing research in this field is expected to drive the development of next-generation biosensors with greater precision, reliability, and accessibility—ultimately contributing to more effective and timely detection of a wide array of biological and chemical targets.

References

1. N.P. Shetti, S.D. Bukkitgar, K.R. Reddy, C.V. Reddy, T.M. Aminabhavi, Nanostructured titanium oxide hybrids-based electrochemical biosensors for healthcare applications, Colloids Surf. B Biointerfaces, 178 (2019) 385–394.
2. D.C. Ferrier, K.C. Honeychurch, Carbon Nanotube (CNT)-Based Biosensors, Biosensors, 11 (2021) 486.
3. D.R. Kauffman, A. Star, Carbon Nanotube Gas and Vapor Sensors, Angew. Chem. Int. Ed., 47 (2008) 6550–6570.
4. J. Wang, Carbon-Nanotube Based Electrochemical Biosensors: A Review, Electroanalysis, 17 (2005) 7–14.
5. A. Khan, E. DeVoe, S. Andreescu, Carbon-based electrochemical biosensors as diagnostic platforms for connected decentralized healthcare, Sens. Diagn., 2 (2023) 529–558.
6. S. Ranjbari, M. Bolourinezhad, P. Kesharwani, M. Rezayi, A. Sahebkar, Applications of carbon nanotube biosensors: Sensing the future, J. Drug Deliv. Sci. Technol., 97 (2024) 105747.
7. J.J. Guzmán-Mendoza, D. Chávez-Flores, S.L. Montes-Fonseca, C. González-Horta, E. Orrantia-Borunda, B. Sánchez-Ramírez, A Novel Method for Carbon Nanotube Functionalization Using Immobilized Candida antarctica Lipase, Nanomaterials, 12 (2022) 1465.
8. Y. Nagai, K. Nakamura, J. Ohno, M. Kawaguchi, T. Fujigaya, Antibody-Conjugated Gel-Coated Single-Walled Carbon Nanotubes as Photothermal Agents, ACS Appl. Bio Mater., 4 (2021) 5049–5056.
9. S. Yazdani, M. Mozaffarian, G. Pazuki, N. Hadidi, I. Gallego, G. Puras, et al., Design of double functionalized carbon nanotube for amphotericin B and genetic material delivery, Sci. Rep., 12 (2022) 1–15.
10. H.R. Jamei, B. Rezaei, A.A. Ensafi, Ultra-sensitive and selective electrochemical biosensor with aptamer recognition surface based on polymer quantum dots and C60/MWCNTs-polyethylenimine nanocomposites for analysis of thrombin protein, Bioelectrochemistry, 138 (2021) 107701.

11. A. Das, A. Wazeer, Graphene and Carbon Nanotubes (CNTs)-Based Biosensor for Life Sciences Applications, Smart Innov. Syst. Technol., 322 (2023) 61–79.
12. K. Sakdaphetsiri, S. Teanphonkrang, A. Schulte, Cheap and Sustainable Biosensor Fabrication by Enzyme Immobilization in Commercial Polyacrylic Acid/Carbon Nanotube Films, ACS Omega, 7 (2022) 19347–19354.
13. R. Acharya, T.V. Patil, S.D. Dutta, J. Lee, K. Ganguly, H. Kim, et al., Single-Walled Carbon Nanotube-Based Optical Nano/Biosensors for Biomedical Applications: Role in Bioimaging, Disease Diagnosis, and Biomarkers Detection, Adv. Mater. Technol., 9 (2024) 2400279.
14. T. Li, Y. Liang, J. Li, Y. Yu, M.M. Xiao, W. Ni, et al., Carbon Nanotube Field-Effect Transistor Biosensor for Ultrasensitive and Label-Free Detection of Breast Cancer Exosomal miRNA21, Anal. Chem., 93 (2021) 15501–15507.
15. X. Liang, N. Li, R. Zhang, P. Yin, C. Zhang, N. Yang, et al., Carbon-based SERS biosensor: from substrate design to sensing and bioapplication, NPG Asia Mater., 13 (2021) 1–36.
16. F. Huang, Z. Xie, Q. Zhang, S. Zada, R. Lin, Y. Deng, et al., Recent Advances in Fluorescence Resonance Energy Transfer (FRET) Biosensors for Exosomes, Curr. Issues Mol. Biol., 47 (2025) 235.
17. T.-T. Wang, X.-F. Huang, H. Huang, P. Luo, L.-S. Qing, Nanomaterial-based optical- and electrochemical-biosensors for urine glucose detection: A comprehensive review, Adv. Sens. Energy Mater., 1 (2022) 100016.
18. M.A. Zamzami, G. Rabbani, A. Ahmad, A.A. Basalah, W.H. Al-Sabban, S. Nate Ahn, et al., Carbon nanotube field-effect transistor (CNT-FET)-based biosensor for rapid detection of SARS-CoV-2 (COVID-19) surface spike protein S1, Bioelectrochemistry, 143 (2022) 107982.
19. L.M. Peng, Z. Zhang, S. Wang, Carbon nanotube electronics: recent advances, Mater. Today, 17 (2014) 433–442.
20. Y. Zheng, Y. Zhang, Z. Xue, H. Li, S. Shen, Wearable biosensor with high specific surface area PGA-CNTs electrode for sweat glucose detection, Microchem. J., 210 (2025) 112965.
21. A. Pokprasert, N. Rasitanon, I. Rahma Lani, I. Jeerapan, Tuning the Surface: Screen-Printed Flexible Porous Nanocomposite Electrodes with Programmable Electrochemical Performances for Wearable Platforms, ACS Sens., 20 (2025) 31.
22. X. Wang, Z. Dong, W. Li, D.D. Xiao, G. Liu, Z. Yu, et al., A high-sensitivity continuous glucose sensor using porous 3D cellulose/carbon nanotube network, Talanta, 283 (2025) 127201.
23. B.O. Murjani, P.S. Kadu, M. Bansod, S.S. Vaidya, M.D. Yadav, Carbon nanotubes in biomedical applications: current status, promises, and challenges, Carbon Lett., 32 (2022) 1207–1226.
24. Z. Shi, H. Zhao, F. Zhou, Y. Mao, Z. Gong, M. Lan, Sensitive Electrochemical Biosensor Using Gold and Manganese (IV) Oxide Nanomaterials on Multiwalled Carbon Nanotubes for the Determination of Homocysteine With a Portable Potentiostat, Anal. Lett., (2024).
25. Q. Cui, J. Li, Y. Li, L. Tang, K. Li, T. Li, et al., Sensitive and rapid detection of bacterial endotoxin with a functional carbon nanotube field-effect transistor biosensor, Talanta, 266 (2024) 125035.
26. S. Ma, Q. Ren, L. Jiang, Z. Liu, Y. Zhu, J. Zhu, et al., A triple-aptamer tetrahedral DNA nanostructures based carbon-nanotube-array transistor biosensor for rapid virus detection, Talanta, 266 (2024) 124973.
27. S. Malinowski, M. Wardak, C. Wardak, Effect of Modification of a Laccase-Based Electrochemical Biosensor with Carbon Nanotubes on Signal Separation of Dihydroxybenzene Isomers, Langmuir, (2023).
28. X. Feng, P. Li, T. Li, X. Cao, D. Liu, M. Xiao, et al., Ultra-sensitive and rapid detection of Salmonella enterica and Staphylococcus aureus to single-cell level by aptamer-functionalized carbon nanotube field-effect transistor biosensors, Biosens. Bioelectron., 257 (2024) 116333.
29. Y. Liang, M. Xiao, J. Xie, J. Li, Y. Zhang, H. Liu, et al., Amplification-Free Detection of SARS-CoV-2 Down to Single Virus Level by Portable Carbon Nanotube Biosensors, Small, 19 (2023) 2208198.
30. M. Yang, H. Wang, P. Liu, J. Cheng, A 3D electrochemical biosensor based on Super-Aligned Carbon NanoTube array for point-of-care uric acid monitoring, Biosens. Bioelectron., 179 (2021) 113082.
31. H. Nasiri, K. Abbasian, M. Salahandish, S.N. Elyasi, Sensitive surface plasmon resonance biosensor by optimized carboxylate functionalized carbon nanotubes/chitosan for amlodipine detecting, Talanta, 276 (2024) 126249.
32. Y. Liang, M. Xiao, D. Wu, Y. Lin, L. Liu, J. He, et al., Wafer-Scale Uniform Carbon Nanotube Transistors for Ultrasensitive and Label-Free Detection of Disease Biomarkers, ACS Nano, 14 (2020) 8866–8874.
33. H. Chen, M. Xiao, J. He, Y. Zhang, Y. Liang, H. Liu, et al., Aptamer-Functionalized Carbon Nanotube Field-Effect Transistor Biosensors for Alzheimer's Disease Serum Biomarker Detection, ACS Sens., 7 (2022) 2075–2083.
34. R. Ho, S. Fuller, H.S. Lee, M.M. Shulaker, Biosensor Chip for Point-of-Care Diagnostics: Carbon Nanotube Sensing Platform for Bacterial Detection and Identification, IEEE Trans. Nanotechnol., 23 (2024) 281–285.
35. M. Amin, B.M. Abdullah, S.R. Wylie, S.J. Rowley-Neale, C.E. Banks, K.A. Whitehead, The Voltammetric Detection of Cadaverine Using a Diamine Oxidase and Multi-Walled Carbon Nanotube Functionalised Electrochemical Biosensor, Nanomaterials, 13 (2022) 36.
36. E.S. Yulianti, S.F. Rahman, M. Rizkinia, A. Zakiyuddin, Low-cost electrochemical biosensor based on a multi-walled carbon nanotube-doped molecularly imprinted polymer for uric acid detection, Arab. J. Chem., 17 (2024) 105692.
37. T.T. Tran, K. Clark, W. Ma, A. Mulchandani, Detection of a secreted protein biomarker for citrus Huanglongbing using a single-walled carbon nanotubes-based chemiresistive biosensor, Biosens. Bioelectron., 147 (2020) 111766.
38. I. Anshori, L.N. Nuraviana Rizalputri, R. Rona Althof, S.S. Surjadi, S. Harimurti, G. Gumilar, et al., Functionalized multi-walled carbon nanotube/silver nanoparticle (f-MWCNT/AgNP) nanocomposites as non-enzymatic electrochemical biosensors for dopamine detection, Nanocomposites, 7 (2021) 97–108.
39. V. Shumeiko, E. Malach, Y. Helman, G. Paltiel, G. Hayouka, et al., A nanoscale optical biosensor based on peptide encapsulated SWCNTs for detection of acetic acid in the gaseous phase, Sens. Actuators B Chem., 327 (2021) 128832.
40. W. Shi, J. Li, J. Wu, Q. Wei, C. Chen, N. Bao, et al., An electrochemical biosensor based on multi-wall carbon nanotube–modified screen-printed electrode immobilized by uricase for the detection of salivary uric acid, Anal. Bioanal. Chem., 412 (2020) 7275–7283.

41. R.E.A. Gwyther, S. Côté, C.S. Lee, H. Miao, K. Ramakrishnan, M. Palma, et al., Optimising CNT-FET biosensor design through modelling of biomolecular electrostatic gating and its application to β-lactamase detection, Nat. Commun., 15 (2024) 1–10.
42. Y. Jang, J. Won, Y. Lee, S.H. Park, J. Oh, Optimization of CNT growth-upheaved nanofilm for highly sensitive fluorescent detection of Alzheimer's disease, Sens. Actuators B Chem., 415 (2024) 135991.
43. A.I. Vorobjova, D.I. Tishkevich, E.A. Outkina, Y. Yao, I.U. Razanau, T.I. Zubar, et al., Fabrication of composite nanostructures for impedance biosensors using anodic aluminum oxide templates and carbon nanotubes, Ceram. Int., 50 (2024) 45703–45712.
44. A. Uniyal, K. Kumba, G. Dhiman, M.Z. Ahmed, A. Pal, D. Pal, et al., Advanced SPR Sensor for Human Sperm Analysis: Leveraging Silver and Nanomaterials for Enhanced Performance, Plasmonics, (2024) 1–12.
45. A. Pathak, S. Parveen, B.D. Gupta, Fibre Optic SPR Sensor Using Functionalized CNTs for the Detection of SMX: Comparison with Enzymatic Approach, Plasmonics, 13 (2018) 189–202.
46. P. Nagarajan, S. Manoharadas, V. Dhasarathan, S. Rajeshkannan, Cancer Detection Using Multi-layered Kretschmann Configuration–based Refractive Index Sensor, Plasmonics, (2024) 1–12.
47. C.K. Song, E. Oh, M.S. Kang, B.S. Shin, S.Y. Han, M. Jung, et al., Fluorescence-based immunosensor using three-dimensional CNT network structure for sensitive and reproducible detection of oral squamous cell carcinoma biomarker, Anal. Chim. Acta, 1027 (2018) 101–108.
48. C. Zhang, R. Lang, X. Wen, An electrochemical biosensor based on β-cyclodextrin modified electrode to determine Paclitaxel as an important agent in treatment of breast cancer, Alexandria Eng. J., 91 (2024) 550–557.
49. J. Chen, R. Hou, S. Li, C. Sun, K. Peng, Y. Dai, et al., PAM/CNTs-Au microcrack sensor with high sensitivity and wide detection range for multi-scale human motion detection, Sens. Actuators A Phys., 370 (2024) 115203.
50. M. Geetha, G.G. Nair, K.K. Sadasivuni, S. Al-maadeed, A.G.A. Muthalif, Electrochemical Nonenzymatic Acetone Sensing: A Novel Approach of Biosensor Platform Based on CNT/CuO Nanosystems, Macromol. Symp., 412 (2023) 2200150.
51. H. Singh, J. Wu, K.A.L. Lagemann, M. Nath, Highly Efficient Dopamine Sensing with a Carbon Nanotube-Encapsulated Metal Chalcogenide Nanostructure, ACS Appl. Nano Mater., 7 (2024) 4814–4823.
52. S. Liu, X.D. Zhang, X. Gu, D. Ming, Photodetectors based on two dimensional materials for biomedical application. Biosens. Bioelectron., 143 (2019), 111617.
53. B. Ren, J. Miao, S. Wang, Y. Xu, Z. Zhai, X. Dong, Z. Liu, Nitrogen-rich melamine-based carbon nanosheets prepared via polyvinyl pyrrolidone/ammonia chloride-mediate strategy as an excellent adsorbent for methylene blue adsorption. Adv. Powder Technol., 32 (2021), 1774-1784.
54. T. Akkaş, M. Reshadsedghi, M. Şen, V. Kılıç, N. Horzum,(2025). The Role of Artificial Intelligence in Advancing Biosensor Technology: Past, Present, and Future Perspectives. Adv. Mat., (2025), 2504796.
55. J. Sengupta, C.M. Hussain, Carbon Nanotube-Based Field-Effect Transistor Biosensors for Biomedical Applications: Decadal Developments and Advancements (2016–2025). Biosens., 15, (2025), 296.
56. L. Dong, C. Zhao, C. Han, Y. Yang, F. Yang, Advancement of AI-assisted self-powered healthcare sensing systems. Med. Mat., 2, (2025), 55-77.