J. Electrochem. Sci. Eng. **16** (2026) 3353; https://doi.org/10.5599/jese.3353

Open Access : : ISSN 1847-9286
https://pub.iapchem.org/ojs/index.php/JESE

Review paper

Recent developments in electrochemical biosensors based on nanomaterials for dopamine detection: a brief overview

Neeta Ukirade

Pratibha College of Commerce and Computer studies, Pune, India

Corresponding Author: nitugatkal@gmail.com

Received: April 10, 2026; Accepted: June 6, 2026; Published: June 22, 2026

Abstract

Dopamine is an important neurotransmitter that regulates mood, memory, endorphin production, etc. Dopamine is a catecholamine neurotransmitter that is extensively distributed throughout the central nervous system. High dopamine levels signify cardiotoxicity, which causes hypertension, heart failure and fast heartbeats. Conversely, reduced dopamine levels in the central nervous system have been connected with a number of neurological conditions, including depression, stress, Parkinson's disease, schizophrenia and Alzheimer's disease. Therefore, the development of sensitive, selective, and trustworthy dopamine detection techniques is crucial for biomedical research and clinical diagnostics. Electrochemical biosensors have become a promising platform in analytical techniques because of their high sensitivity, rapid response time, low cost, and suitability for miniaturization. There have been significant advances in the development of electrochemical biosensors based on nanomaterial platforms for detecting dopamine over the past several years. Researchers have used advanced functional nanomaterials, including carbon nanostructures, metal and metal oxide nanoparticles, conducting polymers, molecularly imprinted polymers and hybrid nanocomposites to enhance the electron transfer rate, improve the selectivity of responses and reduce detection limits on their biosensors. The most recent developments in electrochemical dopamine sensors from 2022 to 2025 are thoroughly reviewed in this paper, with a focus on nanomaterials and electrode engineering. Additionally, current issues are emphasized, such as sensor stability, repeatability and interference from coexisting biomolecules. Finally, future perspectives toward wearable devices, point-of-care diagnostics, and sustainable sensor materials are outlined.

Keywords

Neurotransmitters; Electrode engineering; carbon-based nanomaterials; MXenes; hybrid nanocomposites; polymer based materials

Introduction

Dopamine (DA) is 3,4-dihydroxyphenethylamine, a small catecholamine neurotransmitter composed of an ethylamine chain and a catechol ring. Dopaminergic neurons are primarily located in regions such as the ventral tegmental area and substantia nigra, but they are also present in

peripheral tissues, including renal glomeruli and sympathetic ganglia. Dopamine is a catecholamine neurotransmitter that is widely distributed throughout the central nervous system (CNS). Dopamine affects several rewarding behaviours, motor control, attention and neural plasticity, and is essential to memory and learning. Dopamine (DA) is found in the mammalian central nervous system and is involved in regulating human emotions and thought processes. It also has a major impact on the hormonal, cardiovascular and memory systems [1,2]. The normal level of DA in human serum and blood is 1.0 to 1000.0 nmol L^{-1}. A high dopamine level is a sign of cardiotoxicity, which can cause drug addiction, high blood pressure, heart failure and fast heartbeats. However, several neurological diseases, such as stress, Parkinson's disease, schizophrenia, depression, and Alzheimer's disease, can occur due to low dopamine levels. As a result, DA determination is crucial for the accurate diagnosis and management of related illnesses within biological systems. DA levels can be precisely determined using easy, affordable, sensitive, and selective technologies is essential [2,3].

The conventional methods to measure DA include enzyme assay, liquid chromatography, mass spectrometry and capillary electrophoresis. All of these would provide high sensitivity and accurate measurements. Among the various methods listed, high-performance liquid chromatography (HPLC) combined with mass spectrometry (HPLC/MS) is the most commonly used of conventional methods. The HPLC/MS is also viewed as the preferred method; many of the conventional methods are relatively costly, involve intricate and specialized equipment and are not ideally suited for point-of-care testing. However, electrochemical biosensors are a more affordable option for the detection of DA than previous methods and have many advantages such as low cost, rapid response time, high sensitivity and ability to be used in point-of-care settings [4,5]. Dopamine is an electroactive substance; it can also participate in reversible redox reactions. This means that dopamine can be easily measured using electrochemical methods. A problem that arises when dopamine is measured electrochemically is that other electroactive substances can interfere with the measurement. Coexisting electroactive substances, such as ascorbic acid and uric acid, which are present at significantly higher concentrations than dopamine, are found in combination with dopamine in human bodies, causing significant interference [6,7].

In recent years, the use of nanomaterials to modify electrodes has gained much interest in overcoming these issues. Advanced functional nanomaterials, including graphene and its derivatives as well as carbon nanotubes, metal or metal oxide nanoparticles, conducting polymers, molecularly imprinted polymers and hybrid nanocomposites, have been studied extensively to improve the rate of electron transfer and increase the active surface area of the electrode while also enhancing the selectivity for dopamine. They can also be used to create non-enzymatic and enzyme-free sensing platforms that exhibit improved stability and reproducibility in addition to improving analytical performance [8,9].

Several comprehensive reviews on dopamine biosensors have already been reported in the literature [1-4]. However, most existing reviews focus primarily on material development and sensor fabrication, and comparatively little attention has been paid to systematic performance comparisons and the clear identification of research gaps. Thus, this review provides a comprehensive and critical evaluation of recent advances in the field of nanomaterial-based electrochemical dopamine biosensors, with particular emphasis on comparative analysis and existing limitations. The purpose of this mini-review is to summarize the latest developments (2022 to 2025) in electrochemical biosensors that use nanomaterials as substrates for dopamine detection, with an emphasis on detection mechanisms, material selection, analytical performance,

and real-sample applications. Current challenges and future directions for developing wearable, point-of-care, and environmentally friendly devices for detecting dopamine are also described.

Electrochemical detection of dopamine

Sensing mechanism

Dopamine (DA) is electroactive and can therefore be readily oxidized at an electrode surface, enabling electrochemical detection. The schematic for the electrochemical sensing mechanism of DA is shown in Figure 1. Electrochemical behaviour of DA is primarily controlled by a reversible redox process where dopamine is oxidized to dopamine-o-quinone and then reduced back to dopamine. The redox reaction typically involves the transfer of electrons and protons and is usually defined as quasi-reversible under suitable experimental conditions [10,11]. The process of converting DA to DA-o-quinone by losing electrons during oxidation can lead to further participation in chemical reactions, depending on the solution pH and the electrochemical properties of the electrode surface where the reaction occurs. The redox behaviour of DA can be affected by many factors, including pH of the solution, type of electrode material used, experimental surface modifications to that material and the presence of compounds that interfere with the measurement. In biological fluids, DA is frequently found with other electroactive compounds such as uric acid and ascorbic acid, which have similar oxidation potentials. As such, their presence complicates the selective detection of DA. Therefore, surface engineering of electrodes using nanomaterials to enhance selectivity and sensitivity is necessary [12,13]. Based on this electrochemical behaviour, the performance of DA sensors is strongly dependent on the choice of electrode material and its surface properties. In particular, enhancing electron-transfer kinetics and minimizing interference from coexisting species are critical to achieving accurate and selective detection. Therefore, recent research has focused on the use of advanced nanomaterials and optimized electrochemical techniques to improve sensing performance. In the following section, the commonly used electrochemical techniques for DA detection are discussed in detail.

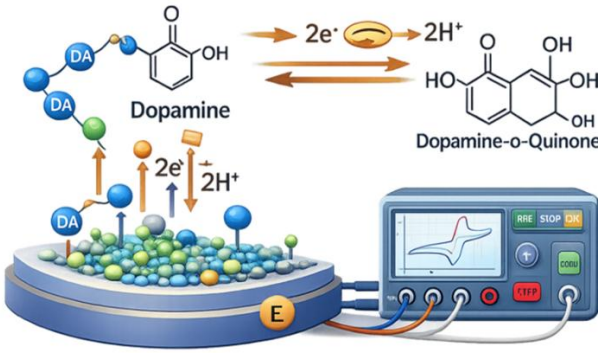

Figure 1. *Schematic illustration of the electrochemical sensing mechanism of dopamine*

Electrochemical techniques

Electrochemical methods are commonly used to detect DA because of their high sensitivity, fast reactions and ease of use. Each of these methods uses either current or impedance changes in response to the redox reaction of DA on the electrode surface to provide accurate quantitative measurements, even at low concentrations [14]. In addition, new techniques such as modifying electrode surfaces and integrating nanomaterials onto electrodes have helped improve the selectivity and analytical performance of these techniques. The techniques covered in this section include cyclic voltammetry, differential pulse voltammetry and amperometry.

Cyclic voltammetry

In cyclic voltammetry (CV) tests, a current is generated by sweeping the potential between two electrodes over a range according to the analyte's redox reaction. This redox reaction changes the peak current, which may be related to the analyte's concentration, yielding specific quantitative analytical data. This approach offers quantitative information from peak current intensity and qualitative information from the peak's probable position [15,16]. For instance, when dopamine is oxidized by cyclic voltammetry, an oxidation peak characteristic of this biomolecule is observed. This molecule can be quantified, and calibration curves can be generated by examining the change in the intensity of the oxidation peak seen in the cyclic voltammograms for varying DA concentrations.

Differential pulse voltammetry

Differential pulse voltammetry (DPV) is a variation of linear sweep voltammetry in which the potential linear sweep is superimposed with a sequence of regular voltage pulses. A popular and extremely sensitive method for detecting low concentrations of DA is differential pulse voltammetry. In DPV, the electrode is held at a base potential selected so that no faradaic reaction occurs. Between pulses, the base potential is raised in equal increments. The current difference is shown against the potential after the current is measured just prior to each potential change. This method improves the signal-to-noise ratio and detection sensitivity by drastically lowering capacitive current. Therefore, in the presence of interfering species, DPV provides better peak resolution, lower detection limits, higher sensitivity, and improved selectivity [17-19].

Amperometry

Amperometric biosensors provide precise quantitative analytical data by measuring the current generated during the oxidation or reduction of an electroactive biological element at a constant voltage applied between a working electrode and a reference electrode. Dopamine biosensors use a constant voltage sufficient to oxidize DA to dopamine-o-quinone *via* a two-electron process. Quantification of DA concentration in the sample is made possible by the current's proportionality to the concentration over a relatively broad concentration range. The magnitude of the oxidation current is directly proportional to the DA concentration within a specific linear dynamic range. This proportionality enables quantitative determination of DA levels in biological and pharmaceutical samples. Due to its rapid response and high sensitivity, amperometry is widely employed for real-time DA monitoring [20,21].

Nanomaterials used in electrochemical biosensors for dopamine detection

Nanomaterials provide an essential solution to improve the analytical performance and characteristics of electrochemical DA biosensors. Nanomaterials can improve sensitivity, selectivity, and detection limits due to their large surface-to-volume ratios, high electrical conductivity, catalytic activity, and biocompatibility. Modifying the electrode surface with nanostructured materials will also enhance electron-transfer kinetics, resulting in a greater effective electroactive surface area than on bare (unmodified) electrodes, thereby improving the sensor's overall performance. In addition, recent studies have confirmed the vital role of nanostructured and catalytic materials in improving the efficiency of electrochemical sensing, particularly through enhanced electrocatalytic activity and faster charge transfer [22,23].

Carbon-based nanomaterials, metal and metal oxide nanoparticles, conducting polymers and hybrid nanocomposites can be described generally as types of nanomaterials for use in DA biosensing

applications. Among these, hybrid nanocomposites have gained increasing attention for their ability to combine the advantages of different material systems and deliver improved sensing performance [22,23].

Carbon-based nanomaterials

Nanoscale carbonaceous materials fall into several different nanostructure categories, such as carbon nanotubes (CNTs), graphene, carbon quantum dots, fullerene, carbon black (CB), carbon nanowires, carbon nanofibers (CNF), carbon nanoribbons, *etc*. Carbon nanomaterials can be categorized by their geometrical configuration into three categories based on their sizes, namely two-dimension (2D), one-dimension (1D) and zero-dimension (0D). Fullerenes are examples of zero-dimensional nanomaterials, carbon nanotubes are examples of one-dimensional and graphene is an example of two-dimensional carbon nanomaterials. Carbon-based nanomaterials exhibit a wide range of unique properties, including excellent electrical conductivity, good chemical stability, high tensile strength, large surface-area-to-volume ratios, and good biocompatibility [24]. Carbon-based nanomaterials commonly used in DA sensing include graphene, carbon nanotubes, carbon nanofibers, carbon black and carbon quantum dots.

Carbon nanotubes

Carbon nanotubes (CNTs) have attracted considerable interest in biology due to their nanoscale dimensions and resistance to corrosion and fouling. CNTs are also of great interest regarding their long-term bio-stability and ability to enable quicker electron kinetics in electronics, semiconductors and biochemical sensor development. Additionally, CNTs form long sp^2-bonded graphite sheets, which can be assembled into supercoiled 3-dimensional chains, thereby providing superior strength compared to other composite materials. These diverse properties make CNTs particularly appealing to neuroscientists seeking to use CNT-based materials in the manufacture of neurological implants [24]. Many advances have been made in detecting dopamine using electrochemistry on CNT electrodes, but little is known about the reaction rates at which dopamine oxidizes on these electrodes. Therefore, there is an obvious need to develop CNT-based materials with better electrochemical properties than current materials to enable more sensitive detection of DA. Kaewda *et al*. [25] developed a label-free electrochemical biosensor for DA detection using polyaniline (PANI) and its aminated derivative, poly(3-aminobenzylamine) (PABA), composited with functionalized multi-walled carbon nanotubes (f-CNTs). This biosensor uses a conducting polymer as a transducing material. Initially, ammonium persulfate was chosen as the oxidizing agent to perform the in situ chemical oxidation polymerization of PANI/f-CNTs and PABA/f-CNTs composite materials. Following the synthesis of these materials, they were used to fabricate electrochemical dopamine biosensors featuring electrospun PANI/f-CNTs or PABA/f-CNTs nanofiber networks on fluorine-doped tin oxide (FTO) coated glass substrates, all under optimized conditions. The f-CNTs incorporated into PANI and PABA enhanced electron transfer within the composite materials, resulting in increased sensitivity, selectivity, and limit of detection (LOD) for the developed DA biosensors. The developed biosensors were employed to conduct label-free electrochemical detection of DA over a range of concentrations (50 to 2000 nM) utilizing the DPV technique, as shown in Figure 2(a) and (b). A clear increase in peak current with increasing concentration confirms the effective electrochemical oxidation of dopamine. The linear calibration plots with high correlation coefficients indicate good sensitivity and reliable quantitative detection. These results yielded sensitivities of 6.88 μA cm^{-2} μM^{-1} for PANI/f-CNTs and 7.27 μA cm^{-2} μM^{-1} for PABA/f-CNTs within the linear range of 50 to 500 nM (R^2 = 0.98) with LODs of 0.0974 and 0.1554 μM for PANI/f-CNTs and PABA/f-CNTs, respectively.

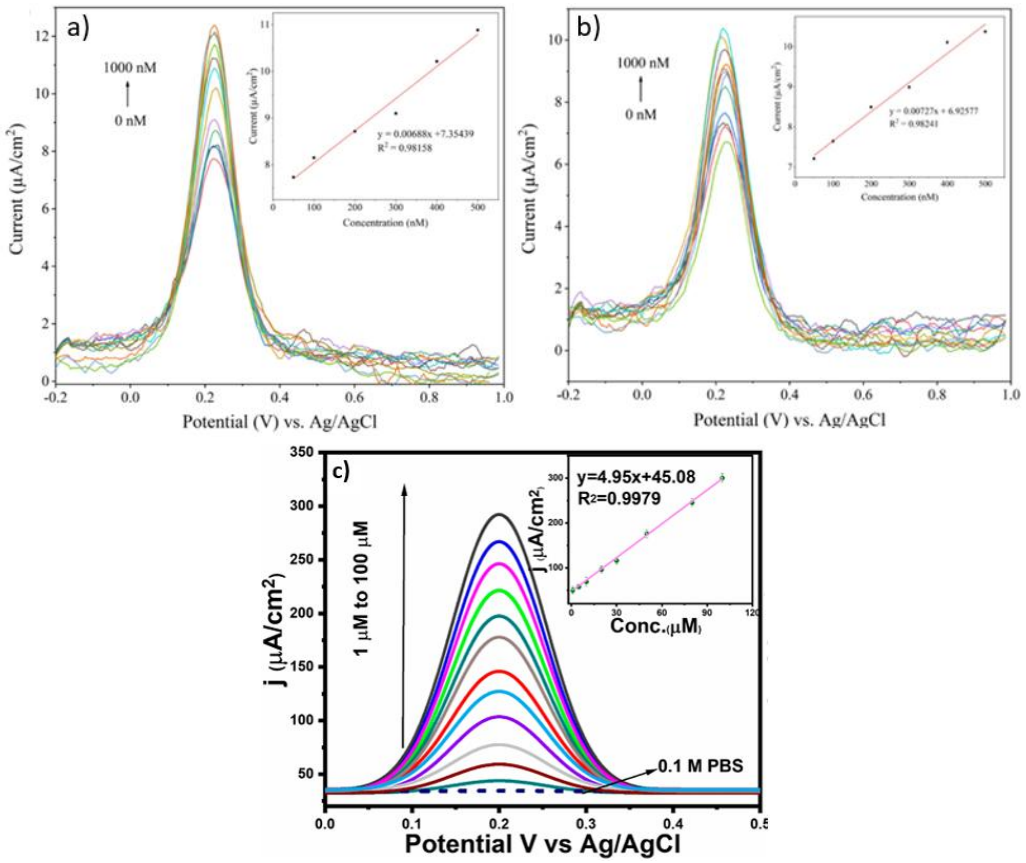

Figure 2. *Differential pulse voltammograms of (a) PANI/f-CNTs (b) PABA/f-CNTs electrospun nanofiber films upon successive addition with increasing concentration of dopamine. Reprinted with permission from [25], (c) DPV plots of NiSe@CNTin 0.1 M PBS buffer in the presence of increasing concentrations of DA Reprinted with permission from [27]*

Additionally, the common interferents, *i.e.,* Glu, ascorbic acid (AA) and uric acid (UA in high concentrations (1 mM) were used to study the selectivity of the electrospun nanofiber films. The DPV responses of electrospun nanofiber films were clearly enhanced after DA injection. These findings showed that, when common interferents are added, the electrospun nanofiber films exhibit good selectivity. The fabricated sensors also demonstrated excellent reproducibility with low RSD values and acceptable repeatability over multiple measurement cycles. Stability studies indicated that composite electrodes retained significant response over several days, which resulted in good stability. Wahyuni *et al.* [26] developed an electrochemical sensor with a high sensitivity based on a reduced graphene oxide (rGO)/multi-walled carbon nanotube (MWCNT) composite for the effective determination and the ability to detect all three materials - hydroquinone (HQ), dopamine and uric acid,-both separately and at the same time, at the surface of the glassy carbon electrode (GCE). The study demonstrated that there is a considerable improvement in the electrocatalytic performance of the rGO/MWCNT composite when using a composition of 1:1 rGO/MWCNT for simultaneous detection of HQ, DA and UA, in concentrations of 1 mg mL^{-1}, when compared to other ratios. Since the improvements are attributed to the synergistic effect between rGO and MWCNT from noncovalent and van der Waals interactions, the signal discrimination and response of the total composite combination will significantly enhance the capabilities in performing these concurrent detections of HQ, DA and UA. The result of these properties of the rGO/MWCNT composite will have an impact on the reduced LODs of HQ, DA and UA of 0.8, 1.0 and 0.6 μM, respectively. Singh *et al.* [27] developed nonenzymatic electrochemical sensors by encapsulating nickel selenide diselenide in carbon nanotubes via a single-step chemical vapor deposition. The oxidation and

reduction behaviour of DA at the modified $NiSe_2$@CNT electrode was investigated by DPV at dopamine concentrations ranging from 1 to 100 µM, as shown in Figure 2(c). The peak current increases proportionally with concentration, indicating efficient electrochemical oxidation of dopamine. The linear calibration plot (R^2 = 0.9979) demonstrates excellent sensitivity and a wide range of composite nanostructures for dopamine detection. This research successfully developed a composite nanostructure made up of nickel detection range. The low background current further confirms good signal stability and reliability of the sensor. The hybrid structure created has a high degree of electrocatalytic activity for the oxidation of DA with a 19.62 µA μM^{-1} cm^{-2} sensitivity, extremely low limit of detection and a broad dynamic range (5 nM to 80 µM). The sensor also shows excellent selectivity in the presence of other common molecules that could interfere with dopamine detection. Given the high sensitivity and selectivity of this composite nanostructure, it has the potential to be used to create simple, selective, sensitive electrochemical sensors for detecting and quantifying dopamine in human tears with high confidence. Carbon nanotubes (CNTs) exhibit moderate sensitivity and relatively high detection limits compared with graphene- and MXene-based sensors. On the other hand, due to their superior structural stability and ease of functionalization, CNTs are more easily developed into stable, repeatable sensing platforms. The performance characteristics of various carbon nanotube-based electrochemical dopamine biosensors reported in recent studies [25,28-30] are summarized in Table 1.

Table 1. *A comparison of performances of carbon nanotube-based electrochemical dopamine biosensors*

Sensor (material)	Linear concentration range, µM	LOD, µM	Ref.
MWCNTs-CTAB/Zn/Co@N-CNSs/GCE	0.10 to 12.0	0.037	[28]
AgNPs/f-MWCNT/Poly(L-cysteine)/PGE	0.10 to 5.0 and 10.0 to 1000	0.068	[29]
α-$NiMoO_4$ @ CNT	100 to 1200	58.2	[30]
PANI/f-CNT	0.05 to 0.5	0.0974	[25]
CNT-encapsulated $NiSe_2$	0.005 to 640	19.62	[27]

CTAB: cetyltrimethylammonium bromide; CNSs: carbon nanosheets;NPs: nanoparticles; PGE: pencil graphite electrode: CNT: carbon nanotubes

Graphene and its derivatives

Graphene is a 2D nanomaterial made of a single layer of sp^2-hybridized carbon atoms, arranged in a hexagonally structured honeycomb lattice. Graphene has extremely high electrical conductivity due to its delocalized π-electron system, enabling rapid electron transfer from dopamine to the electrode surface, resulting in higher oxidation current and improved sensitivity [31,32]. Since its discovery, graphene and its derivatives (graphene oxide and reduced graphene oxide) have been of great interest in electrochemical sensors, due to their unique electrical, mechanical, and surface properties. These properties maximize electrocatalytic oxidation, enhance selectivity against interfering substances, and enable detection limits as low as the nanomolar range. Therefore, graphene-based nanocomposites provide an excellent platform for developing highly sensitive and selective biosensors for dopamine in biomedical and clinical applications [33].

Shinde *et al.* [34] derived a flexible and highly sensitive electrochemical sensor based on $Nb_4C_3T_x$ MXene-silver nanoparticle (AgNP) decorated laser-induced graphene (LIG) electrodes, fabricated on a pyralux polyimide substrate for dopamine detection. In this research, a LIG structure was fabricated on polyimide by laser processing. The LIG structure was modified by incorporating nanosheets of $Nb_4C_3T_x$ MXenes and silver nanoparticles (AgNPs) to produce a nanocomposite, which enhanced the electrochemical performance of the LIG structure due to the complementary catalytic properties of each component. The LIG-$Nb_4C_3T_x$ MXene-AgNPs electrode displayed remarkable electrooxidizing activities for dopamine, which was attributed to the amalgamation of excellent conductivity of graphene,

elevated surface area and metallic conductivity of MXene and the catalytic properties of AgNPs. Amperometric measurements showed a large linear detection range of 100 nM to 10 µM, and the ultra-low detection limit of 1 nM. The sensor also exhibited an impressive sensitivity of 160.96 µA nM^{-1} cm^{-2}. Additionally, the produced electrode showed impressive selectivity towards commonly occurring interfering substances (*i.e.* glucose, ascorbic acid and uric acid), reproducibility, and operational stability. Based on the study's results, the LIG-$Nb_4C_3T_x$ MXene-AgNP nanocomposite flexible electrode has shown potential to serve as an effective and reliable platform to detect dopamine levels with high sensitivity and selectivity and may provide insight into real-time measurements of dopamine levels within the body, such as through urine.

An electrochemical sensor that uses activated graphene to detect DA and UA with high levels of sensitivity was simultaneously reported by Vadivelu *et al*. [35]. They used three separate activation agents (potassium hydroxide, phosphoric acid, and zinc chloride) to chemically activate the graphene, thereby enhancing its electrocatalytic properties. Potassium hydroxide-activated graphene (AGK) showed the highest levels of electrochemical activity of the three activated graphene types. The activation process, which occurred at elevated temperatures, led to a partial recovery of graphene's graphitic crystalline structure. The graphite structure has also improved surface porosity, which is important because it increases the AGK's surface area (making it more electroactive) and reduces the time required for electrons to transfer between the electrodes. Herein, screen-printed carbon electrodes were modified by using activated graphite, and the resulting AGK-modified electrodes showed excellent electrocatalytic properties for the oxidation of both DA and UA, allowing for complete resolution of the peaks at a peak separation of 0.23 V, based on both LSV and DPV testing, while at the same time, demonstrating good resolution from interference due to ascorbic acid. Figure 3 shows two well-defined and separated oxidation peaks corresponding to DA and UA, indicating excellent selectivity and minimal interference. The calibration plots demonstrate a linear increase in current with concentration for both analytes, confirming good sensitivity and reliable quantitative detection.

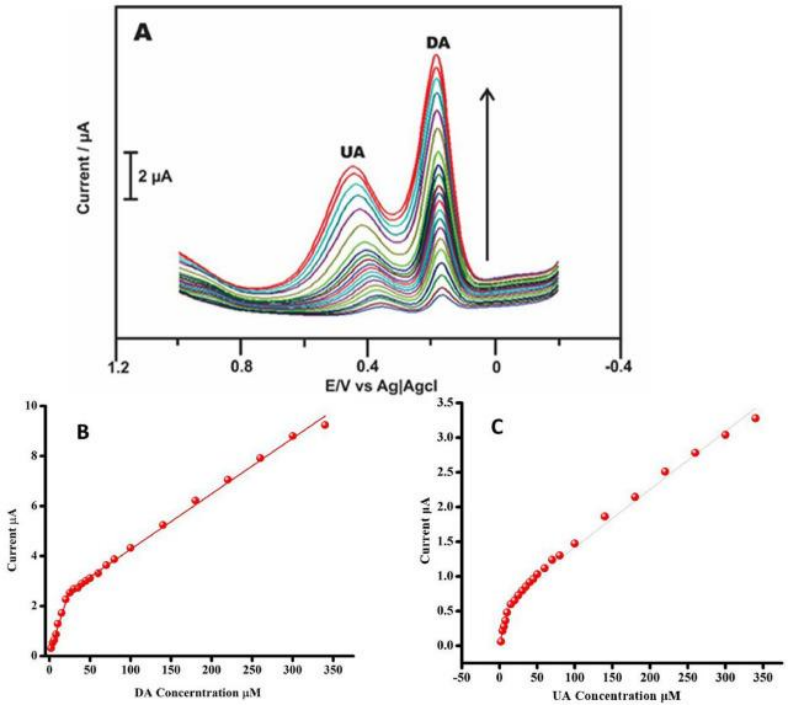

Figure 3. *(A) Differential pulse voltammetry responses and corresponding plots of peak current versus concentration for (B) DA and (C) UA recorded at the AGK-modified SPCE in 0.1 M PBS. The concentrations of DA and UA ranged from 0.02 to 400 µM. Reprinted with permission from [35] distributed under the Creative Commons CC-BY license*

The analytical performance characteristics of the AGK-modified electrode indicate a low detection limit of 0.09 µM for DA and 0.19 µM for UA, with a linear dynamic range of 0.02 to 400 µM for both DA and UA when using DPV, as illustrated in Figure 3. The AGK-modified electrode exhibits great selectivity, reproducibility, and stability when testing laboratory-prepared samples as well as actual clinical samples. In conclusion, KOH-activated graphite is a highly promising candidate as a sensing material for the selective and simultaneous electrochemical detection of DA and UA, and as an efficient, interference-free platform for potential use in real-world medical applications. In comparison to CNT-based sensors, graphene-based materials exhibit superior electron mobility and lower detection limits due to their two-dimensional structure and higher surface area.

However, compared to MXene-based systems, graphene may show slightly lower electrocatalytic activity, particularly in enzyme-free sensing applications. The performance characteristics of various graphene-based electrochemical dopamine biosensors reported in recent studies [36-39] are summarized in Table 2.

***Table 2**. A comparison of performances of graphene based electrochemical dopamine biosensors*

Sensor (material)	Linear concentration range, µM	LOD, µM	Ref.
Apt-Au-N-rGOF	1 to 100	0.5	[36]
rGO/Sm_2O_3	0.5 to 20	0.030	[37]
Graphene-PEDOT:PSS	3.13 to 400	0.19	[38]
rGO/PPy-POM	0 to 10	0.072	[39]

Apt: aptamer; rGOF: reduced graphene oxide fibers; PEDOT: poly(3,4-ethylenedioxythiophene); PSS: polystyrene sulphonate; PPY: polypyrrole; POM: polyoxometalate

MXene materials

MXene materials in 2D form have been identified as promising for electrochemical biosensing due to their unique physical and chemical properties. MXenes are known as "transition metal carbide", which are created from a type of material called MAX phase, consisting of the following $M_{n+1}X_nT_x$; M being a transition metal, X is carbon or nitrogen and T_x are surface functional groups, such as -OH, -O, -F. Among the available MXenes, $Ti_3C_2T_x$ has been studied in detail for its application in electrochemical biosensing. The main characteristics of MXenes include high electrical conductivity, large surface area, extremely hydrophilic surfaces, and excellent electrocatalytic activity, making them suitable candidates for biosensor applications in neurotransmitter detection [40]. Ren *et al*. [41] and Facure *et al.* [40] reported Ti_3C_2 MXene/graphene quantum dots (GQDs)) based electrochemical sensors for detecting DA levels. Using a combination of two-dimensional and zero-dimensional materials, Ti_3C_2 MXene has high electrical conductivity, while GQDs have a high active surface with excellent electrocatalytic properties. Researchers assessed several mixed Ti_3C_2:GQDs ratios using CV and electrochemical impedance spectroscopy to optimize the sensor's electrochemical characteristics. The best composition produced an electrochemical sensor using a Ti_3C_2:GQDs (1:3)- modified glassy carbon electrode, which exhibited a linear response to DA over the range of 40 to 400 µM, with a limit of detection of 1.8 µM. The electrochemical sensor also showed good selectivity in the presence of potential interference and was verified for DA detection in human urine and sweat samples. The improved electrochemical performance can be attributed to the synergistic effects between the MXene's high conductivity and the GQDs' large electroactive area. Given these findings, such composite structures could be used to develop electrochemical sensors for other biomolecules. The performance characteristics of various MXene-based sensors generally demonstrate higher electrocatalytic activity and lower detection limits compared to other

sensors. However, their practical application is limited by challenges such as oxidation instability and reduced long-term durability. MXene-based electrochemical biosensors for dopamine detection reported in recent studies [10,42-46] are summarized in Table 3.

Table 3. *A comparison of performances of MXene based electrochemical dopamine biosensors*

Sensor (Material)	Linear concentration range, μM	LOD, μM	Ref.
Pt/$Ti_3C_2T_x$ MXene/GCE	0.05 to 9000	0.05	[42]
$Ti_3C_2T_x$-MXene/4-APBA	0.04 to 0.5	0.0013	[43]
Ti_3C_2/G-MWCNTs/ZnO/GCE	0.01 to 30	0.0032	[44]
CuO/C/$Ti_3C_2T_x$	0.01 to 2960	6.718	[10]
MXene-ERHG/GCE	0.2 to 125	0.044	[45]
Annealed MOF/MXene (CuO/C/$Ti_3C_2T_x$)	0.01 - 2960	6.718	[46]

4-APBA: 4-aminophenylboronic acid; ERHG: electrochemically reduced holey graphene; MOF: metal organic framework

Metal and metal oxide nanomaterials

Metal and metal oxide nanomaterials have emerged as highly promising materials for electrochemical biosensing applications due to their unique physicochemical and electrochemical properties. In addition, their small size gives them a high surface-area-to-volume ratio, which increases the number of active sites for biomolecular interactions. Metals such as Au, Ag, Pt, and Pd are good conductors of electricity, while many transition-metal oxides, such as ZnO, CuO, NiO, Fe_3O_4, and MnO_2, exhibit intrinsic catalytic activity and chemical stability. Overall, these properties will enhance electron transfer at the electrode-electrolyte interface, thereby improving analytical performance [47,48]. Metals and metal oxides provide enhanced sensitivity and specificity for detecting DA. The oxidation of DA to dopamine o-quinone at the electrode surface involves two reversible electron transfers. Nanostructures composed of metals or metal oxides increase the rate of this oxidation reaction, thereby producing larger peak currents and improving the signal resolution relative to certain common interfering species (*e.g*. ascorbic acid, uric acid) as they will tend to produce larger currents than the interfering species. The enhanced surface area of these nanostructures allows more dopamine molecules to adsorb onto their surfaces, and improved electron-transfer kinetics enable detection of DA at increasingly low concentrations, even at nanomolar levels [47-49].

Naz *et al*. [50] have developed a non-enzymatic electrochemical dopamine sensor based on a hydrothermally synthesized NiO/ZnO hybrid nanocomposite using date fruit extract as a green reducing agent and stabilizer. In this study, NiO was used as the precursor with the incorporation of ZnO to create a hybrid composite with improved electrocatalytic activity. Date fruit extract was served to enhance the catalytic performance and structural organization of NiO/ZnO composite. Electrochemical studies reveal that the NiO/ZnO hybrid exhibits excellent electrocatalytic activity toward the oxidation of DA in phosphate buffer (pH 7.3) without the addition of enzymes. Sensor has a large linear detection range (0.01 to 4 mM) and a low detection limit (0.036 μM). Furthermore, the fabricated sensor demonstrates good selectivity, repeatability, reproducibility, and stability. Analysis of real banana peel and wheat grass extract confirms its practical application. The study concludes that green-synthesized NiO/ZnO hybrid materials containing biomass extracts offer a feasible, low-cost and environmentally friendly method for producing next-generation electrochemical sensors for the detection of DA and other biomedical applications. In addition, researchers have analysed copper oxide nanoparticles for DA detection extensively due to their strong catalytic performance and low-cost synthesis. Additionally, biosynthesized yields of copper oxide nanostructures exhibit faster charge-transfer kinetics and higher sensitivity for the detection of DA, indicating promise for developing environmentally friendly sensing devices [51]. A comparison of

the analytical performance of recently reported metal and metal oxide-based electrochemical dopamine biosensors [50,52-55] is summarized in Table 4.

Table 4. *A comparison of performances of metal and metal oxide-based electrochemical dopamine biosensors*

Sensor (material)	Linear concentration range, μM	LOD, μM	Ref.
NiO/ZnO	10 to 4000	0.036	[50]
ZnO/GCE	0.01 to 100	0.00047	[52]
Au@SiO_2-APTES/GCE	0 to 8	0.014	[53]
Ag_2CrO_4	5 to 45	1.05	[54]
CuO/rGO	1 to 300	1.84	[55]

APTES: 3-aminopropyl triethoxysilane; rGO: reduced graphene oxide

Polymer materials

Polymer materials are widely used in biosensing due to their ability to provide several different functions, their tuneable chemical compositions and properties, flexibility, improved mechanical properties, biocompatibility, and ease of modification. Polymers can serve as the sensing matrix, the conductive layer, and a platform for the immobilization of biomolecules. When polymeric materials are used in the electrochemical detection of dopamine, they increase the rate of electron transfer; enhance sensor selectivity by preventing interference and reducing fouling; and provide stable, sensitive detection of biological samples. Moreover, investigations into chemically modified metal composites incorporating polymers have been conducted to improve their selectivity and stability. An example of this is poly(asparagine)-modified duplex stainless-steel composite electrodes, which have been found to provide highly selective and sensitive methods for detecting DA, due in part to enhancements in both surface features and electron transport properties [56]. When used in conjunction with nanomaterials, polymeric sensors achieve improved analytical performance for clinical and wearable applications.

Conducting polymers and molecularly imprinted polymers

Conducting polymers are widely used modifiers that can be applied chemically or electrochemically from their monomer solutions to bare electrodes. Their exceptional electrical and optical properties arise from electron delocalization in the polymeric backbone, enabled by an extensive π-conjugated structure with alternating single and double bonds throughout the chain. Conducting polymers improve the performance of biosensors by increasing the rate at which electrons move through the sensor's electron-transfer kinetics and by increasing the actual surface area available on the electrode where the reaction occurs. The ability of the polymer to undergo rapid redox reactions, as in an electroactive compound like dopamine, makes conducting polymers ideal candidates for biosensors. Many of these polymers can also be functionalized with biomolecules or used in conjunction with carbon materials and nanoparticles to develop composite sensing interfaces that are more sensitive, selective and stable than the individual components [57,58].

Tejwani *et al.* [59] developed a novel GO/SiO_2@PANI nanocomposite to allow for the electrochemical detection of DA using DPV. In that work, GO, SiO_2, and PANI were successfully used for the first time to create a novel composite material as a sensing platform for DA detection. The composite material was prepared using the *in situ* polymerization method to ensure uniform dispersion of GO/SiO_2 throughout the PANI matrix. The GO/SiO_2@PANI-modified GCE showed increased electrocatalytic ability for DA oxidation due to the combined effect of GO's large surface area, PANI's ability to conduct electricity, and the structural stability of the SiO_2 nanoparticles. The electrochemical performance, as investigated by DPV, is shown in Figure 4. The results showed a linear working range

between 2 and 12 µM, with a detectable limit of 1.7 µM and a relative standard deviation of 2.5 %, indicating good sensitivity and repeatability. Furthermore, the sensor demonstrated excellent selectivity and stability in testing using synthetic urine samples, indicating its suitability for use in complex biological matrices. The authors concluded that the GO/SiO_2@PANI composite is a low-cost, stable and effective method for detecting dopamine and that this technology has great potential for use in clinical diagnostics and in the management of neurological disorders.

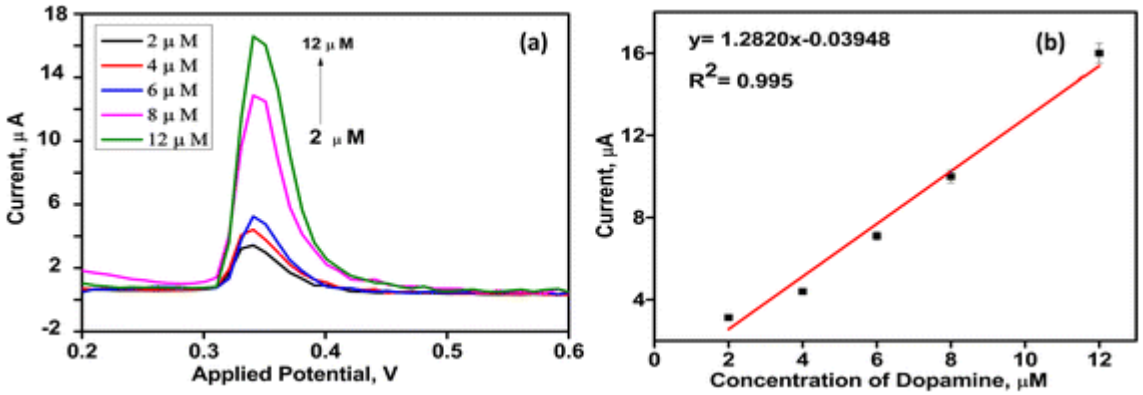

Figure. 4 *(a) DPV for different concentrations of dopamine from 2 to 12 µM with PBS buffer (pH 7.4) and (b) standard calibration curve for respective dopamine concentrations. Reprinted with permission from [59] distributed under the Creative Commons CC-BY license*

Darroudi *et al*. [60] developed a microelectrode-array neural probe that reliably and accurately detects DA release using fast-scan cyclic voltammetry (FSCV). In order to enhance the electrochemical properties of the platinum (Pt) microelectrodes fabricated from a microelectronic process; they deposited carbon nanomaterials such as carboxylated multi-walled carbon nanotubes (COOH-MWCNTs), and carbon quantum dots (CQDs) on the surface of the electrode, as well as conducting polymers, polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT), applied through co-electrodeposition to provide a stable conductive layer to the Pt substrate and attach the carbon nanomaterials together. In this study, the CNT-CQD-PPy modified microelectrode exhibited the best performance compared to the other configurations, such as CNT-CQD-PEDOT, CNT-PPy and CNT-PEDOT, and even bare Pt electrodes. The enhancement in performance of this hybrid microelectrode system is attributed to the synergistic effects of CNTs (providing high surface area and good electrical conductivity), CQDs (enhancing electron-transfer kinetics), and PPy (providing excellent adhesion and structural stability). The dramatically improved LOD for DA using the optimized microelectrode was 35.20 ± 0.77 nM.

Molecularly imprinted polymers (MIPs) are man-made materials made of a polymer that are engineered to have specific recognition sites that match in size, shape, and function (functional groups) with a target molecule. They are made by chemically reacting a functional monomer together with a template molecule to create the binding site. The binding of the template molecule is removed after the polymerization process, and it creates 'selective cavities' within the polymer that have the ability to re-bind to the target analyte. MIPs act as artificial receptors, they are similar to the way antibodies or enzymes selectively bind to their substrates, but they are more chemically and thermally stable [61,62].

An electrochemical sensing platform based on an ultrasensitive MIP for the detection of the physiologically relevant basal level of dopamine in complex biological media was described by Nekoueian *et al.* [63]. The sensor is made up of a combination of molecular imprinting technology and carbon hybrid nanomaterials. Carbon nanofibers (CNFs) were created by growing on tetrahedral amorphous carbon (ta-C) thin films deposited on silicon wafers *via* plasma-enhanced chemical vapor

deposition (PECVD). Dopamine-imprinted PPy was then deposited onto the ta-C/CNF substrate to provide molecular-specific recognition sites. The ta-C/CNF/MIP sensing platform exhibited excellent electrochemical properties due to the combined advantages of the ta-C biocompatibility layer, the CNF's high conductivity, and the MIP's selective characteristics. The analytical performance of the ta-C/CNFs/MIP electrode against various DA concentrations (0.0, 10, 100, 250, 500, 1, 2.5, 5 and 10 µM) was examined by DPV as shown in Figure 5.

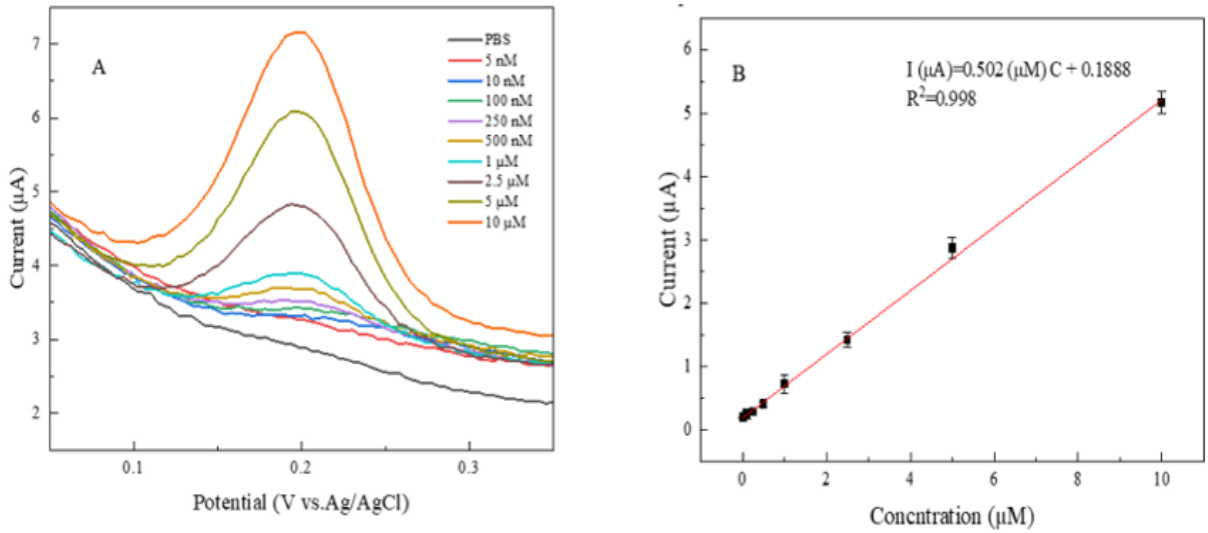

Figure 5. *(A) DPV signals for different concentrations of DA (0.0, 10, 100, 250 and 500 nM, 1, 2.5, 5 and 10 µM) at ta-C/CNFs/MIP electrode in 0.1 M PBS pH 7.4; (B) the corresponding calibration plot for the ta-C/CNFs/MIP electrode in 0.1 M PBS pH 7.4 under optimized conditions (n = 3). The incubation time was 10 min. The pulse time was 0.05 s, the pulse size was 50 mV and the electrode area was 0.07 cm². Reprinted with permission from [63], distributed under the Creative Commons CC-BY license*

An increase in DA concentration improved the response signal. The DA content in the range was directly correlated with the measured peak currents between 10.0 nM and 10 µM with LOD determined to be 5.43 nM. This demonstrated the function of MIP in increasing the sensitivity of ta-C/CNFs.

Uygun and Demir [64] developed a new MIP-based electrochemical sensor to detect DA in a low-cost, sensitive, and selective way. The surface of the sensor was modified by attaching boronic acid residues to the gold electrode used as the sensing platform. Two functional monomers were also attached to the surface of the gold electrode as part of the dopamine imprinting process: amino-phenyl boronic acid (APBA) and pyrrole-3-carboxylic acid (PyCOOH). In this study, a screen-printed gold electrode for the sensing platform meant that the conductivity of this type of electrode would play an important role in the detection of the electrochemical signal generated by the oxidation of DA. However, gold electrodes have lower surface roughness compared to carbon electrodes, which limits their ability to support an adhered polymer film. Therefore, self-assembled monolayers (SAMs) were employed on the surface of the gold electrode to create a surface with functional groups to attach polymers; additional positively charged SAMs were then created to stabilize the functional groups used to imprint onto dopamine, which also improved the interaction between the polymer and the electrode surface. The analytical performance of the sensor was evaluated by calibrating against concentration levels between 100 and 600 pM. The sensor has been found to have a correlation coefficient of 0.9517 with limits of detection 30.34 pM. The selectivity of a sensor for target analytes was investigated with common interferents, urea, acetic acid, serotonin and noradrenaline. Although responses to and acetic acid were negligible, indicating good selectivity, the signal responses to serotonin were low and significantly lower for noradrenaline due to its

structural similarity to dopamine. The results confirm the high specificity of the sensor for dopamine through imprinted recognition sites. The storage stability of the sensor was evaluated over 45 days using electrodes stored at room temperature and at 4 °C. The results showed that electrodes retained ~64 % of their initial response at room temperature, while those stored at 4 °C maintained ~90 % response, indicating better stability under refrigerated conditions. An MIP-based impedimetric sensor can be used as a sensitive and effective means of detecting dopamine. A comparison of the analytical performance of recently reported polymer-based electrochemical dopamine biosensors [65-69] is summarized in Table 5.

***Table 5**. A comparison of performances of polymer-based electrochemical dopamine biosensors*

Sensor (material)	Linear concentration range, μM	LOD, μM	Ref.
PEDOT-PPy/GCE	0.005 to 200	0.005	[65]
PEDOT:P(SS-co-UPyMA)/PGE	0.1 to 300	0.0444	[66]
ErGO/PEDOT:PSS/GCE	3 to 33	0.4	[67]
e-MIP/SPE	0.8 to 45	0.8	[68]
ZIF(MIP)/ZIF(Ru)/Au@$CoFe_2O_4$/GCE	10^{-11} to 0.0005	4.8×10^{-9}	[69]

GO: graphene oxide; PEDOT: poly(3,4-ethylenedioxythiophene); P(SS-co-UPyMA): polystyrene sulfonate-co-2-(3-(6-methyl-4-oxo-1,4-dihydropyrimidin-2-yl) ureido) ethyl methacrylate); PGE: pencil graphite electrode; ErGO: electrochemically reduced graphene oxide; PSS: poly(styrene-4-sulphonate); SPE: screen printed electrode; ZIF: zeolitic imidazolate framework

Enzymatic biosensors for dopamine detection

Dopamine is frequently detected using enzymatic biosensors because of their high catalytic efficiency and selectivity. Enzymes are used as biorecognition elements for catalysing the oxidation of dopamine and provide an electrochemical signal that can be measured by several methods, including CV, DPV and amperometry in dopamine biosensors. Commonly utilized enzymes for DA biosensors are tyrosinase, laccase and polyphenol oxidase, which catalyse the oxidation of dopamine to dopamine-o-quinone, generating electroactive species that produce a measurable current proportional to the amount of dopamine present in the sample. Enzymes are typically immobilized on the electrode surface using various polymeric or nanomaterial-based materials, or a combination of both, to enhance enzyme stability, facilitate rapid electron transfer between the enzyme and substrate, and increase sensor sensitivity [70].

There has been an increase in interest in the combination of enzymes with nanomaterials, including gold nanoparticles, carbon nanotubes, graphene, and metal oxides, to enhance sensor electrochemical performance. Enzyme immobilization on these nanomaterials has been shown to provide larger surface areas and improved electron transfer speeds and therefore reduced detection limits and expanded linear detection ranges for DA sensing. These enzymatic DA biosensors have demonstrated excellent sensitivity and selectivity across a variety of complex biological matrices, including blood serum, urine, and cell culture media. However, limitations such as enzyme instability, high cost, and limited operational lifetime have motivated researchers to develop alternative sensing strategies, including non-enzymatic and biomimetic sensors. A schematic of an enzymatic biosensor for the detection of DA [71] is shown in Figure 6.

Demkiv *et al.* [71] developed innovative laccase-mimetic ianozyme-based amperometric sensors for electrochemical detection of DA. Many different types of nanozymes, including nAuCu, nPtCu, nCuMnCo and nCoCuCe, were synthetized using a simple hydrothermal procedure and had high levels of laccase-type catalytic activity toward oxidation of DA. Of these nanozymes, nAuCu and nPtCu exhibited optimal performance and were subsequently used to develop DA sensors by modifying glassy carbon electrodes with AuPt nanoparticles to increase both their catalytic activity and sensitivity.

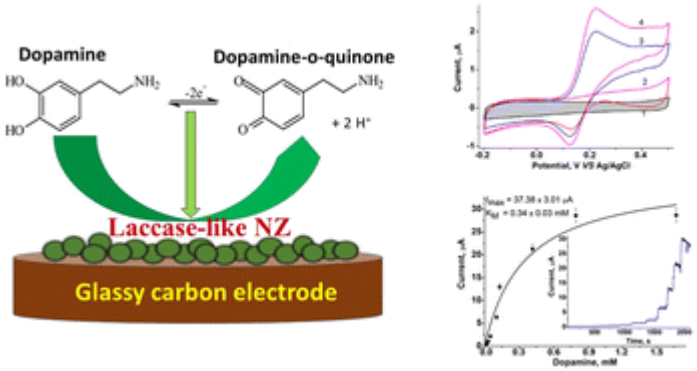

Figure 6. *Schematic of enzymatic biosensor for detection of dopamine. Reprinted with permission from [71]*

The optimized nAuCu/nAuPt/GCE sensor exhibited a large linear detection range from 10 to 170 µM, a low detection limit 20 nM, and a high sensitivity of 10650 ± 8.25 A M^{-1} m^{-2} at a low working potential of 0.2 V. Nanozyme-based sensors had a much greater degree of stability than natural laccase enzyme-based sensors and were approximately two-times more sensitive than sensors based on laccase enzymes. Additionally, the developed sensor demonstrated good selectivity, long-term stability and resistance against interference caused by other compounds and was used successfully for determining the concentration of DA in pharmaceutical samples, indicating its usefulness for both practical applications and monitoring the level of dopamine associated with neurological disorders. While significant advancements have been made in the design and development of nanomaterial-based DA biosensors, it is equally important to evaluate their effectiveness in practical, real-world scenarios.

Real-world application of electrochemical dopamine biosensors

Advancements in nanomaterials, electrode fabrication techniques and electrochemical sensing approaches have greatly improved the performance of DA biosensors over the last several years. Many DA sensors exhibit high sensitivity and specificity in the lab, but for these sensors to be useful in practice, we must evaluate their performance under real-world conditions. To determine whether we can successfully use DA biosensors as clinical diagnostic devices, we need to evaluate them using a variety of real-world biological samples. As per the current research findings, dopamine detection has been achieved successfully in a variety of real-world samples, including human serum, saliva, urine, cerebrospinal fluid and pharmaceutical products. Also, in addition to the traditional laboratory method, dopamine biosensors are being integrated more often into portable, wearable and implantable devices for long-term monitoring of neurotransmitter levels. Together, these developments will create new opportunities for point-of-care testing, monitoring neurological disorders and providing personalized healthcare.

The electrochemical detection of DA from biological fluids such as serum, saliva, and cerebrospinal fluid (CSF) presents significant challenges to the analytical chemist. Each of these substrates contains multiple interfering species (*e.g.* AA and uric acid (UA)), exhibits a wide range of ionic strengths, and typically provides low concentrations of DA <1 µM. However, nanomaterial (NM)-based electrochemical sensors have shown potential for high DA sensitivity, excellent recovery, and acceptable reproducibility in real biological matrices [72].

Mwaurah *et al.* [73] developed a cost-effective, flexible electrochemical sensor for the simultaneous detection of DA and UA in human sweat samples. The sensor was developed by using MWCNTs as a conductive filler in a β-cyclodextrin (βCD)/reduced graphene oxide (rGO) composite gel. The β-cyclodextrin enabled host-guest interactions that provided selective recognition of DA and UA,

whereas the rGO and MWCNT improved the electrical conductivity and electrocatalytic capability of the electrochemical sensor through composite materials chosen based on previously published research. Through experimental evaluation, the resulting SPE/MWCNTs/βCD/rGO electrochemical sensor demonstrated a linear concentration response for DA from 0.25 to 16 μM with a linear LOD at 0.08 μM and a sensitivity of 3.63 μA μM^{-1} cm^{-2}. Notably, the flexible electrochemical sensor successfully determined both DA and UA from exercise-induced arrest samples obtained from exercising individuals and demonstrated good repeatability and sufficient recovery. Collectively, our findings indicate the significant capabilities of the flexible electrochemical sensor for non-invasive monitoring of DA in wearable applications and in real-sample analytical procedures. Although various nanomaterial-based sensors demonstrate promising real-world applicability, a systematic comparison is necessary to better understand their relative performance, strengths, and limitations.

Comparative analysis of nanomaterials for electrochemical dopamine detection

A detailed comparison of various types of nanomaterial-based electrochemical dopamine biosensors, as shown in Tables 1 to 5, illustrates that no single material achieves satisfactory performance across all criteria. Carbon-based material systems such as graphene and carbon nanotubes provide good electric conductivity and high surface area for greater sensitivity; however, CNT-based sensor systems tend to have a higher detection limit than graphene sensors. MXene-based sensor systems have demonstrated superior electrocatalytic activity and ultra-low detection limits; however, practical use is hindered by oxidation-induced instability and low durability in long-term tests. Metal and metal oxide nanomaterials exhibit strong catalytic activity and improved signal response but generally suffer from poor selectivity in complex biological matrices. Alternatively, polymer-based nanomaterials provide excellent selectivity and resistance to biofouling but may reduce sensitivity. Therefore, combining multiple nanomaterials into a hybrid nanocomposite offers the greatest potential to create a sensing device that combines the advantages of the individual nanomaterials while mitigating the disadvantages of each class [74]. This comparative evaluation supports the need for establishing optimized, durable, and highly selective sensor platforms for the practical detection of DA. These observations provide a clear basis for identifying the key research gaps that limit the practical implementation of these sensing systems.

Research gaps

There has been significant advancement in electrochemical biosensors for the detection of DA using nanomaterials; however, many challenges remain that hinder their effective use in real-world applications. The latest literature shows several major gaps in research on electrochemical DA sensor performance.

Different studies employ various experimental conditions, such as electrolyte composition, electrode configuration, pH, and measurement methods. This lack of standardization makes it difficult to compare sensor performance and can lead to overestimating these sensors' analytical capabilities. However, a number of sensors exhibit good performance when tested under controlled laboratory conditions, but validation of these sensors using real biological matrices (*e.g.* blood, CSF, saliva) has been limited. In practical scenarios, matrix effects and interference from coexisting biomolecules significantly affect the accuracy and reliability of DA detection. These research gaps indicate that despite promising analytical performance, several practical and operational limitations remain. Therefore, it is essential to examine the specific challenges associated with sensor design, stability, selectivity, and real-world applicability, which are discussed in the following section.

Challenges and limitations of electrochemical biosensors

Interference from coexisting biomolecules

The presence of several electroactive species, such as AA, UA and glucose, makes it difficult to detect DA selectively in real biological samples like saliva, serum, and cerebrospinal fluid. These analytes, with overlapping oxidation potentials, can interfere with DA signals, making reduced selectivity and precise measurement challenging [75].

Reproducibility and fabrication challenges

Advanced nanomaterials such as graphene, MXene, and carbon nanotubes are essential to several high-performance dopamine sensors. Nevertheless, it is still difficult to achieve uniform electrode modification and consistent synthesis. Poor repeatability between sensors might result from differences in electrode preparation, surface functionalization, and nanomaterial morphology.

Long-term stability and reusability

For biomedical use, sensors need to operate reliably for long periods. Unfortunately, the sensors used to measure dopamine exhibit significant sensitivity variability due to electrode surface changes and nanomaterial degradation over time. Thus, making sensing platforms more durable and reusable is the most important factor for successfully implementing these technologies into reality.

Biocompatibility

An important challenge in developing dopamine biosensors is biocompatibility, especially when fabricating wearable and implantable sensing technologies. *In vivo* sensors should not result in any cytotoxicity, inflammation or immunological response when interacting with biological tissues and fluids. To this end, many high-performance dopamine sensors employ advanced nanomaterials like MXene, graphene or carbon nanotubes. These types of nanomaterials have excellent conductivity, exhibit large surface areas to promote analysis, and can be incorporated into biosensor devices more efficiently than traditional materials. Although these types of nanomaterials provide high levels of conductivity for sensing applications, they can also be cytotoxic to living tissues and elicit biological responses upon direct contact. In addition, when materials are implanted for extended periods, they can undergo protein absorption and elicit foreign body responses, degrading the performance and reliability of the sensors. To ensure safe and reliable use of clinical and in vivo monitoring systems with dopamine biosensors, it is critical to improve the biocompatibility of the sensing material through surface functionalization, polymer coatings, or the selection of biocompatible substrates. Addressing the above challenges is essential for advancing the practical applicability of dopamine biosensors; therefore, future research directions must focus on overcoming these limitations through innovative material design and system integration.

Future perspective in development of electrochemical biosensors

Electrochemical biosensors for DA detection have made great strides toward translational development, from lab prototype to clinical device; however, more work remains to achieve this. Future studies on electrochemical DA systems must emphasize improved sensitivity, stability, and real-time measurements as well as reliable performance in complex biological environments. The efficacy of electrochemical sensor systems for detecting neurotransmitter molecules such as dopamine has been greatly enhanced by the use of two-dimensional (2D) nanomaterials. Some advantages of using these materials include their large surface area, adjustable electrical conductivity, and ease of modification. Recent advances in the field have improved the performance

of electrochemical sensors through surface engineering, heteroatom doping, hybrid nanostructures, and signal-integrity amplification. Improvements in these areas have substantially enhanced the ability to transfer electrons by providing more active sites and reducing interference from other compounds such as ascorbic acid and uric acid [76].

A growing area of research involves combining wearable or implantable devices, often referred to collectively as biosensors, with dopamine biosensors. For instance, flexible electrodes can be fabricated on polymer substrates and used to continuously and noninvasively monitor dopamine in biological fluids such as sweat or saliva. The advent of microfabrication and flexible electronics may also support the development of portable platforms that allow for real-time measurement of neurochemicals. Another rapidly evolving area is point-of-care (POC) diagnostic systems that are becoming increasingly miniaturized. Combining portable electrochemical devices with smartphone-based signal processing would enable fast, on-site analysis of dopamine levels, allowing patients to be diagnosed and treated earlier than they otherwise would, thereby improving their chances of recovering from a neurological disorder. Dopamine biosensors are anticipated to become powerful tools for neurological research, disease detection, and individualized healthcare monitoring with further advances in nanotechnology, materials science, and bioelectronics.

Conclusions

This review provides an overview of advancements in electrochemical dopamine biosensors from 2022 to 2025, with an emphasis on electrochemical biosensors based on nanomaterial-modified electrodes. The advancements primarily came from the use of multiple nanomaterials, including graphene, MXene, metal nanoparticles, metal oxides, carbon-based nanomaterials, and conducting polymers. These materials provide a large electroactive surface area, high electrical conductivity and strong electrocatalytic activity, which promotes rapid electron transfer and enhances the dopamine oxidation signal. Therefore, many of the newly reported sensors show much greater sensitivity than before, high specificity, much larger linear ranges of detection, and extremely low detection limits, in some instances down to the picomolar range.

Additionally, various studies show that dopamine biosensors are viable tools used within many biological samples, including serum, urine, saliva, and sweat. The use of nanomaterial-based electrodes integrated into portable, miniaturized electrochemical devices signifies their potential as point-of-care diagnostic tools and for real-time monitoring of neurotransmitters. However, there remain several obstacles that must be overcome, such as interference by other biochemical molecules, biofouling on the surface of the electrode, long-term stability and biocompatibility of the sensors when used externally (wearable) or embedded inside the body (implanted). Development of new materials, surface engineering and device miniaturization will be crucial in transitioning laboratory-developed dopamine biosensor devices to usable clinical diagnostic devices. Overall, it is anticipated that ongoing advancements in electrochemical sensing techniques, nanotechnology, and device integration would significantly improve the functionality and usefulness of dopamine biosensors. These developments will help future advancements in neurochemical monitoring and individualized healthcare, as well as the creation of trustworthy diagnostic instruments for neurological illnesses.

Conflicts of interest: *There are no conflicts to declare.*

Acknowledgment: *Neeta Ukirade is grateful to Pratibha College of Commerce and Computer Studies for providing the facility to carry out the research work for a Ph.D. degree*

Funding: *No funding*

References

[1] J. Wannassi, H. Essousi, H. Kahri, H. Barhoumi, Recent progress in nanostructured materials for electrochemical dopamine detection, *Microchemical Journal* **210** (2025) 115941. https://doi.org/10.1016/j.microc.2025.115941

[2] X. Liu, J. Liu, Biosensors and sensors for dopamine detection, *VIEW* **2(1)** (2021) 20200102. https://doi.org/10.1002/VIW.20200102

[3] A. Karim, M. Yasser, A. Ahmad, H. Natsir, A.W. Wahab, S. Fauziah, P. Taba, I. Pratama, A. Rajab, Progress and trend advantage of dopamine electrochemical sensor, *Journal of Electroanalytical Chemistry* **959** (2024) 118157. https://doi.org/10.1016/j.jelechem.2024.118157

[4] M. Shinde, G. Slaughter, Advanced nanocomposite-based electrochemical sensor for ultra-sensitive dopamine detection in physiological fluids, *Frontiers in Lab on a Chip Technologies* **4** (2025) 1549365. https://doi.org/10.3389/frlct.2025.1549365

[5] R. Sangubotla, J. Paul, J. Kim, Selective electrochemical sensing of dopamine *via* solid-state hydrothermal β-cyclodextrin-functionalized selenium quantum dots-embedded with multiwall carbon nanotubes, *Applied Surface Science* **687** (2025) 162275. https://doi.org/10.1016/j.apsusc.2024.162275

[6] M. Sajid, N. Baig, K. Alhooshani, Chemically modified electrodes for electrochemical detection of dopamine: Challenges and opportunities, *TrAC Trends in Analytical Chemistry* **118** (2019) 368-385. https://doi.org/10.1016/j.trac.2019.05.042

[7] Y.-R. Kim, S Bong, Y.-J. Kang, Y. Yang, R. K. Mahajan, J. S. Kim, H. Kim, Electrochemical detection of dopamine in the presence of ascorbic acid using graphene modified electrodes, *Biosensors and Bioelectronics* **25(10)** (2010) 2366-2369. https://doi.org/10.1016/j.bios.2010.02.031

[8] Z. Hsine, R. Mlika, N. Jaffrezic-Renault, H. Korri-Youssoufi, Recent progress in graphene based modified electrodes for electrochemical detection of dopamine*, Chemosensors* **10 (7)** (2022) 249. https://doi.org/10.3390/chemosensors10070249

[9] V. Sharma, P. Singh, A. Kumar, N. Gupta, Electrochemical detection of dopamine by using nickel supported carbon nanofibers modified screen printed electrode, *Diamond and Related Materials* **133** (2023) 109677. https://doi.org/10.1016/j.diamond.2023.109677

[10] L. Ji, Q. Wang, X. Gong, J. Chen, X. Zhu, Z. Li, P. Hu, Ultrasensitive and simple dopamine electrochemical sensor based on the synergistic effect of Cu-TCPP frameworks and graphene nanosheets, *Molecules* **28 (6)** (2023) 2687. https://doi.org/10.3390/molecules28062687

[11] R. P. Bacil, L. Chen, S. H. P. Serrano, R. G. Compton, Dopamine oxidation at gold electrodes: mechanism and kinetics near neutral pH, *Physical Chemistry Chemical Physics* **22 (2)** (2020) 607-614. https://doi.org/10.1039/C9CP05527D

[12] N. Umek, B. Geršak, N. Vintar, M. Šoštarič, J. Mavri, Dopamine autoxidation is controlled by acidic pH, *Frontiers in Molecular Neuroscience* **11** (2018) 467. https://doi.org/10.3389/fnmol.2018.00467

[13] B. Patella, A. Sortino, F. Mazzara, G. Aiello, G. Drago, C. Torino, A. Vilasi, A. O'Riordan, R. Inguanta, Electrochemical detection of dopamine with negligible interference from ascorbic and uric acid by means of reduced graphene oxide and metals-NPs based electrodes, *Analytica Chimica Acta* **1187** (2021) 339124. https://doi.org/10.1016/j.aca.2021.339124

[14] H. Zhu, G. Xu, Electrochemical biosensors for dopamine, *Clinica Chimica Acta* **566** (2025) 120039. https://doi.org/10.1016/j.cca.2024.120039

[15] B. Lakard, Electrochemical biosensors based on conducting polymers: a review, *Applied Sciences* **10 (18)** (2020) 6614. https://doi.org/10.3390/app10186614

[16] J. Ding, W. Qin, Recent advances in potentiometric biosensors, *TrAC Trends in Analytical Chemistry* **124** (2020) 115803. https://doi.org/10.1016/j.trac.2019.115803

[17] W. Li, L. Ding, Q. Wang, B. Su, Differential pulse voltammetry detection of dopamine and ascorbic acid by permselective silica mesochannels vertically attached to the electrode surface, *Analyst* **139 (16)** (2014) 3926-3931. https://doi.org/10.1039/C4AN00605D
[18] L. Wu, L. Feng, J. Ren, X. Qu, Electrochemical detection of dopamine using porphyrin-functionalized graphene, *Biosensors and Bioelectronics* **34 (1)** (2012) 57-62. https://doi.org/10.1016/j.bios.2012.01.007
[19] M. Hadi, A. Rouhollahi, Simultaneous electrochemical sensing of ascorbic acid, dopamine and uric acid at anodized nanocrystalline graphite-like pyrolytic carbon film electrode, *Analytica Chimica Acta* **721** (2012) 55-60. https://doi.org/10.1016/j.aca.2012.01.051
[20] S. Lupu, C. Lete, P. C. Balaure, D. I. Caval, C. Mihailciuc, B. Lakard, J. Y. Hihn, F. J. Campo, Development of amperometric biosensors based on nanostructured tyrosinase-conducting polymer composite electrodes, *Sensors* **13(5)** (2013) 6759-6774. https://doi.org/10.3390/s130506759
[21] J. Njagi, M. M. Chernov, J. C. Leiter, S. Andreescu, Amperometric detection of dopamine *in vivo* with an enzyme based carbon fiber microbiosensor, *Analytical Chemistry* **82(3)** (2010) 989-996. https://doi.org/10.1021/ac9022605
[22] R. Ramkumar, P. Veerakumar, S. Rajendrachari, G. Dhakal, J. Yun, J. J. Shim, W. K. Kim, Copper aerogel frameworks—Electrochemical detection of dopamine and catalytic reduction of 4-nitrophenol, *Microchemical Journal* **208** (2025) 112486. https://doi.org/10.1016/j.microc.2024.112486
[23] S. Rajendrachari, E. Altaş, A. Erdogan, Y. Küçük, M. S. Gök, F. Khosravi, Electrochemical determination of dopamine by poly (methyl orange) shape memory alloy modified carbon paste electrode, *Inorganic Chemistry Communications* **167** (2024) 112826. https://doi.org/10.1016/j.inoche.2024.112826
[24] B. Swamy, B. Venton, Carbon nanotube-modified microelectrodes for simultaneous detection of dopamine and serotonin *in vivo*, *Analyst* **132(9)** (2007) 876-884. https://doi.org/10.1039/B705552H
[25] C. Kaewda, S. Sriwichai, Label-free electrochemical dopamine biosensor based on electrospun nanofibers of polyaniline/carbon nanotube composites, *Biosensors* **14(7)** (2024) 349. https://doi.org/10.3390/bios14070349
[26] W.T. Wahyuni, S. A. H. Ta'alia, A. Y. Akbar, B. R. Elvira, Irkham, I. Rahmawati, R. A. Wahyuono, B.R. Putra, Electrochemical sensors based on the composite of reduced graphene oxide and a multiwalled carbon nanotube-modified glassy carbon electrode for simultaneous detection of hydroquinone, dopamine, and uric acid, *RSC Advances* **14(38)** (2024) 27999-28016. https://doi.org/10.1039/D4RA05537C
[27] H. Singh, J. Wu, K. A. L. Lagemann, M. Nath, Highly efficient dopamine sensing with a carbon nanotube-encapsulated metal chalcogenide nanostructure, *ACS Applied Nano Materials* **7 (5)** (2024) 4814-4823. https://doi.org/10.1021/acsanm.3c05422
[28] L. Zhang, F. Wu, Q. Zou, J. Fei, Y. Xie, A novel dopamine electrochemical sensor based on multiwall carbon nanotubes-cetyltrimethylammonium bromide/nitrogen doped ultra-thin carbon nanosheets composites modified glassy carbon electrode, *Microchemical Journal* **195** (2023) 109485. https://doi.org/10.1016/j.microc.2023.109485
[29] M. B. Arvas, N. Koçyiğit, S. Yazar, K. Uzbiçen, S. Yaylagül, Ö. Yağcı, M. Şahin, Sensitive, low cost and disposable electrochemical dopamine sensor based on Ag-NP/f-MWCNT/Poly(L-Cysteine)/PGE, *Applied Physics A* **131 (5)** (2025) 395. https://doi.org/10.1007/s00339-025-08534-7
[30] H. Arif, A. Sajid, A. Ali, N. Ahmed, M. Iqbal, S. Akyürekli, M. Kaleli, N. Alwadai, U. Shafique A. Nazir, Selective non-enzymatic electrochemical detection of dopamine using nickel

molybdate nano-dots anchored on CNT fiber microelectrodes, *RSC Advances* **15 (43)** (2025) 36596-36606. https://doi.org/10.1039/D5RA05187H

[31] R. Wahyuono, J. Jovin, I. G.Chano, A. F. Putra, A. S. Ningrum, M. Y. H. Widianto, I. Irkham, Y. W. Hartati, W. T. Wahyuni, I. Rahmawati, C. H. Huang. Graphene-supported Pd/Pt nano-catalysts for enhanced colorimetric detection of dopamine and NADH using paper-based microfluidic devices, *ADMET and DMPK* 14 (2026) 3247. https://doi.org/10.5599/admet.3247

[32] Z. L. Hou, W. L. Song, P. Wang, M. J. Meziani, C. Y. Kong, A. Anderson, H. Maimaiti, G. E. LeCroy, Flexible graphene-graphene composites of superior thermal and electrical transport properties, *ACS Applied Materials & Interfaces* **6 (17)** (2014) 15026-15032. https://doi.org/10.1021/am502986j

[33] M. Pumera, A. Ambrosi, A. Bonanni, E. L. K. Chng, H. L. Poh, Graphene for electrochemical sensing and biosensing, *TrAC Trends in Analytical Chemistry* **29(9)** (2010) 954-965. https://doi.org/10.1016/j.trac.2010.05.011

[34] M. Shinde, S. R. Torati, G. Slaughter, $Nb_4C_3T_x$ MXene-AgNPs decorated laser-induced graphene for selective detection of dopamine, *Journal of Electroanalytical Chemistry* **959** (2024) 118180. https://doi.org/10.1016/j.jelechem.2024.118180

[35] Y. Vadivelu, A. S. Raj, R. Muniyandi, S. R. Srither, B. Ramachandran, Fabrication of activated graphene based electrodes for ultrasensitive simultaneous electrochemical detection of uric acid and dopamine, *Talanta Open* **12** (2025) 100477. https://doi.org/10.1016/j.talo.2025.100477

[36] C. Zhang, T. Chen, Y. Ying, J. Wu, Detection of dopamine based on aptamer-modified graphene microelectrode, *Sensors* **24 (9)** (2024) 2934. https://doi.org/10.3390/s24092934

[37] R. V. Blasques, V. A. P. Oliani da Silva, A. C. N. Sousa, T. M. B. Freitas, L. T. Arenas, G. Cruz, A New Electrochemical Sensor for Dopamine Detection Based on Reduced Graphene Oxide Modified with Samarium Oxide Nanoparticles, *ACS Omega* **10(46)** (2025) 56290-56301. https://doi.org/10.1021/acsomega.5c08166

[38] S. Makaluza, N. Midzi, F. O. G. Olorundare, B. N. Zwane, D. Nkosi, O. A. Arotiba, An electrochemical sensor for dopamine on a graphene-poly (3, 4-ethylenedioxythiophene): polystyrene sulphonate hybrid ink nanoplatform, *Discover Applied Sciences* **7(4)** (2025) 288. https://doi.org/10.1007/s42452-025-06694-y

[39] Y. Si, J. Liu, Y. Ma, X. Li, X. Li, Z. Zhu, K. Liu, S. Wang, Dual-Analyte Detection of Dopamine and Folic Acid Using a 3D Honeycomb Structured Reduced Graphene Oxide/Polypyrrole-Polyoxometalate Porous Film, *Langmuir* **41(37)** (2025) 25535-25545. https://doi.org/10.1021/acs.langmuir.5c03394

[40] M. H. M. Facure, B. S. Sampaio, L. A. Mercante, D. S. Correa, The beneficial impact of MXene on the electrochemical performance of graphene quantum dots for dopamine detection, *Materials Today Communications* **42** (2025) 111197. https://doi.org/10.1016/j.mtcomm.2024.111197

[41] Z. Ren, Q. Zhu, L. Cao, L. Fan, L. Xu, S. Xiong, Microwave-assisted ultrafast synthesis of TiO_2/MXene/rGO heterojunction electrodes for high-sensitivity electrochemical dopamine detection, *Microchemical Journal* **218** (2025) 115753. https://doi.org/10.1016/j.microc.2025.115753

[42] R. Zhou, B. Tu, D. Xia, H. He, Z. Cai, N. Gao, G. Chang, Y. He, High-performance Pt/$Ti_3C_2T_x$ MXene based graphene electrochemical transistor for selective detection of dopamine, *Analytica Chimica Acta* **1201** (2022) 339653. https://doi.org/10.1016/j.aca.2022.339653

[43] S. G. Chavan, P. R. Rathod, A. Koyappayil, A. Go, M. H. Lee, Two-step signal amplification for ultrasensitive detection of dopamine in human serum sample using $Ti_3C_2T_x$-MXene, *Sensors and Actuators B: Chemical* **404** (2024) 135308. https://doi.org/10.1016/j.snb.2024.135308

[44] M. Ni, J. Chen, C. Wang, Y. Wang, L. Huang, W. Xiong, P. Zhao, Y. Xie, J. Fei, A high-sensitive dopamine electrochemical sensor based on multilayer Ti_3C_2 MXene, graphitized multi-walled

carbon nanotubes and ZnO nanospheres, *Microchemical Journal* **178** (2022) 107410. https://doi.org/10.1016/j.microc.2022.107410

[45] L Zhang, C Li, Y Yang, J Han, W Huang, J Zhou, Y Zhang, Anti-biofouling $Ti_3C_2T_X$ MXene-holey graphene modified electrode for dopamine sensing in complex biological fluids, *Talanta* **247** (2022) 123614. https://doi.org/10.1016/j.talanta.2022.123614

[46] K. Amarnath, T. S. Gopal, A. C. J. Malathi, S. Pandiaraj, M. Alruwaili, A. Alshammari, A. N. Alodhayb, C. Abeykoon, A. N. Grace, V. G. Kumar, Electrochemical detection of dopamine and uric acid with annealed metal-organic framework/MXene ($CuO/C/Ti_3C_2T_x$) nanosheet composites for neurotransmitter sensing, *ACS Applied Nano Materials* **8(24)** (2025) 12661-12675. https://doi.org/10.1021/acsanm.5c01758

[47] A. S. Agnihotri, A. Varghese, M. Nidhin, Transition metal oxides in electrochemical and bio sensing: A state-of-art review, *Applied Surface Science Advances* **4** (2021) 100072. https://doi.org/10.1016/j.apsadv.2021.100072

[48] V. Maciulis, A. Ramanaviciene, I. Plikusiene, Recent advances in synthesis and application of metal oxide nanostructures in chemical sensors and biosensors, *Nanomaterials* **12(24)** (2022) 4413. https://doi.org/10.3390/nano12244413

[49] Z.-F. Lin, H. Li, Z.-C. Chen, G.-C. Han, X.-Z. Feng, H.-B. Kraatz, Advances in dopamine electrochemical sensors: Properties and application prospects of different modified materials, *Microchemical Journal* **212** (2025) 113535. https://doi.org/10.1016/j.microc.2025.113535

[50] I. Naz, A. Tahira, A. B. Mallah, E. Dawi, L. Saleem, R. M. Ibrahim, Z. H. Ibupoto, Detection of dopamine using hybrid materials based on NiO/ZnO for electrochemical sensor applications, *Catalysts* **15(2)** (2025) 116. https://doi.org/10.3390/catal15020116

[51] S. Rajendrachari, G. Kudur Jayaprakash, A. Pandith, A. C. Karaoglanli, O. Uzun, Electrocatalytic investigation by improving the charge kinetics between carbon electrodes and dopamine using bio-synthesized CuO nanoparticles, *Catalysts* **12(9)** (2022) 994. https://doi.org/10.3390/catal12090994

[52] M. Y. Pabel, M. H. Kabir, M. S. Hossain, F. Mojumder, S. Datta, M. S. Bashar, S. Yasmin, Dopamine detection using leaf-shaped ZnO synthesized from zinc shells of recycled batteries, *Materials Advances* **6(7)** (2025) 2243-2252. https://doi.org/10.1039/D5MA00001G

[53] A. Dhaffouli, P. A. Salazar-Carballo, S. Carinelli, M. Holzinger, B. V. M. Rodrigues, H. Barhoumi, Electrochemical detection of dopamine with a non-enzymatic sensor based on Au@SiO_2-APTES composite, *Chemosensors* **13(3)** (2025) 87. https://doi.org/10.3390/chemosensors13030087

[54] L. Mgenge, C. Saha, P. Kumari, S. K. Ghosh, H. Singh, K. Mallick, Electrochemical sensing of dopamine using nanostructured silver chromate: Development of an IoT-integrated sensor." *Analytical Biochemistry* **698** (2025) 115726. https://doi.org/10.1016/j.ab.2024.115726

[55] R. Deo, M. Devi, Selective, Non-Enzymatic Electrochemical Detection of Dopamine Using a Green-Synthesized CuO/rGO Nanocomposite-Modified Electrode, *Diamond and Related Materials* **163** (2026) 113407. https://doi.org/10.1016/j.diamond.2026.113407

[56] S. Rajendrachari, H. Nagarajappa, V. D. Neelalochana, R. G. Shivaraju, E. Demir, S. Antherjanam, K. E. Karaoglanli, Poly (asparagine)-modified duplex stainless steel composite carbon paste electrode for selective electrochemical detection of dopamine, *Journal of Electrochemical Science and Engineering* **16** (2026) 3157. https://doi.org/10.5599/jese.3157

[57] B. S. Dakshayini, K. R. Reddy, A. Mishra, N. P. Shetti, S. J. Malode, S. Basu, S. Naveen, A. V. Raghu, Role of conducting polymer and metal oxide-based hybrids for applications in ampereometric sensors and biosensors, *Microchemical Journal* **147** (2019) 7-24. https://doi.org/10.1016/j.microc.2019.02.061

[58] S. Shrivastava, N. Jadon, R. Jain, Next-generation polymer nanocomposite-based electrochemical sensors and biosensors: A review, *TrAC Trends in Analytical Chemistry* **82** (2016) 55-67. https://doi.org/10.1016/j.trac.2016.04.005
[59] A. Tejwani, U. Sonkar, K. Shrivas, K. Tandey, I. Karbhal, M. K. Deb, S. Pervez, Differential pulse voltametric detection of dopamine using polyaniline-functionalized graphene oxide/silica nanocomposite for point-of-care diagnostics, *RSC Advances* **15(20)** (2025) 15870-15878. https://doi.org/10.1039/D5RA00714C
[60] M. Darroudi, K. A. White, M. A. Crocker, B. N. Kim, Dopamine measurement using engineered CNT-CQD-polymer coatings on Pt microelectrodes, *Sensors* **24(6)** (2024) 1893. https://doi.org/10.3390/s24061893
[61] Y. Liu, L. Wang, H. Li, L. Zhao, Y. Ma, Y. Zhang, J. Liu, Y. Wei, Rigorous recognition mode analysis of molecularly imprinted polymers—Rational design, challenges, and opportunities, *Progress in Polymer Science* **150** (2024) 101790. https://doi.org/10.1016/j.progpolymsci.2024.101790
[62] G. Vasapollo, R. D. Sole, L. Mergola, M. R. Lazzoi, A. Scardino, S. Scorrano, G. Mele, Molecularly imprinted polymers: present and future prospective, *International Journal of Molecular Sciences* **12(9)** (2011) 5908-5945. https://doi.org/10.3390/ijms12095908
[63] K. Nekoueian, M. Akhoundian, N. Wester, T. Laurila, An ultra-sensitive dopamine measurement platform based on molecularly imprinted polymer-carbon hybrid nanomaterials for *in vitro* use, *Electrochimica Acta* **445** (2023) 142029. https://doi.org/10.1016/j.electacta.2023.142029
[64] H. D. Ertuğrul Uygun, M. N. Demir, A novel molecularly imprinted polymers on self-assembly monolayer gold electrode impedimetric detection of dopamine, *Journal of Materials Science: Materials in Electronics* **36(7)** (2025) 441. https://doi.org/10.1007/s10854-025-14375-0
[65] A. Sanmugam, C. Vanitha, A. I. Almansour, K. Karuppasamy, T. Maiyalagan, H. S. Kim, D. Vikraman, A. Alfantazi, Unveiling the PEDOT-polypyrrole hybrid electrode for the electrochemical sensing of dopamine, *Scientific Reports* **15 (1)** (2025) 10989. https://doi.org/10.1038/s41598-024-82355-1
[66] D. Thirumalai, D. Subramani, J. Kim, T. Rajarathinam, J. H. Yoon, H. Paik, J. Lee, S. C. Chang, Conductive PEDOT: PSS copolymer electrode coatings for selective detection of dopamine in *ex vivo* mouse brain slices, *Talanta* **267** (2024) 125252. https://doi.org/10.1016/j.talanta.2023.125252
[67] S. A. H. Ta'alia, E. Rohaeti, B. R. Putra, W. T. Wahyuni, Electrochemical sensors for simultaneous detection of dopamine and uric acid based on a composite of electrochemically reduced graphene oxide and PEDOT: PSS-modified glassy carbon electrode, *Results in Chemistry* **6** (2023) 101024. https://doi.org/10.1016/j.rechem.2023.101024
[68] D. Merli, A. Cutaia, I. Hallulli, A. Bonanni, G. Alberti, Molecularly imprinted polypyrrole-modified screen-printed electrode for dopamine determination, *Polymers* **16(17)** (2024) 2528. https://doi.org/10.3390/polym16172528
[69] J.-L. Pu, P.-H. Tong, Y.-J. Meng, J.-P. Li, Development of a molecularly imprinted electrochemiluminescence sensor based on bifunctional bilayer structured ZIF-8-based magnetic particles for dopamine sensing, *Chinese Journal of Analytical Chemistry* **51(3)** (2023) 100226. https://doi.org/10.1016/j.cjac.2022.100226
[70] Z. Fredj, B. Singh, M. Bahri, P. Qin, M. Sawan, Enzymatic electrochemical biosensors for neurotransmitters detection: recent achievements and trends, *Chemosensors* **11(7)** (2023) 388. https://doi.org/10.3390/chemosensors11070388
[71] O. Demkiv, W. Nogala, N. Stasyuk, H. Klepach, T. Danysh, M. Gonchar, Highly sensitive amperometric sensors based on laccase-mimetic nanozymes for the detection of dopamine, *RSC Advances* **14 (8)** (2024) 5472-5478. https://doi.org/10.1039/D3RA07587G

[72] T. G. Beatto, W. E. Gomes, A. Etchegaray, R. Gupta, R. K. Mendes, Dopamine levels determined in synthetic urine using an electrochemical tyrosinase biosensor based on ZnO@Au core-shell, *RSC Advances* **13 (47)** (2023) 33424-33429. https://doi.org/10.1039/D3RA06277E

[73] M. Mwaurah, J. Mathiyarasu, A. Mohan, MWCNTs-Beta-Cyclodextrin-reduced graphene oxide gel based electrochemical sensor for simultaneous detection of dopamine and uric acid in human sweat samples, *Carbohydrate Polymers* **350** (2025) 123060. https://doi.org/10.1016/j.carbpol.2024.123060

[74] H. Nagarajappa, R. G. Shivaraju, V. D. Neelalochana, B. G. Mahadevappa, S. Rajendrachari, G. Honnu, T. H. Kim, Carbon-Based Electrochemical Sensors and Voltammetry for the Detection of Biologically Active Molecules: Fundamentals, Theoretical Aspects, and Emerging Perspectives, *Langmuir* **42 (1)** (2026) 10-31. https://doi.org/10.1021/acs.langmuir.5c04408

[75] S. A. Leau, C. Lete, S. Lupu, Nanocomposite materials based on metal nanoparticles for the electrochemical sensing of neurotransmitters, *Chemosensors* **11 (3)** (2023) 179. https://doi.org/10.3390/chemosensors11030179

[76] B. Ghrib, Two-dimensional layered nanomaterials for electrochemical dopamine sensing: Recent advances, challenges, and future perspectives, *Sensing and Bio-Sensing Research* **51** (2026) 100980. https://doi.org/10.1016/j.sbsr.2026.100980