ISSN 1023-1935, Russian Journal of Electrochemistry, 2022, Vol. 58, No. 5, pp. 341–359. © Pleiades Publishing, Ltd., 2022.

Nanoparticles Application in the Determination of Uric Acid, Ascorbic Acid, and Dopamine

Charlton van der Horst[a] and Vernon Somerset[a, *, **]

[a] *Department of Chemistry, Faculty of Applied Sciences, Cape Peninsula University of Technology, Bellville, 7535 South Africa*

**e-mail: vsomerset@gmail.com*

***e-mail: somersetv@cput.ac.za*

Received January 25, 2021; revised May 19, 2021; accepted July 6, 2021

Abstract—This review describes the application of nanomaterials for the individual and simultaneous detection of dopamine (DA), uric acid (UA), and ascorbic acid (AA). Scientists have worked over the past years to modify electrode surfaces by using different nanomaterials to improve the selectivity, limits of detection, and sensitivity of sensors. In this review, the authors have briefly discussed the nanomaterials that were extensively applied in the construction and modification of working electrode surfaces for the detection of DA, UA, and AA. The electrochemical detection of DA, UA, and AA were categorized into three main sections including the detection in the presence of interferents, individual detection and the simultaneous detection of these molecules. For the individual detection of DA, UA, and AA the lowest detection limit was achieved by a Au/PDDA–rGO sensor in the detection of UA in urine samples. A detection limit of 0.0008 μM with a wide linear range of 0.25 to 150 μM was recorded. In the simultaneous detection of DA, UA, and AA in serum and urine samples, a Fe_3O_4–SnO_2–Gr sensor gives the lowest detection limits (0.0071 μM for DA, 0.005 μM for UA, 0.0062 μM for AA) with good linear range (0.02 to 2.8 μM for DA, 0.015 to 2.40 μM for UA, 0.1 to 23 μM for AA). In the case of the simultaneous detection of DA and UA in serum and urine samples, the lowest detection limits were obtained by Au–Pt sensor. The detection limits (0.006 μM for DA, 0.038 μM for UA) with good linear range (0.1 to 400 μM for DA, 1 to 1000 μM for UA).

Keywords: uric acid, ascorbic acid, dopamine, nanoparticles, electrochemical sensors

DOI: 10.1134/S102319352205010X

INTRODUCTION

The human body is a very complex environment, there are several small biological molecules that have significant effects on the physiological cycle, and human health is affected by the changes in their component concentrations [1]. Dopamine (DA), uric acid (UA), and ascorbic acid (AA) are electrochemically active biomolecules, co-exist in physical fluids and play a very important role in human metabolic processes [2–5]. The detection of UA, AA, and DA might provide important information regarding certain diseases and genetic diagnoses. So the construction of simple, suitable and fast procedures for the individual or simultaneous detection of these molecules is important.

In the field of applied sciences, a wide variety of analytical techniques has been established for the detection of DA, UA, and AA. The majority of these techniques are based on analytical instrumentation methods. The most popular techniques in the detection of DA, UA, and AA are titrimetric [6], colorimetric assay [7], chromatographic [8], fluorimetry [9] and fluorescence sensing [10]. These methods can determine DA, UA, and AA with very high sensitivity, selectivity and has control over the interference effects, but imply prior pre-concentration or matrix separation steps to assess concentrations at the required ultra-low levels. On the other hand, modern electrochemistry provides powerful analytical techniques and is greatly applied in the determination of UA, AA, and DA due to their high sensitivity and selectivity, low cost, simple operation, portability and short analytical time. Voltammetric techniques such as differential pulse voltammetry [11], linear sweep voltammetry [12], square wave voltammetry [13] and cyclic voltammetry [14] have been widely applied in biomolecules analysis. In the detection of DA, UA, and AA various electrochemical techniques have been constructed, with many kinds of working electrodes such as carbon paste electrodes [15], bimetallic nanoparticles [16], polymers [12] and graphene composite film modified electrode [17], etc.

However, AA, DA, and UA normally coexist in the human biological systems. Unmodified solid electrodes such as the bare GCE resulting in overlapping of oxidation peaks with fouling effects at the surfaces

of these electrodes making it difficult to simultaneously detect AA, DA, and UA. So the simultanoues detection of these biomolecules resulting in poor sensitivity and selectivity. Furthermore, the practical application of these unmodified electrodes have some drawbacks limiting the simultaneous detection of AA, DA, and UA in the presence of interferents present in biological systems. In literature the anodic oxidation peak potentials of AA, and UA are close to the oxidation potential of DA at almost all unmodified solid electrodes. This observation result in the lack of good resolution between AA, UA, and DA anodic peak potentials. Hence, in order to improve the resolution of the anodic peaks and sensing performances, the studying of electrodes modified with nanomaterials is highly desirable.

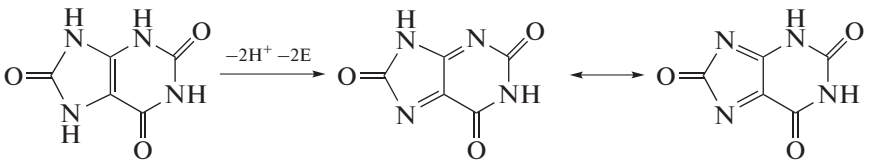
In the modern society, nanomaterials have been applied progressively important roles in different applications such as medical care, environmental protection, new energy resources, domestic appliances, engineering industry, and textile industry due to their specific properties. They have been employed as sensors, biomedicine, nanocatalysts, fine chemicals, nanotubes, nano-semiconductors, etc. [18, 19]. The modification of nanomaterials with metal oxides [20, 21], noble metals [22–26], carbon-based nanomaterials [27–30] and polymers [31, 32] have been applied to increase the sensitivity and selectivity of the UA, AA, and DA. For example, in recent years, Sajid et al. (2016) constructed an assessment of electrodes that were chemically modified for electrochemical detection of DA in the presence of UA and AA [33]. Recently, Tukimin et al. (2018a) presented a review on the application and performances of modified electrodes using various materials such as carbon-based, graphene-based, metal-based, fiber-based and conducting polymer-based for simultaneous and individual detection of DA, UA, and AA [17].

On the other hand, DA, and AA can be harmfull when overdose or abused and can also influence various organs as well as disruption in central nervous system, respiratory rate and low blood pressure. In addition, DA, and AA analysis in pharmaceuatical samples such as tablets has been applied both in forensic cases and pharmokinetic studies. All these facts points towards the need for developing a selective, sensitive and convenient electrochemical method for the strict and accurate monitoring of AA, and DA in many pharmaceutical and biological samples.

Our study focuses on the recently published developments on the application of nanomaterials in the electrochemical detection of DA, UA, and AA in different real samples. In this review, the performance of working electrodes modified with various nanomaterials such as metallic and bimetallic nanoparticles, magnetic nanoparticles and metal oxide nanoparticles impregnated into carbon-based materials, electroactive polymers and other materials for individual and simultaneous detection of UA, DA, and AA will be discussed. The performance parameters compared and evaluated include detection limits, linear ranges, detection methods, repeatability, reproducibility and detection sensitivities. These parameters are very important in finding the best suitable sensor for the detection of simultaneous and individual detection of DA, UA, and AA.

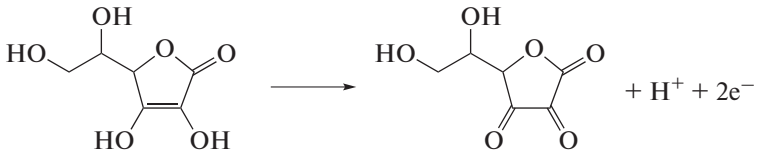
BIOLOGICAL MOLECULES

In the determination of UA, many electrochemical sensors have been developed by using nanomaterials modified with other electroactive materials such as carbon quantum dot modified with Fe_3O_4 hybrid composites [34], polyoxometalates-doped Au nanoparticles and reduced graphene oxide [35] and Cu_2ZnSnS_4 (CZTS) nanoparticles [36]. Uric acid or 2,6,8-trihydroxypurine is biologically important and is the basic end-product of nitrogenous base-like purine in human metabolism [37]. Diseases such as gout, obesity, high blood pressure, hyperuricemia, high cholesterol, Lesch-Nyan disease, diabetes, kidney and heart diseases are reported to be associated with deviations in UA levels [38]. So the accurate monitoring of biological analytes such as UA in body fluids is of high importance and might enable scientist to the early diagnosis of these diseases. Electrochemical procedures combined with nanoparticles are favourable for the on-site determination of these important biological molecules [34]. Scheme 1 is an illustration of the solution dependence on the electrooxidation of UA on modified electrodes. In this mechanism the electrons and protons equally play their part in the UA oxidation.



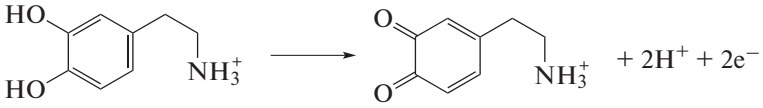
Scheme 1. Schematic illustration of the electrochemical oxidation of UA on the modified electrodes.

2-(1,2-dihydroxyethyl)-4,5-dihydroxyfuran-3-one or ascorbic acid (AA) also known as Vitamin C are an essential compound that plays an essential anti-oxidant role in biological systems and food products [39]. Vitamin C plays a critical role in human metabolism and had been extensively applied for preventing and treating mental illness, common cold, cancer, AIDS, and infertility [31]. So the construction of a sensitive, quick and reliable procedure for precise detection of AA is of great importance. In the dtermination of AA using modified electrodes, two electrons (n = 2.26) have been calculated by Harraz et al. 2019 [40]. They concluded that the oxidation of AA at the TiO_2/reduced graphene oxide nanocomposite sensor proceeds via a duffusion-controlled electrode kinetics. The process involved a two-electron, two-proton electro-oxidation process result in the formation of dehydroascorbic acid and are illustrated in the scheme below. The sensors consisting of nanomaterials modified with other electroactive materials, including TiO_2/reduced graphene oxide nanocomposite [40], multi-walled carbon nanotubes (MWCNTs) [41], carbon-supported $NiCoO_2$ nanoparticles [42] were used to detect AA in various type of samples.



Scheme 2. Schematic illustration of the electrochemical oxidation of AA on the modified electrodes.

Dopamine (DA) or 3,4-dihydroxyphenylalanine is a very important catecholamine neurotransmitter in the mammal central nervous system [43]. It also plays an important part in the continuation of functional activities of cardiovascular, renal and hormonal systems [33, 44]. Dopamine transfers signals in the central nervous system and abnormal levels of DA in body fluids will lead to several serious illnesses, such as Parkinson's disease [45], Alzheimer's [46] and mental disorder such as schizophrenia [47]. For these reasons, countless efforts were created to construct electrochemical sensors with high selectivity and sensitivity for the detection of DA. So it is important to improve a reliable and simple procedure for accurate and rapid detection of DA. The mechanism used for the sensing of dopamine on the surface of modified electrodes are showcase in scheme 2 below. In this scheme we observed two-electron transfer in the oxidation of DA as well as two-protons. Electrochemical oxidation of DA will take place at the electrode surface with the release of two electrons and two protons to form dopamine-o-quinone. At the electrode surface, the generated electrons produce a faradic current which is dependant on the concentration of dopamine. The reversible process ensures that in the cathodic scan, dopamine-o-quinone is reduced to form DA again. Scientists have studied working electrodes modified with nanomaterials to improve the sensing performance of these working electrodes [48–50]. In these studies, a large number of nanoparticles and nanocomposites were used for the modification of bare electrodes for DA detection, which improves sensor performances.



Scheme 3. Schematic illustration of the electrochemical oxidation of DA on the modified electrodes.

Ascorbic acid, DA, and UA usually co-exists with its common interferents such as glycine, diclofenac (DF), citric acid (CA), glucose (GLU), urea, salicylic acid (SA), sucrose and they undergo similar two electrons and two protons reaction at most of the electrodes. Therefore, a sensitive and selective method which is capable of detecting AA, UA, and DA in presence of its interferences is more advantageous. Electroanalytical methods serve as excellent methods to meet this critical need and are more suitable for the detection of these electroactive biomolecules.

NANOMATERIALS FOR ELECTROCHEMICAL SENSORS

Nanotechnology has developed as an important technology interdisciplinary with medicine, chemistry, material science, physics and biology in recent

Table 1. An illustration to compare the different nanomaterials applied for the individual detection of UA, AA, and DA

Nanomaterials	Analyte	Sample	Detection methods	Detection limits, μM	Linear range, μM	References
Au/PDDA–rGO	UA	Urine	DPV	0.0008	0.25–150	[35]
Cu_2ZnSnS_4	UA	Zobell	DPV	0.066	0–700	[36]
α-Fe_2O_3/Pan NTs	UA	Urine	DPV	0.038	0.01–5	[72]
Bi–Ag	AA	Fruit & tablets	DPV	0.16	0.4–1.2	[75]
Pd–Ag	UA	Urine	DPV	0.005543	0.00469–0.273	[79]
CdONPs	AA	Fruit juice	DPV	0.0535	5–150	[80]
CNCo	UA	Serum	DPV	0.83	2.0–110	[82]
AgNPs–PSi	AA	Tablet	AMP	0.83	20–600	[83]
Branch-truck Ag HN	AA	Orange & urine	AMP	0.06	0.17–1925	[84]
TOAB/YD/MWCNT	AA	Tablets	AMP	0.18	18.7–1850	[85]
PT/Au/CNT-4.5	DA	Aqueous	DPV	0.69	1.0–10	[86]
Ag@C/Au	DA	Aqueous	DPV	0.21	0.5–4278	[87]
PMo_9V_3–Pd@Pt/CNTs	DA	Serum	DPV	12.5	0.025–178	[88]
MoO_x	DA	Pharmaceutical	SWV	0.043	0.01–650	[89]
Ag@MoS_2	DA	Aqueous	DPV	0.2	1–500	[90]

years. The nanomaterials used in the electrochemical sensor application for AA, UA, and DA detection are mainly metallic and bimetallic nanoparticles, magnetic nanoparticles, metal oxide nanoparticles incorporated into carbon-based nanomaterials and electroactive polymers [17].

Metallic and Bimetallic Nanoparticles

Nanoparticles (NPs) have many outstanding chemical, physical, and electronic properties compared with bulk materials [51–69]. The properties of NPs can be determined by the nature of the material employed in the synthesis of NPs. Many stabilizers have been applied in the preparation of NPs using chemical reduction of metal salts. Metallic NPs such as silver (Ag) [70], palladium (Pd) [71], gold (Au) [35] and magnetite (Fe_3O_4) [72] have attracted significant attention in recent years in the analysis of biomolecules using modified electrodes. Compared with bare electrodes, these metallic NPs used to modify electrodes show high sensitivity and selectivity towards the detection of biomolecules.

Both from a scientific and technological viewpoint, it has been showcased that bimetallic NPs have drawn increased attention compared to monometallic NPs, due to the two different metals involved [73, 74]. The properties of bimetallic nanoparticles are determined by constituting metals and their nanometric size. Various bimetallic NPs have been synthesized and applied for AA, UA and DA detection such as bismuth–silver (Bi–Ag) [75, 76], silver–gold (Ag–Au) [77], nickel–copper (Ni–Cu) [1], platinum–nickel (Pt–Ni) [78], nickel–cobalt (Ni–Co) [42] and palladium silver (Pd–Ag) [79], etc. The nanomaterials applied in the individual detection of DA, UA and AA are summarized in Table 1.

A screen-printed carbon electrode (SPCE) was modified with cadmium oxide (CdO) nanoparticles and reported by Gopalakrishnan et al. (2018) for non-enzymatic detection of ascorbic acid (AA) in commercial fruit juice that was very stable with a detection limit in the nanomolar range. This disposable SPCE was used to evaluate the electrocatalytic activity of CdO by cyclic voltammetry and differential pulse voltammetry (DPV) methods using AA as a model solution. At the surface of the CdO–SPCE, hydroxyl and oxygen functional groups help the AA molecules get absorbed onto the CdO–SPCE surface with e^- shifts between CdO–SPCE and AA. A two electron oxidation occur for AA to produce dehydroascorbic acid and during the oxidation of AA, $2e^-$ with $2H^+$ ions were released wich result in an increase in current as AA concentration increases. The newly developed electrode shows under optimal DPV conditions that AA can be detected in a wide range of concentrations from 5 to 150 μM with detection level at the ultra-low level (53.5 nM). The repeatability, reliability and stability investigations were performed with one electrode and a relative standard deviation of 3.7% was achieved for the detection of AA. Furthermore, in the presence of interfering electroactive compounds (UA, citric acid, urea, glucose, sucrose and Na^+), the disposable SPCE exhibited excellent selectivity and was highly stable towards the detection of AA [80].

In recent years, a GCE/Bi-AgNPs sensor was developed by a group of scientists [81] using bismuth-

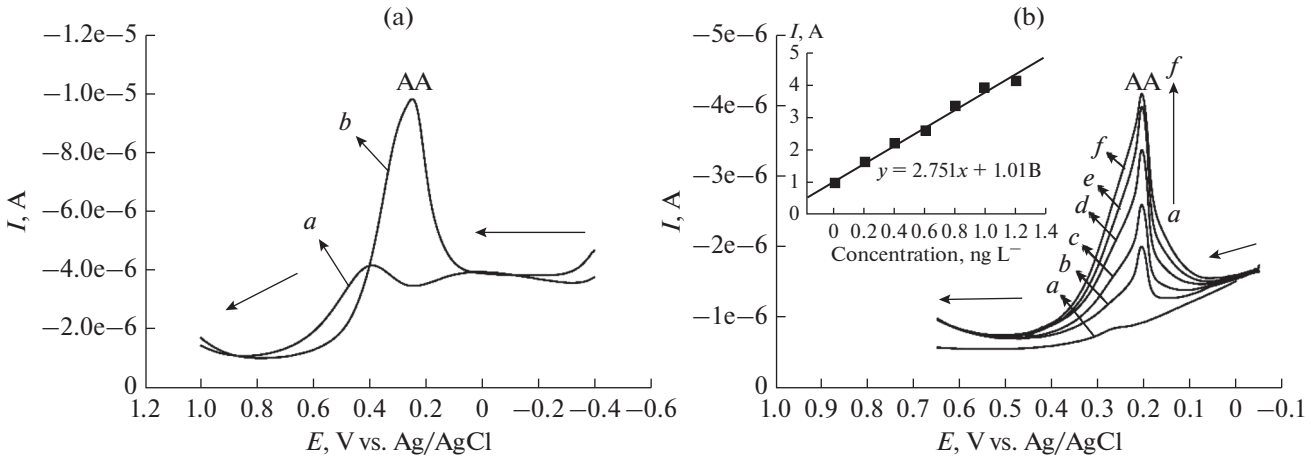


Fig. 1. In A the DPV curves of the clean bare disk GCE (a) and the GCE/Bi–AgNPs (b) containing 0.4 mM AA. The DPV curves of 0 to 1.2 μM of AA in solution of 0.1 M phosphate buffer solution (pH 5.0) in B [75].

silver bimetallic nanoparticles (Bi–AgNPs) that was chemically synthesized to detect platinum group metals in real environmental samples. These Bi–AgNPs were also used in pharmaceuticals and fruit juice samples for sensitive detection of AA (Fig. 1). For this application, the detection limit was in the micromolar range (0.16 μM) with linear ranges between 0.4 to 1.2 μM [75, 76]. The same GCE/Bi–AgNPs sensor was repeatedly used for 10 times to determined the repeatability and a relative standard deviation of 5.84% was achieved indicating excellent repeatability. Also the selectivity of this sensor was studies by adding potential interfering ions such as K^+, Na^+, Mg^{2+}, Cl^-, SO_4^{2-}, NO_3^-, and $H_2PO_4^-$ with AA. In a slight acidic buffer solution no interfence was observed with AA by these interfering ions.

Magnetic Nanoparticles

Recently, magnetic nanoparticles have been used as carriers and support in electrochemical sensors for the detection of biomolecules such as AA, UA, and DA. In addition to the good biocompatibility and large surface area, the outstanding advantage of magnetic nanoparticles is that the location and transport can be controlled by a magnetic field [91]. Carbon nanotubes (CNTs), graphite, 2D-graphene sheets or reduced graphene oxide (RGO) are called carbon skeleton materials and are used to modify the surface of magnetic nanoparticles of the electrode for cycling stability, electronic conductivity improvement and electrochemical performance towards the battery and sensor application [92–103].

A sensitive, selective, low cost, superior performance, and portable electrochemical sensor were constructed by Thamilselvan et al. (2019) in the detection of DA at a nanomolar level. A magnetic ($Au@Fe_3O_4$) composite film ($Au@Fe_3O_4$/GCE) was applied to modify a bare glassy carbon disk electrode (GCE) and to fabricate this sensing platform [104]. With the scan rate studies, a linear increase in the reduction and oxidation peak currents with the square root of the scan rates illustrates that the electrochemical kinetics of the $Au@Fe_3O_4$/GCE sensor was a diffusion controlled process. The Randles-Sevick equation was applied to calculate the diffusion coefficients of DA for the $Au@Fe_3O_4$/GCE sensor and a value of 7.04×10^{-5} cm^2 s^{-1} was obtained. The diffusion coefficient value can be ascribed to the electroactive surface area of the $Au@Fe_3O_4$/GCE sensor. The $Au@Fe_3O_4$/GCE sensor limit of detection was found to be 2.7 nM with a linear range of 0 to 0.8 μM for DA. In the investigation of the reprocucibility and repeatability of the $Au@Fe_3O_4$/GCE sensor, ten electrodes were constructed and immersed into a soltion with a fixed DA concentration. The sensor showcase good reproducibility and repeatability with relative standard deviation of 2.8 and 2.5%, respectively. For the selectivity test, the sensor was investigated by the addition of inorganic ions and organic compounds to a 0.1 M DA solution and showed no significant interference signals between DA and the interferering ions and compounds. The developed analytical procedure was successfully employed for DA detection in three human urine samples and the actual values found was 0.056 to 0.020 μM, respectively. The concentration of DA in the real samples are very low (0.020 μM) but is detectable due to the very low detection limit (2.7 nM). The recoveries found range from 97.2 to 103.4%, indicating that the proposed electrode can be successfully applied to detect DA in human urine samples [105].

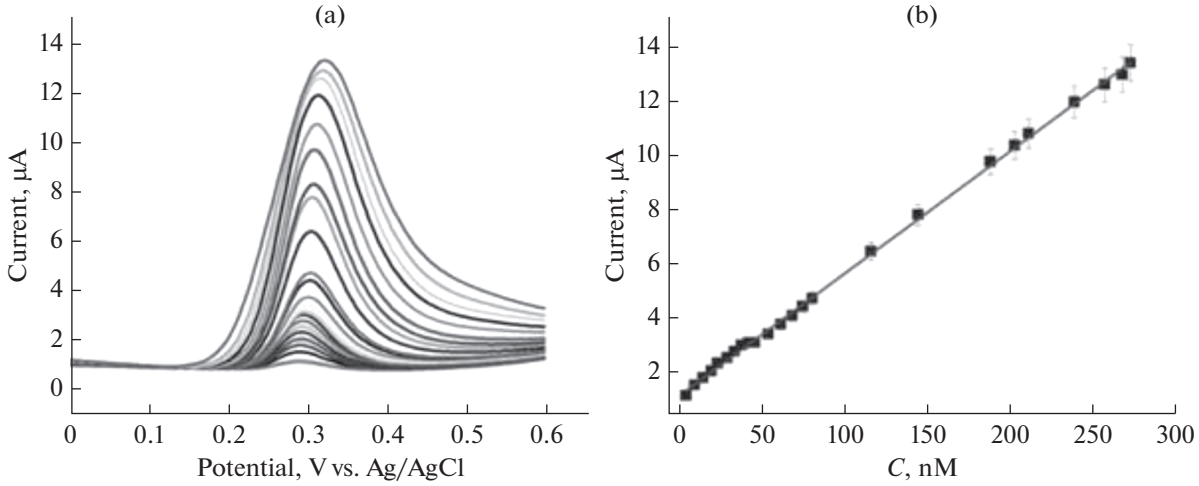


Fig. 2. DPV curves for the Pd–Ag/CPE sensing of 4.69 to 273 nM UA in 0.1 M phosphate buffer solution (pH 7.0) and (b) A calibration plot of I_{pa} vs. concentration for the detection of UA [79].

Nanomaterials Modified with Carbon-Based Materials

In the field of nanotechnology, scientists have extensively developed nanomaterials simple properties by modifying their synthesis procedures [106]. Carbon-based nanostructures such as graphene and its derivatives and carbon nanotubes have gained great attention regarding electrochemical sensors modification because the sensor's electrochemical performances have been effectively improved [107, 108]. Nanomaterials are used in the modification of working electrodes surfaces. In the development of electrochemical sensors nanomaterials have been employed as catalysts to catalyze the redox process arising at the electrode surfaces [109]. Due to their outstanding physical, chemical and electrical properties, carbon-based nanomaterials have been considered as potential alternatives for the improvement of electrochemical sensors [110–112].

Carbon-Materials

Liu et al. (2019) have used a bimetallic metal-organic framework-derived porous carbon to develop a novel electrochemical sensor based on the detection of uric acid in human serum samples. A direct carbonization method was used to prepare the porous carbon material. The facile electrochemical sensor illustrates for UA detection enhanced electrochemical catalytic activity. The bimetallic metal-organic framework-derived porous carbon/glassy carbon electrode (CNCo/GCE) had a broad range of linearity between 2.0 to 110 μM with a good limit of detection of 0.83 μM toward the detection of UA [82]. The CNCo/GCE sensor anti-interfering ability was assessed by the addition of potential interfering substances that are contained in real samples. Substances like ascorbic acid, glucose, SO_4^{2-}, Na^+, NO_3^-, and K^+ did not interfere with UA, indicating good anti-interference ability of the CNCo/GCE sensor. In the case of the reproducibility, seven electrodes were prepared under the same condition and submersed into a PBS (pH 7.0) containing 50 μM UA and produced a RSD of 3.07%. For the repeatability investigation, seven measurements were recorded with the same electrode and revealed a RSD of 3.26% for the CNCo/GCE sensor which display satisfactory repeatability and good reproducibility.

In another study, Mallikarjuna et al. (2018) synthesized palladium silver bimetallic nanoparticles (Pd–Ag NPs) by using a fungal extracted aqueous method. This bimetallic nanoparticle synthesized procedure was simple, cost-effective and environmentally friendly. Uric acid electrooxidation on the Pd–Ag/CPE sensor illustrates equal amount of electrons and protons. This modified electrode consisting of Pd-Ag displayed the highest electrocatalytic activity for UA detection (Fig. 2). The Pd–Ag/CPE sensor had a very good LOD of 5.543 nM and LOQ of 16.64 nM towards UA detection with linear ranges between 4.69 to 273 μM. The practical application of the Pd–Ag/CPE sensor was done by determine UA in human serum and urine samples. Adequate recoveries such as 93–103% were obtained by the Pd–Ag/CPE sensor showing extraordinary sensitivity for UA in human urine [79].

In another study, Yang et al. (2019) used a platinum nanoparticle (Pt NPs) modified nanoporous gold tin (Au–Sn) alloy on carbon fiber paper (CFP) for the simultaneous detection of DA, UA, and AA in urine samples. The newly developed platinum nanoparticles modified nanoporous gold–tin alloy on carbon fiber paper (Pt@NP–AuSn/Ni/CFP) sensor have a very high specific surface area, hierarchical pore structure and displayed excellent catalytic activity. This sensor illustrates high detection sensitivity for UA, AA, and DA,

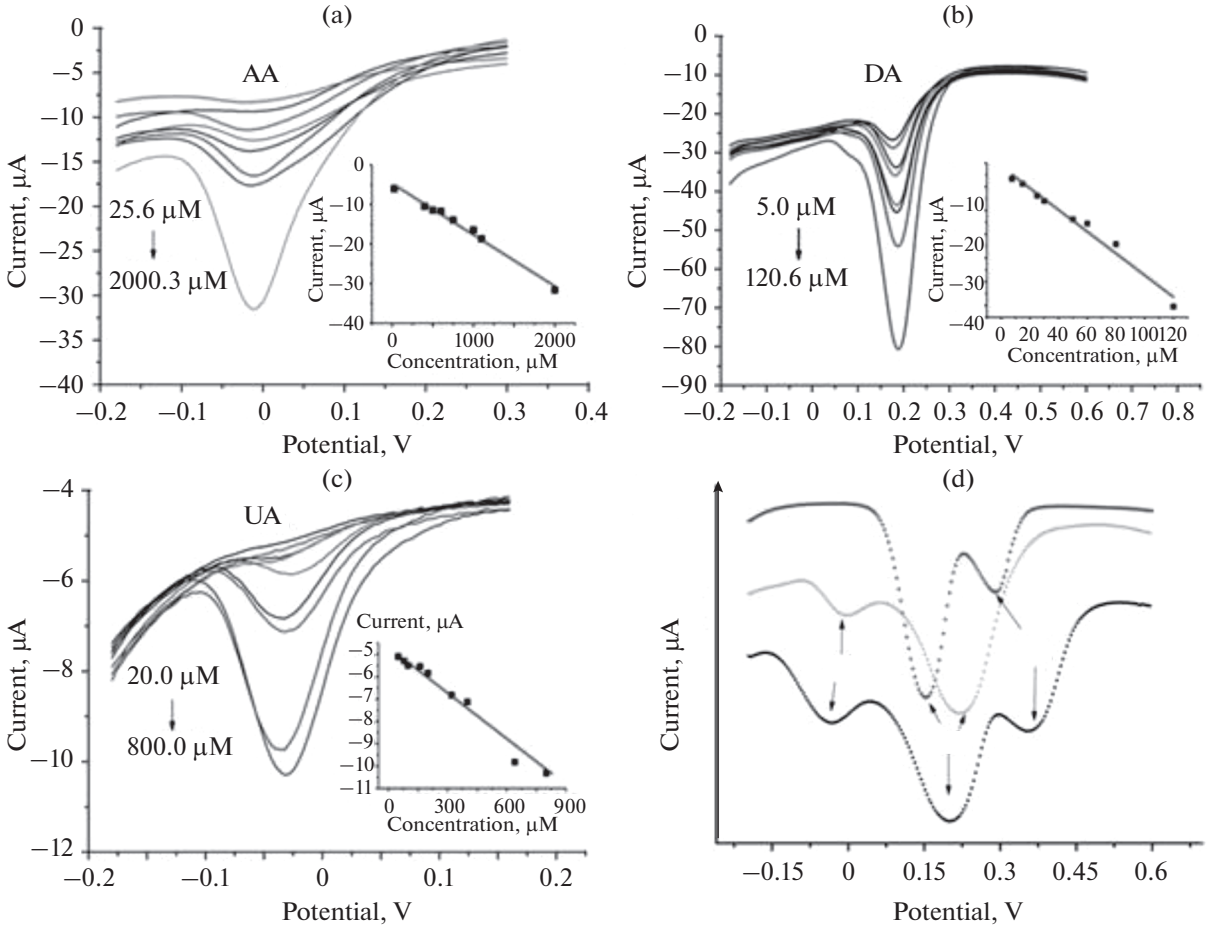


Fig. 3. DPV curves of the CNTs/CFE in a 0.1 M phosphate buffer solution (pH 7.0) containing (a) 25.6–2000.3 μM AA, (b) 5.0–120.6 μM DA, (c) 20.0–800.0 μM UA and (d) Selective detection of DA in the presence of AA and/or UA, with scan rate of 50 mV/s [114].

with sensitivities of 0.14, 15.23, 0.28 μA μM^{-1} cm^{-2} under the of linear range of 200 to 2000 μM, 1 to 10 μM, and 25 to 800 μM for UA, AA, and DA, respectively. The limit of detection for the sensor were 0.7, 0.31, and 13.4 μM (S/N = 3) for UA, DA and AA, respectively. In practical detection the anti-interference ability was also investigated using common interferents. Citric acid, glycine, glucose, NaCl, NH_4Cl, and KCl were the chosen as the interferents for the detection of UA, DA, and AA. From the results obtained, there was no significant change for oxidation current AA, DA and UA detection with these interferents. For the real sample application, the Pt@NP–AuSn/Ni/CFP sensor shown recoveries of 95 to 105% and these recoveries confirmed a great potential to detect DA, UA, and AA simultaneously in urine samples [113].

Zhao et al. (2018) developed an electrochemical sensor using a carbon fiber electrode (CFE) modified with carbon nanotubes (CNTs) via chemical vapour deposition to simultaneously detect UA, AA, DA using the DPV method (Fig. 3). The experimental results illustrate that the chemical vapour deposition step, under optimized conditions, increased the sensitivity and decreased the limit of detection of dopamine. For the electrooxidation peak current of AA, DA, and UA was found to be linear to their concentrations in the ranges of 25.6–2000.3 μM AA, 5.0–120.6 μM, and 20.0–800.0 μM. The limits of detection for DA, UA, and AA using the CNTs/CFE sensor were 0.03 μM, 0.6 μM, and 10.0 μM (S/N = 3), respectively. The interaction of the electron transfer velocity and the surface area was effectively increased by carbon nanotubes between neurotransmitters and electrode on the surface of the carbon fiber electrode [114]. The authors indicated the large electroactive surface area by using the Randles–Sevcik equation ($I_p = 2.69 \times 10^5 AD^{1/2}n^{3/2}v^{1/2}C$) with an average value of $(9.15 \pm 0.21) \times 10^{-2}$ cm^2 ($n = 6$) for the CNTs/CFE sensor.

Reddy et al. (2018) developed a carbon paste electrode (CPE) for selective detection of UA through the combination of dipicolinic acid (DPA) with a nanocomposite of $SiO_2@Fe_3O_4$. This poly(DPA)$SiO_2@Fe_3O_4$/CPE sen-

sor showed excellent electrochemical activity towards the detection of UA in the presence of AA, and DA in human blood and urine samples. At the poly(DPA)SiO_2@Fe_3O_4/CPE sensor surface the Nernstian equation indicates for the oxidation of UA a process of two electrons or two protons. The poly(DPA)SiO_2@Fe_3O_4/CPE sensor consist of oxygen atoms which interact with the biomolecules through hydrogen bonding, activating the NH_2 and OH groups and result in faster electronic charge transfer kinetics of target biomolecules on the modified sensor. The poly(DPA)SiO_2@Fe_3O_4/CPE sensor has high electroactive surface area suitable for rapid mass transfer of UA, DA, and AA in the supporting electrolyte. Under the optimized experimental conditions, it showcased good quantification limit (LOQ) and detection limit (LOD) of 1.2 and 0.4 μM, respectively, with a linear response for the sensing of uric acid in the range of 1.2 to 1.8 μM. Significant sensitivity and selectivity were shown by the poly(DPA)SiO_2@Fe_3O_4/CPE sensor towards the sensing of UA in the presence of DA and AA without any interference. The lowest concentration found for UA in human blood serum and urine samples was 0.108 mM and 0.095 mM indicating that this sensor can be used for real sample analysis [115].

Graphene-Materials

Graphene is a single layer of carbon atoms which is a two-dimensional nanomaterial structure invented by Geim and Novoselov, (2007). Graphene and its derivatives (e.g., reduced graphene oxide and graphene oxide) have gained considerable technological and scientific attention due to their outstanding physicochemical properties, such as electrical conductivity and high tensile strength [107]. Different types of electrodes that are modified by the chemical method have been constructed by introducing different nanomaterials onto graphene to enhance the determination of DA, UA, and AA [116]. The following section provides a summary of the applications of nanomaterials impregnated into graphene to developed electrochemical sensors for biological applications.

Edris et al. (2018) report on gold nanoparticles modified with reduced graphene oxide (ERGO)-poly(eriochrome black T) (pEBT) that were prepared electrochemically for the simultaneous detection of UA, AA, and DA in a phosphate buffer solution (pH 6.0). The effective electrical conductivity of the ERGO–pEBT/AuNPs sensor was described by the highest peak current observed in a solution containing 5.0 mM K_3[Fe $(CN)_6$] and 0.1 M KCl at a scan rate of 100 mV s^{-1}. The Randles–Sevcik equation ($I_p = 2.69 \times 10^5 AD^{1/2}n^{3/2}v^{1/2}$C) was employed to determine ERGO–pEBT/AuNPs/GCE active surface area and was larger compared with the bare GCE. High electrochemical catalytic activity was showcased by this modified glassy carbon electrode (GCE) which possessed high sensitivity and selectivity in oxidizing UA-DA and DA-AA solutions compared with the bare GCE. The limits of detection for DA, UA, and AA were 0.009, 0.046, and 0.53 μM (S/N = 3) with linear response ranges of 10 to 900 μM, 0.5 to 20 μM and 2 to 70 μM, respectively. The sensitivities of the modified sensor were recorded as 0.164, 0.034, and 0.003 μA/μM for DA, UA, and AA, respectively. Five different ERGO–pEBT/AuNPs electrodes were used for the reproducible study. For DA, UA, and AA the relative standard deviation was 2.8, 3.5, and 4.8%, respectively, indicating that the ERGO-pEBT/AuNPs sensor has high reproducibility for practical application. In the interferent investigation, interfering species such as Ca^{2+}, Fe^{3+}, L-cystine, Na^+, K^+, glucose, glycine, and Cu^{2+} does not affect the peak currents of DA, UA, and AA. The constructed electrochemical nanosensor was employed for the detection of UA, AA, and DA in a urine sample and vitamin C tablets with actual values of 1.2 and 11.36 μM, respectively, showing good recovery for the ERGO–pEBT/AuNPs/GCE sensor [117].

In another study, bimetallic Pd-Au-reduced graphene oxide nanocomposites were reported by Zou et al. (2017) for the electrochemical sensing of DA, UA, and AA in mouse urine and serum samples. Good linear responses such as 1.25 to 73.75 μM, 2.5 to 66.25 μM and 12.5 to 700 μM were observed for DA, UA, and AA, with limits of detection of 2.5, 0.75, and 12.5 μM, respectively [118]. Cyclic voltammetric responses were obtained for six different Pd–Au/RGO/GCE electrodes containing UA, DA, and AA in 0.1 M PBS (pH 7.0) recording relative standard deviations of 2.5, 2.3, and 4.1% for UA, DA, and AA, respectively, showing excellent reproducibility.

In 2015, Pruneanu et al. (2015) prepared an electrochemical sensor using gold working electrodes decorated with a composite of graphene–Au (Au/Gr–Au) for the detection of dopamine (DA). At the electrode surface, high-frequency electron transfer happens with fast electrochemical processes. With low frequency, ion diffusion is associated with slow electrochemical processes. In acidic solution, dopamine is present as a cationic form (aminoethyl group and hydroxyl group). The electrochemical oxidation for DA occurs as two electrons/two protons process, forming o-dopaminoquinone. In basic and natural solutions, when the amine group of o-dopaminoquinone is deprotonated, a cyclization reaction occurs, which yield leucodopaminochrome. The electrochemical sensor exhibited a linear response within concentrations of 3×10^{-7} to 3×10^{-4} M and the detection limit was found to be 2.05×10^{-7} M (S/N = 3) for DA detection. In contrast, a narrower linear range of 10^{-5} to 10^{-4} M and a higher detection limit of 3.03×10^{-5} M was observed for the electrochemical sensor. In this investigation, the interfering effect of UA and AA were studied, since they are the most problematic spe-

cies since the oxidation potential of dopamine is close to their oxidation potentials. The presence of uric acid and ascorbic acid in the solution led to an increase in the peak current with no peak potential shift for dopamine (+0.24 V) instead [119]. The working electrodes that are modified with graphene and other nanocomposites such as Pd–Ag bimetallic nanoparticles [120], Ag nanoparticles (AgNPs) and poly(L-arginine) (P(Arg)) [121], gold nanoparticles (AuNPs) [122], bimetallic Pd–Au nanoparticles [123] were used to detect AA, UA and DA.

Carbon Nanotubes (CNTs)

A tube-like structure consisting of a nanometre-scale is called a nanotube. Carbon nanotubes (CNTs) are known as practical nanomaterials for electrode modification in the field of electrochemistry due to their extraordinary characteristics. CNTs have gained enormous attention in numerous scientific and engineering fields for different applications since their invention in 1991 and are found in two classifications such as single-walled carbon nanotube (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). Over the past decade, many scientists [124] have studied the extraordinary properties of CNTs, such as high electron-transfer rate, low electrode fouling, high electro-catalytic activity, and large effective detection surface because these extraordinary properties make them suitable as substrates for biomolecules detection in pharmaceuticals [125–127].

In electrochemistry, one type of CNT that exhibits exceptional properties such as significant mechanical strength, large electrode surface area, high electron-transfer rate, and good chemical stability are multi-walled carbon nanotubes (MWCNTs) [128]. In the field of material science, MWCNTs have attracted considerable attention as an electrode component, for electrode modification and to increase the anti-interference properties and sensitivity of these working electrodes. In the following section, the authors summarized the application of CNTs modified with different nanoparticles in the fabrication of electrochemical nanosensors for AA, UA and DA detection.

A polythiophene gold nanoparticle carbon nanotube (PT/Au/CNTs)-composite was synthesized by Inagaki et al. (2019) and successfully employed to determine DA in the model standard solution. A simple and versatile route was used to synthesize these nanocomposite thin films and the morphology was done by transmission electron microscope (TEM), scanning electron microscope (SEM), profilometry and electron dispersed spectroscopy (EDS). Whereas the elementary composition was done by Fourier-transformed infrared (FT-IR), Raman spectroscopy, thermogravimetric analysis (TGA), ultraviolet-visible spectroscopy (UV-Vis) and X-ray spectroscopy (DRX). For this PT/Au/CNT sensor, the best results were found after 4.5 h of reaction, with a limit of detection of 0.69 $\mu M\ L^{-1}$. For the repeatability, a relative standard deviation of 3.6% for fifteen followed measurements of DA for one electrode of PT/Au/CNT sensor was recorded. The reproducibility study involved five replicates of each film, demonstrating a standard deviation of 6.9%, for PT/Au/CNT. The influence of co-existence interfering species such as glucose, UA, and AA in the detection of DA with no significative interference was observed using this PT/Au/CNT sensor was recorded [86].

Silver–gold bimetallic nanoparticles (Ag–Au NPs) were used by Arvinte et al. (2018) to modify CNTs based electrodes for DA detection using differential pulse voltammetry. A limit of detection for the Ag–AuNP/CNT/SPE sensor was determined to be 52 nM in the linear range of 1 to 173 nM under optimized conditions. The Ag–AuNP/CNT/SPE sensor reproducibility was evaluated by using five different constructed electrodes and a relative standard deviation of 2.3% was achieved. Ascorbic acid was the interferent in this investigation and shown no significant interfering effect towards the detection of DA. The detection of DA in real samples by this sensor was limited due to the co-existence of high concentration AA and oxidized close to the potentials of DA. In the extracellular fluid of the nervous system, the concentration of AA ranges from 100 to 500 μM and compared to 0.01 to 1 μM [77].

In another study, a novel PMo_9V_3-Pd@Pt/CNTs/ITO nanosensor was constructed by Jiao et al. (2018) for the electrochemical determination of DA in human serum samples. Palladium–platinum alloy nanoparticles (Pd@Pt) decorated polyoxometalate (PMo_9V_3) were plated on indium-tin-oxide (ITO) electrodes surfaces which were pre-modified by multiwalled CNTs. This fabricated sensor revealed a low detection limit of 1.25×10^{-8} M (S/N = 3) with wide linearity of 2.50×10^{-8} to 1.78×10^{-4} M. The selectivity study for the PMo_9V_3–Pd@Pt/CNTs/ITO nanosensor were performed by adding six common interferents (glucose, UA, AA, L-cysteine, L-glutamate, and L-tryptophan) to a solution containing DA with no interferences. A relative standard deviation of 5.09% was found for the determination of DA using the PMo_9V_3–Pd@Pt/CNTs/ITO nanosensor. For real samples analysis, a standard addition method was used with no actual values found in human serum samples. Satisfied recoveries from 95.1 to 105.6% was obtained showing good accuracy of DA detection [88].

In the case of MWCNTs, Chang et al. (2019) have proposed a nanosensor for the electrochemical determination of DA via electropolymerization of poly beta-cyclodextrin. This polymer was combined with oxidized (–OH) multi-walled carbon nanotubes β-CD(f-MWCNTs) onto anion-doped polyaniline (PANI) drop cast onto a disk glassy carbon electrode (GCE) surface. Scanning electron microscopy (SEM), transmission electron microscopy (TEM),

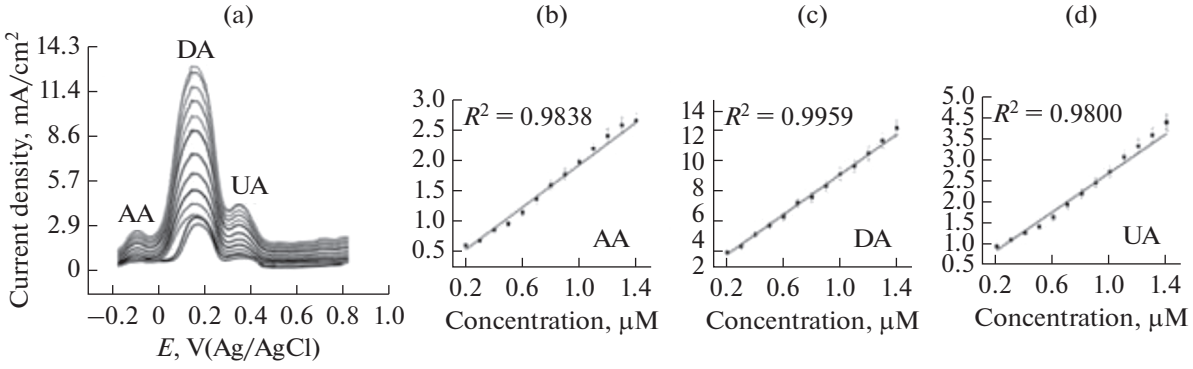


Fig. 4. (a) An illustration of DPV curves of monodisperse ZnNiNPs@f-MWCNT composite sensor for UA, AA, and DA determination in 0.1 M phosphate buffer solution. Corresponding calibration plots of monodisperse ZnNi NPs@f-MWCNT composite sensor for AA (b), DA (c) and UA (d) at increasing concentrations of 0.2 to 1.4 mM [130].

Fourier-transform infrared (FT-IR), and electrochemical impedance spectroscopy (EIS) were applied for the characterization of the developed poly-β-CD(f-MWCNTs)/PANI composite. Based on the CV results obtained, a combined kinetic process for the electrochemical process was observed and are scan rate dependable. Van der Waals force and hydrogen bonding result that DA molecules are adsorbed on to the poly-β-CD(f-MWCNTs)/PANI at low scan rates. At high scan rates, the DA molecules adsorption process is limited due to inadequate time and this forced the DA molecules by diffusion through the electrolyte solution to the surface of the sensor surface. The electrochemical transfer kinetic parameters of DA on modified electrode such as the number of electrons transfer (n), electron transfer coefficient (α), and the standard electron transfer rate constant (K_s) was calculated by the following Laviron's equations:

$$E_{pa} = a + \frac{2.303RT}{(1-\alpha)nF}\log v, \quad (1)$$

$$E_{pa} = b - \frac{2.303RT}{\alpha nF}\log v, \quad (2)$$

$$\log K_s = \alpha\log(1-\alpha) + (1-\alpha)\log\alpha - \log\frac{RT}{nFv} - \alpha(1-\alpha)\frac{nF\Delta E_p}{RT}, \quad (3)$$

$$I_p = \frac{n^2F^2A\Gamma v}{4RT}. \quad (4)$$

From these equations, the number of electrons (n) involved in this electrochemical process and electron transfer coefficient (α) was estimated to be 2 and 0.54, respectively. The average value of K_s was estimated to be 2.01 s^{-1} which proved that the poly-β-CD(f-MWCNTs)/PANI sensor has the excellent catalytic capacity to enhance electron transfer kinetic of DA. Furthermore, the surface concentration of the electroactive species DA (Γ) was calculated to be 8.1887×10^{-6} mol cm^{-2} according to equation (4).

$$\frac{I_{cat}}{I_L} = (\pi K_{cat}c_0 t)^{1/2}, \quad (5)$$

$$I_{cat} = nFAD^{1/2}c_0\pi^{-1/2}t^{-1/2}. \quad (6)$$

Therefore, at 0.5 mM DA concentration, the value of K_{cat} was to be 23.8 M^{-1} s^{-1} and was determined by equation (5). Cotrell's law was employed to determined the diffusion coefficient (D) and was estimated to be 2.14×10^{-4} cm^2 s^{-1}. The concentration of DA was determined by differential pulse voltammetric (DPV) technique, and under optimum conditions, a low detection limit (LOD) was achieved (0.0164 μmol L^{-1} (S/N = 3)) with a linear response that ranges from 2 μmol L^{-1} to 24 μmol L^{-1} and high sensitivity of 26.79 μA μM^{-1} cm^{-2}. For the repeatability, five measurements were collected with the same poly-β-CD(f-MWCNTs)/PANI electrode and a relative standard deviation was found to be 1.10% illustrates good repeatability. Five different electrodes were prepared for reproducibility and yield a relative standard deviation of 3.15% showing excellent reproducibility for the poly-β-CD(f-MWCNTs)/PANI sensor. The developed sensor was applied to human urine samples to showcase acceptable practicality for the determination of DA [129].

Savk et al. (2019) developed a novel, highly precise and stable nanosensor that was modified using a hybrid nanocomposite, consisting of ZnNi bimetallic nanoalloy and one-dimensional MWCNTs (Fig. 4). The so-called ZnNiNPs@f-MWCNT electrochemical sensor has been employed for the simultaneous detection of DA, UA and AA in human serum samples using differential pulse voltammetry (DPV) measurements with limits of detection of 0.0655 μM for DA, 0.0882 μM for UA, and 0.5110 μM for AA, respectively. The constructed electrochemical sensor showcased wide linear responses of 0.3 to 1.1 mM for AA,

Table 2. Nanomaterials for the simultaneous detection of UA, DA and AA

Nanomaterial	Sample	Limits of detection, μM			Linear range, μM			References
		AA	UA	DA	AA	UA	DA	
Fe_3O_4–SnO_2–Gr	Serum & urine	0.062	0.005	0.0071	0.1–23	0.015–2.40	0.02–2.8	[11]
HNP–PtTi	Serum	24.2	5.3	3.2	200–1000	100–1000	4–500	[16]
Pt@NP–AuSn/Ni/CFP	Urine	5.51	0.67	0.13	200–2000	25–800	1–10	[113]
CNTs/CFE	Urine	10.0	0.6	0.03	25.6–2000.3	20.0–800.0	5.0–120.6	[114]
ERGO–pEBT/AuNPs	Urine & tablets	0.53	0.009	0.046	10–900	2–70	0.5–20	[117]
PdAu/RGO	Urine & serum	12.5	2.5	0.75	12.5–700	2.5–66.25	1.25–73.75	[118]
AgNPs/P(Arg)–GO	Urine	0.984	0.142	0.01	4.0–2400	0.5–150	0.5–50	[121]
ZnNi NPa@f-MWCNT	Serum	0.5110	0.0882	0.0655	300–1100	200–1100	200–1200	[130]
Au/PDDA/GNS		80.0	2.0	1.0	600–4200	6–156	2.0–28.0	[131]
3DGH-Fc/GCE	Serum	0.183	0.067	0.042	20–450	8–400	10–180	[132]

0.2 to 1.2 mM for DA and 0.2 to 1.1 mM for UA. Figure 4 illustrates the DPV curves of monodisperse ZnNiNPs@f-MWCNT composite for the simultaneous detection of UA, AA, and DA in 0.1M phosphate buffer solution with their correspondent calibration plots [130]. An essential chemical sensor parameter such as anti-interference measurements for the determination of UA, AA, and DA was also observed. Glucose, glucosamine, NaCl, $CuCl_2$, KCl, $AlCl_3$, and $CaCl_2$ are present in body fluids and human blood and are used for the interferents study. No interference was observed at the ZnNiNPs@f-MWCNT using these interfering species.

Table 2 summarize the comparison of the linear range and limits of detection results obtained for the simultaneous detection of DA, UA, and AA.

Nanomaterials Modified with Polymers

Different organic polymers such as conducting and chelating polymers have been employed in the simultaneous detection of DA, UA, and AA. These polymers were added either by the co-polymerization of monomers and after the modification of electrodes by polymerized products. The most commonly used electroactive/conductive polymers for the modification of electrodes to determine AA, UA, and DA include PANI [72], polypyrrole (PPy) [133], poly(3,4-ethylene dioxythiophene (PEDOT) [134], poly(ericochrome black T) (PEBT) [117] and poly(4-vinyl pyridine) (PVP) [135]. The use of nanomaterials impregnated into polymers has been encouraged by a huge number of scientists [116]. Scientists had explored the active states of polymer nanocomposites which encourage the ability of polymer nanocomposites to produce high electrical conductivity, and their large surface area increases the ability to transfer electrons in electrochemical reactions. These properties have improved sensitivity and selectivity and lower the limits of detection [106].

The work done by Mahmoudian et al. (2019) demonstrates the synthesis of an α-Fe_2O_3/polyaniline nanotube (PAnNTs) composite as an electroactive material to construct an electrochemical nanosensor for uric acid (UA) detection. The α-Fe_2O_3/PAnNTs had a working linear response for UA concentrations between 0.01 μM and 5 μM and detection limit of 0.038 μM, respectively. The electrochemical nanosensor had a sensitivity of 0.433 μA μM^{-1} and the reliability of the sensor towards UA detection was investigated in solutions consisting of ascorbic acid (AA), citric acid (CA), and succinic acid (SA). The results have shown no significant interference between UA and the interferents (AA, CA, and SA) using the α-Fe_2O_3/PanNTs/GCE sensor. A relative standard deviation of 5.49% was observed after 10 days from five-time determination and illustrates good repeatability. For the real urine sample, the actual result was measured at 2.53 μM [72]. The nanomaterials employed for the simultaneous detection of DA and UA are summarized in Table 3.

Ali et al. (2017) have constructed a sensor for the simultaneous detection of DA and UA in neutral phosphate buffer solutions. In this study, ethylene dioxythiophene (EDOT) and chloroauric acid ($HAuCl_4$) ratio range from 2 : 1 to 1 : 2 were synthesized by a method of in-situ polymerization to produce hollow nano-

Table 3. Nanomaterials for the simultaneous detection of DA and UA

Nanoparticles	Sample	Method	Detection limits, μM		Linear range, μM		References
			UA	DA	UA	DA	
$PtNi@MoS_2$	Urine	DPV	0.1	0.1	0.5–600	0.5–150	[78]
PEDOT/AuNPs	Aqueous	DPV	0.08	0.07	1.5–150	0.15–330	[136]
Au-Pt	Urine & serum	DPV	0.038	0.006	1–1000	0.1–400	[137]
HNP–AuAg	Aqueous	DPV	1.0	0.2	5–425	5–335	[138]
$Au–SiO_2$	Serum	DPV	2.58	1.98	10–500	10–100 200–500	[139]
CuO nano-rice	Urine & serum	DPV	1.2	0.42	1.0–160	1.0–150	[140]
GNP/FTO	Serum	DPV	0.28	0.22	1–100	1–100	[141]

spheres of poly(3,4-ethylene dioxythiophene)/Gold (PEDOT/Au) composition. The PEDOT/Au (1 : 1) modified electrode revealed excellent electrocatalytic activity with faster electron charge transfer kinetics that was showcased by the electrochemical experiments. The DPV results revealed an excellent linear response with 0.15 to 330 μM and 1.5 to 150 μM for the PEDOT/Au (1 : 1) electrode in UA and DA detection, respectively. Low detection limits (S/N = 3) were obtained for DA and UA detection (0.08 and 0.07 μM). Excellent stability (0.6%) and repeatability (2.9%) with good reproducibility (3.1%) was showcased by this PEDOT/Au (1 : 1) electrode [136].

Nanomaterials Modified with Other Materials

Recently, porous silicon decorated silver nanoparticles (AgNPs–PSi) was synthesized by Harraz et al. (2019) via stain etching of Si, followed by a simple immersion plating of Ag and applied for the successful determination of AA. The newly constructed AgNPs-PSi sensor detect AA with remarkable sensing performances with fast response time (<5 s), high sensitivity of 1.279 μA μM cm^2, a low detection limit of 0.83 μM, wide linear range between 20 to 600 μM and excellent anti-interference using AA, DA, citric acid and glucose. The repeatability behaviour was performed for ten successive measurements and led to a relative standard deviation of 3.5%. This AgNPs–PSi sensor was also applied to the analysis of a vitamin C supplement that was commercially available with satisfactory detection results [83].

In another study done by Zhang et al. (2018), a hydrothermal process was employed to construct a novel branch-trunk Ag hierarchical nanostructures and then fabricated on Tellurium (Te) nanowires via the reaction of galvanic replacement using a microwave-assisted synthesis method. The investigation of newly synthesized hierarchical nanostructures in the development of electrochemical sensors for the detection of AA in orange juice and human urine samples produced satisfactory results. The branch-trunk Ag hierarchical nanostructures sensor showed a detection limit of 0.06 μM (S/N = 3) with linearity that ranges from 0.17 μM to 1.80 mM (R = 0.999) in AA determination [84]. The actual results obtained for AA in orange juice and human urine samples was 11.3 and 18.5 μM, respectively. Interfering species such as glucose, CA, H_2O_2, and DA were exploited in the determination of AA with no effects on the selective determination of AA.

Recently, Liu et al. (2019) have constructed a simple electrochemical sensor for the detection of DA using the Au nanocomposites with the Ag@C core-shell structure (Ag@C/Au) and illustrated in Fig. 5. The Ag@C/Au composite was synthesized by a one-pot hydrothermal method for Ag@C core–shell nanoparticles followed by the in-situ reduction process of Au nanoparticles. This sensor shown under the optimum experimental conditions, with a detection limit of 0.21 μM (S/N = 3) with linearity that ranges from 0.5 to 27.5 μM, 27.5 to 0.2775 mM and 0.2775 to 4.278 mM for DA. For reproducibility, five different electrodes were prepared under the same practical conditions. A relative standard deviation of 4.5% was calculated for the five measurements. Also for this study, the anti-interference ability for the Ag@C/Au/GCE sensor was carefully studied. Anti-interference species such as citric acid, glycine, lysine, glucose, H_2O_2, UA, and AA were added to a 0.1 mol L^{-1} PBS containing DA. From the scans, no interference was observed after adding these common interference species. The Ag@C/Au/GCE sensor exhibited good selectivity and anti-interference ability towards the detection of DA. A comparison of the linear range and limit of detection results are summarized in Table 1, which illustrates various working electrodes that were modified with different nano-

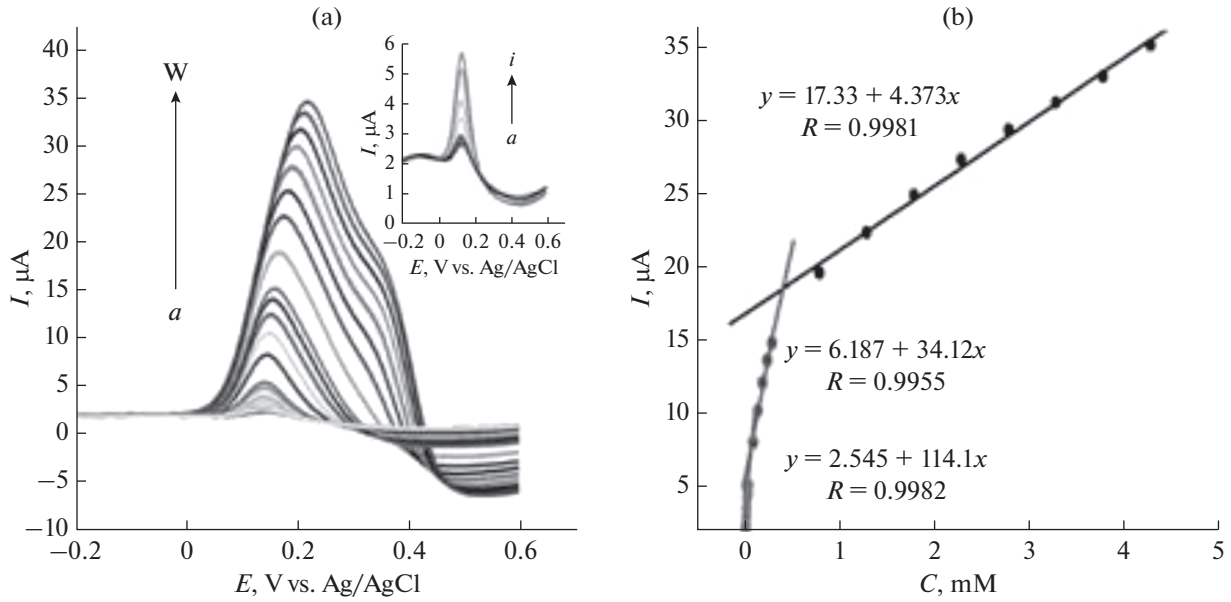


Fig. 5. DPV curves of Ag@C/Au/GCE sensor in 0.1 M phosphate buffer solution (pH 7.0) with increasing concentrations of 0.50 to 4.28 mM DA in (a). Corresponding calibration curves of the peak currents versus the increasing concentrations of DA in (b) [87].

materials for the individual detection of DA, UA, and AA [87].

CONCLUSIONS

The detection of DA, UA, and AA in samples such as pharmaceuticals and human serum is very problematic for the analytical scientist. Over the past years, nanomaterials modified with different materials have been expanding the need for economic, simple and rapid sensors and have become part of electrochemistry and analytical chemistry. In this study, we have summarized the different roles that metallic and bimetallic nanoparticles play in UA, AA, and DA detection in clinical, pharmaceutical and food samples. Furthermore, we observed that the application of iron and platinum-based nanoparticles are not frequently used in the detection of DA, UA, and AA in pharmaceuticals. The lowest detection limit for both individual and simultaneous detection of DA, UA, and AA in real samples was achieved by Au/PDDA–rGO sensor. Finally, this investigation showcased the challenges on the construction of nanocomposite sensors which has no practical difficulty in producing reliable and reproducible results for the detection of DA, UA, and AA in pharmaceuticals.

CONFLICT OF INTEREST

No conflict of interest was declared by Charlton van der Horst and Vernon Somerset.

REFERENCES

1. He, W., Ding, Y., Ji, L., Zhang, X., and Yang, F., A high-performance sensor based on bimetallic NiCu nanoparticles for the simultaneous determination of five species of biomolecules, *Sens. Actuators B-Chem.,* 2017, vol. 241, p. 949.
2. Arrigoni, O. and Tullio, M.C.D., Ascorbic acid: much more than just an antioxidant, *Biochim. Biophys. Acta,* 2002, vol. 1569, p. 1.
3. Yang, F.Q., Guan, J., and Li, S.P., Fast simultaneous determination of 14 nucleotides and nucleobases in cultured Cordyceps using ultra-performance liquid chromatography, *Talanta,* 2007, vol. 73, p. 269.
4. Damier, P., Hirsch, E.C., Agid, Y., and Graybiel, A.M., The substantia nigra of the human brain II. Patterns of loss of dopamine-containing neurons in Parkinson's disease, *Brain,* 1999, vol. 122, p. 1437.
5. Li, Y., Chen, S., Shao, X., Guo, J., Liu, X., and Liu, A., Association of uric acid with metabolic syndrome in men, premenopausal women and postmenopausal women, *Int. J. Environ. Res. Public Health,* 2014, vol. 11, p. 2899.
6. Wang, L., Gong, C., Shen, Y., Ye, W., Xu, M., and Song, Y., A novel ratiometric electrochemical biosensor for sensitive detection of ascorbic acid, *Sens. Actuators B,* 2017, vol. 242, p. 625.
7. Kim, M.C., Kwak, J., and Lee, S.Y., Sensing of uric acid via cascade catalysis of uricase and a biomimetic catalyst, *Sens. Actuators B-Chem.,* 2016, vol. 232, p. 744.
8. Li, X.-L., Li, G., Jiang, Y.-Z., Kang, D., Jin, C.H., Shi, Q., Jin, T., Inoue, K., Todoroki, K., Toyo'oka, T., and Min, J.Z., Human nails metabolite analysis: a rapid and simple method for quantification of uric acid in human fingernail by high-performance liquid chroma-

tography with UV-detection, *J. Chromatogr. B,* 2015, vol. 1002, p. 394.

9. Sha, R. and Badhulika, S., Facile green synthesis of reduced graphene oxide/tin oxide composite for highly selective and ultra-sensitive detection of ascorbic acid, *J. Electroanal. Chem.,* 2018, vol. 816, p. 30.
10. Li, Y., Ran, G., Yi, W.J., Luo, H.Q., and Li, N.B., A glassy carbon electrode modified with graphene and poly(acridine red) for sensing uric acid, *Microchim. Acta,* 2012, vol. 178, p. 115.
11. Bagheri, H., Pajooheshpour, N., Jamali, B., Amidi, S., Hajian, A., and Khoshsafar, H., A novel electrochemical platform for sensitive and simultaneous determination of dopamine, uric acid and ascorbic acid based on Fe_3O_4-SnO_2-Gr ternary nanocomposite, *Microchem. J.,* 2017, vol. 131, p. 120.
12. Motshakeri, M., Travas-Sejdic, J., Phillips, A.R.J., and Kilmartin, P.A., Rapid electroanalysis of uric acid and ascorbic acid using a poly(3,4-ethylenedioxythiophene)-modified sensor with application to milk, *Electrochim. Acta,* 2018, vol. 265, p. 184.
13. Kenarkob, M. and Pourghobadi, Z., Electrochemical sensor for acetaminophen based on a glassy carbon electrode modified with ZnO/Au nanoparticles on functionalized multiwalled carbon nanotubes, *Microchem. J.,* 2019, vol. 146, p. 1019.
14. Cinti, S., Colozza, N., Cacciotti, I., Moscone, D., Polomoshnov, M., Sowade, E., Baumann, R.R., and Arduini, F., Electroanalysis moves towards paper-based printed electronics: carbon black nanomodified inkjet-printed sensor for ascorbic acid detection as a case study, *Sens. Actuators B-Chem.,* 2018, vol. 265, p. 155.
15. Ganesh, P.S. and Kumara Swamy, B.E., Simultaneous electroanalysis of norepinephrine, ascorbic acid and uric acid using poly(glutamic acid) modified carbon paste electrode, *J. Electroanal. Chem.,* 2015, vol. 752, p. 17.
16. Zhao, D., Yu, G., Tian, K., and Xu, C., A highly sensitive and stable electrochemical sensor for simultaneous detection towards ascorbic acid, dopamine, and uric acid based on the hierarchical nanoporous PtTi alloy, *Biosens. Bioelectron.,* 2016, vol. 82, p. 119.
17. Tukimin, N., Abdullah, J., and Sulaiman, Y., Review-electrochemical detection of uric acid, dopamine and ascorbic acid, *J. Electrochem. Soc.,* 2018, vol. 165, no. 7, p. B258.
18. Zhang, X.D., Liu, X.J., Zhang, L., Li, D.L., and Liu, S.H., Novel porous Ag_2S/ZnS composite nanospheres: fabrication and enhanced visible-light photocatalytic activities, *J. Alloys Compd.,* 2016, vol. 655, p. 38.
19. Mao, C.J., Chen, X.B., Niu, H.L., Song, J.M., Zhang, S.Y., and Cui, R.J., A novel enzymatic hydrogen peroxide biosensor based on Ag/C nano cables, *Biosens. Bioelectron.,* 2012, vol. 31, p. 544.
20. Teymourian, H., Salimi, A., and Khezrian, S., Fe_3O_4 magnetic nanoparticles/reduced graphene oxide nanosheets as a novel electrochemical and bioelectrochemical sensing platform, *Biosens. Bioelectron.,* 2013, vol. 49, p. 1.
21. Yue, H.Y., Huang, S., Chang, J., Heo, C., Yao, F., Adhikari, S., Gunes, F., Liu, L.C., Lee, T.H., Oh, E.S., Li, B., Zhang, J., Huy, T.Q., Luan, N., Van, and Lee, Y.H., ZnO nanowire arrays on 3D hierarchical graphene foam: biomarker detection of Parkinson's disease, *ACS Nano,* 2014, vol. 8, p. 1639.
22. Abellán-Llobregat, A., Jeerapan, I., Bandodkar, A., Vidal, L., Canals, A., Wang, J., and Morallón, E., A stretchable and screen-printed electrochemical sensor for glucose determination in human perspiration, *Biosens. Bioelectron.,* 2017, vol. 91, p. 885.
23. Abellán-Llobregat, A., Vidal, L., Rodríguez-Amaro, R., Berenguer-Murcia, A., Canals, A., and Morallón, E., Au-IDA microelectrodes modified with Au-doped graphene oxide for the simultaneous determination of uric acid and ascorbic acid in urine samples, *Electrochim. Acta,* 2017, vol. 227, p. 275.
24. Huang, Y., Miao, Y.E., Ji, S., Tjiu, W.W., and Liu, T., Electrospun carbon nanofibers decorated with Ag–Pt bimetallic nanoparticles for selective detection of dopamine, *ACS Appl. Mater. Interfaces,* 2014, vol. 6, p. 12449.
25. Sun, C.L., Chang, C.T., Lee, H.H., Zhou, J., Wang, J., Sham, T.K., and Pong, W.F., Microwave-assisted synthesis of a core–shell MWCNT/GONR heterostructure for the electrochemical detection of ascorbic acid, dopamine, and uric acid, *ACS Nano,* 2011, vol. 5, p. 7788.
26. Sun, C.L., Lee, H.H., Yang, J.M., and Wu, C.C., The simultaneous electrochemical detection of ascorbic acid, dopamine, and uric acid using graphene/size-selected Pt nanocomposites, *Biosens. Bioelectron.,* 2011, vol. 26, p. 3450.
27. Cai, W., Lai, J., Lai, T., Xie, H., and Ye, J., Controlled functionalization of flexible graphene fibres for the simultaneous determination of ascorbic acid, dopamine and uric acid, *Sens. Actuator B-Chem.,* 2016, vol. 224, p. 225.
28. Deng, W., Yuan, X., Tan, Y., Ma, M., and Xie, Q., Three-dimensional graphene-like carbon frameworks as a new electrode material for electrochemical determination of small biomolecules, *Biosens. Bioelectron.,* 2016, vol. 85, p. 618.
29. Jiang, J. and Du, X., Sensitive electrochemical sensors for simultaneous determination of ascorbic acid, dopamine, and uric acid based on Au@Pd-reduced graphene oxide nanocomposites, *Nanoscale,* 2014, vol. 6, p. 11303.
30. Yang, Y.J. and Li, W., CTAB functionalized graphene oxide/multiwalled carbon nanotube composite modified electrode for the simultaneous determination of ascorbic acid, dopamine, uric acid and nitrite, *Biosens. Bioelectron.,* 2014, vol. 56, p. 300.
31. Kalimuthu, P. and John, S.A., Simultaneous determination of ascorbic acid, dopamine, uric acid and xanthine using a nanostructured polymer film modified electrode, *Talanta,* 2010, vol. 80, p. 1686.
32. Lin, K.-C., Tsai, T.-H., and Chen, S.-M., Performing enzyme-free H_2O_2 biosensor and simultaneous determination for AA, DA, and UA by MWCNT-PEDOT film, *Biosens. Bioelectron.,* 2010, vol. 26, p. 608.

33. Sajid, M., Nazal, M.K., Mansha, M., Alshara, A., Jillani, S.M.S., and Basheer, C., Chemically modified electrodes for electrochemical detection of dopamine in the presence of uric acid and ascorbic acid: a review, *Trends Anal. Chem.,* 2016, vol. 76, p. 15.

34. Abbas, M.W., Soomro, R.A., Kalwar, N.H., Zahoor, M., Avci, A., Pehlivan, E., Hallam, K.R., and Willander, M., Carbon quantum dot coated Fe_3O_4 hybrid composites for sensitive electrochemical detection of uric acid, *Microchem. J.,* 2019, vol. 146, p. 517.

35. Bai, Z., Zhou, C., Xu, H., Wang, G., Pang, H., and Ma, H., Polyoxometalates-doped Au nanoparticles and reduced graphene oxide: a new material for the detection of uric acid in urine, *Sens. Actuators B-Chem.*, 2017, vol. 243, p. 361.

36. Jain, S., Verma, S., Singh, S.P., and Sharma, S.N., An electrochemical biosensor based on novel butylamine capped CZTS nanoparticles immobilized by uricase for uric acid detection, *Biosens. Bioelectron.,* 2019, vol. 127, p. 135.

37. El Ridi, R. and Tallima, H., Physiological functions and pathogenic potential of uric acid: a review, *J. Adv. Res.,* 2017, vol. 8, no. 5, p. 487.

38. Grassi, D., Ferri, L., Desideri, G., Giosia, P.D., Cheli, P., Pinto, R.D., Properzi, G., and Ferri, C., Chronic hyperuricemia, uric acid deposit and cardiovascular risk, *Curr. Pharm. Des.,* 2013, vol. 19, no. 13, p. 2432.

39. Sekli-Belaidi, F., Temple-Boyer, P., and Gros, P., Voltammetric microsensor using PEDOT-modified gold electrode for the simultaneous assay of ascorbic and uric acids, *J. Electroanal. Chem.,* 2010, vol. 647, p. 159.

40. Harraz, F.A., Faisal, M., Ismail, A.A., Al-Sayari, S.A., Al-Salami, A.E., Al-Hajry, A., and Al-Assiri, M.S., TiO_2/reduced graphene oxide nanocomposite as efficient ascorbic acid amperometric sensor, *J. Electroanal. Chem.,* 2019, vol. 832, p. 225.

41. Huang, D., Li, X., Chen, M., Chen, F., Wan, Z., Rui, R., Wang, R., Fan, S., and Wu, H., An electrochemical sensor based on a porphyrin dye-functionalized multiwalled carbon nanotubes hybrid for the sensitive determination of ascorbic acid, *J. Electroanal. Chem.,* 2019, vol. 841, p. 101.

42. Zhang, X., Yu, S., He, W., Uyama, H., Xie, Q., Zhang, L., and Yang, F., Electrochemical sensor based on carbon-supported $NiCoO_2$ nanoparticles for selective detection of ascorbic acid, *Biosens. Bioelectron.,* 2014, vol. 55, p. 446.

43. Zhang, W.X., Zheng, J.Z., Shi, J.G., Lin, Z.Q., Huang, Q.T., Zhang, H.Q., Wei, C., Chen, J.H., Hu, S.R., and Hao, A.Y., Nafion covered core-shell structured Fe_3O_4@graphene nanospheres modified electrode for highly selective detection of dopamine, *Anal. Chim. Acta,* 2015, vol. 853, p. 285.

44. Vilian, A.T.E., An, S., Choe, S.R., Kwak, C.H., Huh, Y.S., Lee, J., and Han, Y.-K., Fabrication of 3D honeycomb-like porous polyurethane-functionalized reduced graphene oxide for detection of dopamine, *Biosens. Bioelectron.,* 2016, vol. 86, p. 122.

45. Lu, Y., Dong, L., Jianshe, H., and Tianyan, Y., Simultaneous determination of dopamine, ascorbic acid and uric acid at electrochemically reduced graphene oxide modified electrode, *Sens. Actuators B-Chem.,* 2014, vol. 193, p. 166.

46. Fu, Y.Y., Sheng, Q.L., and Zheng, J.B., The novel sulfonated polyaniline-decorated carbon nanosphere nanocomposites for electrochemical sensing of dopamine, *New J. Chem.,* 2017, vol. 41, p. 15439.

47. Abdul, R.P. and Jae-Seung, L., Recent advances in optical detection of dopamine using nanomaterials, *Microchim. Acta,* 2017, vol. 184, p. 1239.

48. Van der Horst, C., Silwana, B., Iwuoha, E., and Somerset, V., Spectroscopic and voltammetric analysis of platinum group metals in road dust and roadside soil, *Environments,* 2018, vol. 5, p. 120.

49. Silwana, B., Van der Horst, C., Iwuoha, E., and Somerset, V., A brief review on recent developments of electrochemical sensors in environmental application for PGMs, *J. Environ. Sci. Health Part A,* 2016, vol. 51, p. 1233.

50. Zeng, Y., Zhu, Z., Du, D., and Lin, Y., Nanomaterial-based electrochemical biosensors for food safety, *J. Electroanal. Chem.,* 2016, vol. 781, p. 147.

51. Laffont, L., Hezard, T., Gros, P., Heimbürger, L.E., Sonke, J.E., Behra, P., and Evrard, D., Mercury(II) trace detection by a gold nanoparticle-modified glassy carbon electrode using square-wave anodic stripping voltammetry-including a chloride desorption step, *Talanta,* 2015, vol. 141, p. 26.

52. Van der Horst, C., Silwana, B., Iwuoha, E., and Somerset, V., Application of a bismuth-silver nanosensor for the simultaneous determination of Pt–Rh and Pd–Rh complexes, *J. Nano Res.,* 2016, vol. 44, p. 126.

53. Silwana, B., Van der Horst, C., Iwuoha, E., and Somerset, V., Synthesis, characterisation and electrochemical evaluation of reduced graphene oxide modified antimony nanoparticles, *Thin Solid Films,* 2015, vol. 592, p. 124.

54. Al-Hossainy, A.F., Abd-Elmageed, A.A.I., and Ibrahim, A.T.A., Synthesis, structural and optical properties of gold nanoparticle-graphene-selenocysteine composite bismuth ultrathin film electrode and its application to Pb(II) and Cd(II) determination, *Arab. J. Chem.,* 2019, vol. 12, no. 8, p. 2853.

55. Wong, A., Razzino, C.A., Silva, T.A., and Fatibello-Filho, O., Square-wave voltammetric determination of clindamycin using a glassy carbon electrode modified with graphene oxide and gold nanoparticles within a cross-linked chitosan film, *Sens. Actuators B-Chem.,* 2016, vol. 231, p. 183.

56. Zhou, Y., Tang, L., Zeng, G., Zhang, C., Xie, X., Liu, Y., Wang, J., Tang, J., Zhang, Y., and Deng, Y., Label-free detection of lead using impedimetric sensor based on ordered mesoporous carbon-gold nanoparticles and DNA enzyme catalytic beacons, *Talanta,* 2016, vol. 146, p. 641.

57. Hezard, T., Fajerwerg, K., Evrard, D., Collière, V., Behra, P., and Gros, P., Gold nanoparticles electrodeposited on glassy carbon using cyclic voltammetry: application to Hg(II) trace analysis, *J. Electroanal. Chem.,* 2012, vol. 664, p. 46.

58. Zhu, L., Xu, L., Huang, B., Jia, N., Tan, L., and Yao, S., Simultaneous determination of Cd(II) and Pb(II)

using square wave anodic stripping voltammetry at a gold nanoparticle-graphene-cysteine composite modified bismuth film electrode, *Electrochim. Acta,* 2014, vol. 115, p. 471.

59. Kamyabi, M.A. and Aghaei, A., Electromembrane extraction coupled to square wave anodic stripping voltammetry for selective preconcentration and determination of trace levels of As(III) in water samples, *Electrochim. Acta,* 2016, vol. 206, p. 192.
60. Gan, X., Zhao, H., Quan, X., and Zhang, Y., An electrochemical sensor based on p-aminothiophenol/Au nanoparticle-decorated H_xTiS_2 nanosheets for specific detection of picomolar Cu(II), *Electrochim. Acta,* 2016, vol. 190, p. 480.
61. Idris, A.O., Mabuba, N., and Arotiba, O.A., Electroanalysis of selenium in water on an electrodeposited gold-nanoparticle modified glassy carbon electrode, *J. Electroanal. Chem.,* 2015, vol. 758, p. 7.
62. Wan, H., Sun, Q., Li, H., Sun, F., Hu, N., and Wang, P., Screen-printed gold electrode with gold nanoparticles modification for simultaneous electrochemical determination of lead and copper, *Sens. Actuators B-Chem.,* 2015, vol. 209, p. 336.
63. Silwana, B., Van der Horst, C., Iwuoha, E., and Somerset, V., A sensitive reduced graphene oxide-antimony nanofilm sensor for simultaneous determination of PGMs, *J. Nano Res.,* 2016, vol. 44, p. 134.
64. Zhang, B., Chen, J., Zhu, H., Yang, T., Zou, M., Zhang, M., and Du, M., Facile and green fabrication of size-controlled AuNPs/CNFs hybrids for the highly sensitive simultaneous detection of heavy metal ions, *Electrochim. Acta,* 2016, vol. 196, p. 422.
65. Silwana, B., Van der Horst, C., Iwuoha, E., and Somerset, V., Reduced graphene oxide impregnated antimony nanoparticle sensor for electroanalysis of platinum group metals, *Electroanalysis,* 2016, vol. 28, p. 1.
66. Van der Horst, C., Silwana, B., Iwuoha, E., and Somerset, V., Bismuth-silver bimetallic nanosensor application for the voltammetric analysis of dust and soil samples, *J. Electroanal. Chem.,* 2015, vol. 752, p. 1.
67. Fan, H.L., Zhou, S.F., Gao, J., and Liu, Y.Z., Continuous preparation of Fe_3O_4 nanoparticles through Impinging Stream-Rotating Packed Bed reactor and their electrochemistry detection toward heavy metal ions, *J. Alloys Compd.,* 2016, vol. 671, p. 354.
68. Li, W.J., Yao, X.Z., Guo, Z., Liu, J.H., and Huang, X.J., Fe_3O_4 with novel nanoplate-stacked structure: surfactant-free hydrothermal synthesis and application in detection of heavy metal ions, *J. Electroanal. Chem.,* 2015, vol. 749, p. 75.
69. Zhou, S.F., Han, X.J., and Liu, Y.Q., SWASV performance toward heavy metal ions based on a high-activity and simple magnetic chitosan sensing nanomaterials, *J. Alloys Compd.,* 2016, vol. 684, p. 1.
70. Zhang, X. and Zheng, J., Hollow carbon sphere supported Ag nanoparticles for promoting electrocatalytic performance of dopamine sensing, *Sens. Actuator B-Chem.,* 2019, vol. 290, p. 648.
71. Alexander, C. and Bandyopadhyay, K., Two-dimensional palladium nanoparticle assemblies as electrochemical dopamine sensors, *Inorg. Chim. Acta,* 2017, vol. 468, p. 171.
72. Mahmoudian, M.R., Basirun, W.J., Sookhakian, M., Woi, P.M., Zalnezhad, E., Hazarkhani, H., and Alias, Y., Synthesis and characterization of a-Fe_2O_3/polyaniline nanotube composite as electrochemical sensor for uric acid detection, *Adv. Powder Technol.,* 2019, vol. 30, p. 384.
73. Sharma, G., Gupta, V.K., Agarwal, S., Kumar, A., Thakur, S., and Pathania, D., Fabrication and characterization of Fe@ MoPO nanoparticles: ion exchange behaviour and photocatalytic activity against malachite green, *J. Mol. Liq.,* 2016, vol. 219, p. 1137.
74. Toshima, N. and Yonieawa, T., Bimetallic nanoparticles: novel materials for physical and chemical applications, *New J. Chem.,* 1998, vol. 11, p. 1179.
75. Van der Horst, C., Silwana, B., Iwuoha, E., Gil, E., and Somerset, V., Improved detection of ascorbic acid with a bismuth-silver nanosensor, *Food Anal. Methods,* 2016, vol. 9, p. 2560.
76. Van der Horst, C., Silwana, B., Gil, E., Iwuoha, E., and Somerset, V., Simultaneous detection of paracetamol, ascorbic acid, and caffeine using a bismuth-silver nanosensor, *Electroanalysis,* 2020, vol. 32, p. 3098.
77. Arvinte, A., Crudu, I.-A., Doroftei, F., Timpu, D., and Pinteala, M., Electrochemical co-deposition of silver–gold nanoparticles on CNT-based electrode and their performance in electrocatalysis of dopamine, *J. Electroanal. Chem.,* 2018, vol. 829, p. 184.
78. Ma, L., Zhang, Q., Wu, C., Zhang, Y., and Zeng, L., PtNi bimetallic nanoparticles loaded MoS_2 nanosheets: preparation and electrochemical sensing application for the detection of dopamine and uric acid, *Anal. Chim. Acta,* 2019, vol. 1055, p. 17.
79. Mallikarjuna, K., Veera Manohara Reddy, Y., Sravani, B., Madhavi, G., Kim, H., Agarwal, S., and Kumar Gupta, V., Simple synthesis of biogenic Pd-Ag bimetallic nanostructures for an ultrasensitive electrochemical sensor for sensitive determination of uric acid, *J. Electroanal. Chem.,* 2018, vol. 822, p. 163.
80. Gopalakrishnan, A., Sha, R., Vishnu, N., Kumar, R., and Badhulika, S., Disposable, efficient and highly selective electrochemical sensor based on cadmium oxide nanoparticles decorated screen-printed carbon electrode for ascorbic acid determination in fruit juices, *Nano-Struct. Nano-Objects,* 2018, vol. 16, p. 96.
81. Van der Horst, C., Silwana, B., Iwuoha, E., and Somerset, V., Synthesis and characterization of bismuth-silver nanoparticles for electrochemical sensor applications, *Anal. Lett.,* 2015, vol. 48, no. 8, p. 1311.
82. Liu, L., Liu, L., Wang, Y., and Ye, B.-C., A novel electrochemical sensor based on bimetallic metal-organic framework-derived porous carbon for detection of uric acid, *Talanta,* 2019, vol. 199, p. 478.
83. Harraz, F.A., Faisal, M., Al-Salami, A.E., El-Toni, A.M., Almadiy, A.A., Al-Sayari, S.A., and Al-Assiri, M.S., Silver nanoparticles decorated stain-etched mesoporous silicon for sensitive, selective detection of ascorbic acid, *Mater. Lett.,* 2019, vol. 234, p. 96.
84. Zhang, Y., Liu, P., Xie, S., Chen, M., Zhang, M., Cai, Z., Liang, R., Zhang, Y., and Cheng, F., A novel electrochemical ascorbic acid sensor based on branch-

trunk Ag hierarchical nanostructures, *J. Electroanal. Chem.,* 2018, vol. 818, p. 250.

85. Huang, D., Li, X., Chen, M., Chen, F., Wan, Z., Rui, R., Wang, R., Fan, S., and Wu, H., An electrochemical sensor based on a porphyrin dye-functionalized multiwalled carbon nanotubes hybrid for the sensitive determination of ascorbic acid, *J. Electroanal. Chem.,* 2019, vol. 841, p. 101.
86. Inagaki, C.S., Oliveira, M.M., Bergamini, M.F., Marcolino-Junior, L.H., and Zarbin, A.J.G., Facile synthesis and dopamine sensing application of three-component nanocomposite thin films based on polythiophene, gold nanoparticles and carbon nanotubes, *J. Electroanal. Chem.,* 2019, vol. 840, p. 208.
87. Liu, X., Fu, Y., Sheng, Q., and Zheng, J., Au nanoparticles attached Ag@C core-shell nanocomposites for highly selective electrochemical detection of dopamine, *Microchem. J.,* 2019, vol. 146, p. 509.
88. Jiao, J., Zuo, J., Pang, H., Tan, L., Chen, T., and Ma, H., A dopamine electrochemical sensor based on Pd-Pt alloy nanoparticles decorated polyoxometalate and multiwalled carbon nanotubes, *J. Electroanal. Chem.,* 2018, vol. 827, p. 103.
89. Fazio, E., Spadaro, S., Bonsignore, M., Lavanya, N., Sekar, C., Leonardi, S.G., Neri, G., and Neri, F., Molybdenum oxide nanoparticles for the sensitive and selective detection of dopamine, *J. Electroanal. Chem.,* 2018, vol. 814, p. 91.
90. Sookhakian, M., Basirun, W.J., Goh, B.T., Woi, P.M., and Alias, Y., Molybdenum disulfide nanosheet decorated with silver nanoparticles for selective detection of dopamine, *Colloids Surf. B: Biointerfaces,* 2019, vol. 176, p. 80.
91. Zeng, Y., Zhu, Z., Du, D., and Lin, Y., Nanomaterial-based electrochemical biosensors for food safety, *J. Electroanal. Chem.,* 2016, vol. 781, p. 147.
92. Li, Y., Jing, T., Xu, G., Tian, J., Dong, M., Shao, Q., Wang, B., Wang, Z., Zheng, Y., Yang, C., and Guo, Z., 3-D magnetic graphene oxide-magnetite poly(vinyl alcohol) nanocomposite substrates for immobilizing enzyme, *Polymer,* 2018, vol. 149, p. 13.
93. Mengyao, D., Qiang, L., Liu, H., Chuntai, L., Wujcik, E.K., Shao, Q., Ding, T., Ma, X., Shen, C., and Guo, Z., Thermoplastic polyurethane–carbon black nanocomposite coating: fabrication and solid particle erosion resistance, *Polymer,* 2018, vol. 158, p. 381.
94. Zhang, J., Li, P., Zhang, Z., Wang, X., Tang, J., Liu, H., Shao, Q., Ding, T., Umar, A., and Guo, Z., Solvent-free graphene liquids: promising candidates for lubricants without the base oil, *J. Colloid Interface Sci.,* 2019, vol. 542, p. 159.
95. Jiang, D., Murugadoss, V., Wang, Y., Lin, J., Ding, T., Wang, Z., Shao, Q., Wang, C., Liu, H., Lu, N., Wei, R., Subramania, A., and Guo, Z., Electromagnetic interference shielding polymer sand nanocomposites—a review, *Polym. Rev.,* 2019, vol. 59, no. 2, p. 280.
96. Song, B., Wang, T., Sun, H., Shao, Q., Zhao, J., Song, K., Hao, L., Wang, L., and Guo, Z., Two-step hydrothermally synthesized carbon nanodots/WO_3 photocatalysts with enhanced photocatalytic performance, *Dalton Trans.,* 2017, vol. 46, p. 15769.
97. Wu, N., Xu, D., Wang, Z., Wang, F., Liu, J., Liu, W., Shao, Q., Liu, H., Gao, Q., and Guo, Z., Achieving superior electromagnetic wave absorbers through the novel metal-organic frameworks derived magnetic porous carbon nanorods, *Carbon,* 2019, vol. 145, p. 433.
98. Cheng, C., Fan, R., Ren, Y., Ding, T., Qian, L., Guo, J., Li, X., An, L., Lei, Y., Yin, Y., and Guo, Z., Radiofrequency negative permittivity in random carbon nanotubes/ alumina nanocomposites, *Nanoscale,* 2017, vol. 9, p. 5779.
99. Du, H., Zhao, C.X., Lin, J., Guo, J., Wang, B., Zhen, H., Shao, Q., Pan, D., Wujcik, E.K., and Guo, Z., Carbon nanomaterials in direct liquid fuel cells, *Chem. Rec.,* 2018, vol. 18, p. 1365.
100. Gu, H., Zhang, H., Ma, C., Xu, X., Wang, Y., Wang, Z., Wei, R., Liu, H., Liu, C., Shao, Q., Mai, X., and Guo, Z., Trace electrosprayed nanopolystyrene facilitated dispersion of multiwalled carbon nanotubes: simultaneously strengthening and toughening epoxy, *Carbon,* 2019, vol. 142, p. 131.
101. Huang, J., Cao, Y., Shao, Q., Peng, X., and Guo, Z., Magnetic nanocarbon adsorbents with enhanced hexavalent chromium removal: morphology dependence of fibrillar vs particulate structures, *Ind. Eng. Chem. Res.,* 2017, vol. 56, p. 10689.
102. Li, Z., Wang, B., Qin, X., Wang, Y., Liu, C., Shao, Q., Wang, N., Zhang, J., Shen, C., and Guo, Z., Super hydrophobic/superoleophilic polycarbonate/carbon nanotubes porous monolith for selective oil adsorption from water, *ACS Sustain. Chem. Eng.,* 2018, vol. 6, p. 13747.
103. Wang, C., Murugadoss, V., Kong, J., He, Z., Mai, X., Shao, Q., Chen, Y., Guo, L., Liu, C., Angaiah, S., and Guo, Z., Overview of carbon nanostructures and nanocomposites for electromagnetic wave shielding, *Carbon,* 2018, vol. 140, p. 696.
104. Thamilselvan, A., Manivel, P., Rajagopal, V., Nesakumar, N., and Suryanarayanan, V., Improved electrocatalytic activity of Au@Fe_3O_4 magnetic nanoparticles for sensitive dopamine detection, *Colloids Surf. B: Biointerfaces,* 2019, vol. 180, p. 1.
105. Hu, B., Liu, Y., Wang, Z-W., Song, Y., Wang, M., Zhang, Z., and Liu, C.-S., Bimetallic-organic framework derived porous Co_3O_4/Fe_3O_4/C-loaded g-C_3N_4 nanocomposites as non-enzymic electrocatalysis oxidization toward ascorbic acid, dopamine acid, and uric acid, *Appl. Surf. Sci.,* 2018, vol. 441, p. 694.
106. Zhao, G., Wang, H., and Liu, G., Recent advances in chemically modified electrodes, microfabricated devices and injection systems for the electrochemical detection of heavy metals: a review, *Int. J. Electrochem. Sci.,* 2017, vol. 12, p. 8622.
107. Geim, A.K. and Novoselov, K.S., The rise of graphene, *Nat. Mater.,* 2007, vol. 6, p. 183.
108. Shahmiri, M.R., Bahari, A., Karimi-Maleh, H., Hosseinzadeh, R., and Mirnia, N., Ethynylferrocene–NiO/MWCNT nanocomposite modified carbon paste electrode as a novel voltammetric sensor for simultaneous determination of glutathione and acetaminophen, *Sens. Actuators B-Chem.,* 2013, vol. 177, p. 70.

109. Brownson, D.A.C. and Banks, C.E., Graphene electrochemistry: an overview of potential applications, *Analyst,* 2010, vol. 135, p. 2768.

110. Wang, J., Carbon-nanotube based electrochemical biosensors: a review, *Electroanalysis,* 2005, vol. 17, p. 7.

111. Shao, Y., Wang, J., Wu, H., Liu, J., Aksay, I.A., and Lin, Y., Graphene-based electrochemical sensors and biosensors: a review, *Electroanalysis,* 2010, vol. 22, p. 1027.

112. Zhou, M., Zhai, Y., and Dong, S., Electrochemical sensing and biosensing platform based on chemically reduced graphene oxide, *Anal. Chem.,* 2009, vol. 81, p. 5603.

113. Yang, H., Zhao, J., Qiu, M., Sun, P., Han, D., Niu, L., and Cui, G., Hierarchical bi-continuous Pt decorated nanoporous Au–Sn alloy on carbon fibre paper for ascorbic acid, dopamine and uric acid simultaneous sensing, *Biosens, Bioelectron.,* 2019, vols. 124–125, p. 191.

114. Zhao, Y., Yang, Z., Fan, W., Wang, Y., Li, G., Cong, H., and Yuan, H., Carbon nanotube/carbon fibre electrodes via chemical vapour deposition for simultaneous determination of ascorbic acid, dopamine and uric acid, *Arab. J. Chem.,* 2018, vol. 13, no. 1.

115. Reddy, Y.V.M., Sravani, B., Agarwal, S., Gupta, V.K., and Madhavi, G., Electrochemical sensor for detection of uric acid in the presence of ascorbic acid and dopamine using the poly(DPA)/SiO_2@Fe_3O_4 modified carbon paste electrode, *J. Electroanal. Chem.,* 2018, vol. 820, p. 168.

116. Beluomini, M.A., da Silva, J.L., Cardoso de Sa, A., Buffon, E., Pereira, T.C., and Stradiotto, N.R., Electrochemical sensors based on molecularly imprinted polymer on nanostructured carbon materials: a review, *J. Electroanal. Chem.,* 2019, vol. 840, p. 343.

117. Edris, N.M.M.A., Abdullah, J., Kamaruzaman, S., Saiman, M.I., and Sulaiman, Y., Electrochemical reduced graphene oxide-poly (eriochrome black T)/gold nanoparticles modified glassy carbon electrode for simultaneous determination of ascorbic acid, dopamine and uric acid, *Arab. J. Chem.,* 2018, vol.11, p. 1301.

118. Zou, C., Zhong, J., Li, S., Wang, H., Wang, J., Yan, B., and Du, Y., Fabrication of reduced graphene oxide-bimetallic PdAu nanocomposites for the electrochemical determination of ascorbic acid, dopamine, uric acid and rutin, *J. Electroanal. Chem.,* 2017, vol. 805, p. 110.

119. Pruneanu, S., Biris, A.R., Pogacean, F., Socaci, C., Coros, M., Rosu, M.C., Watanabe, F., and Biris, A.S., The influence of uric and ascorbic acid on the electrochemical detection of dopamine using graphene-modified electrodes, *Electrochim. Acta,* 2015, vol. 154, p. 197.

120. Shang, L., Zhao, F., and Zeng, B., Highly dispersive hollow PdAg alloy nanoparticles modified ionic liquid functionalized graphene nanoribbons for electrochemical sensing of nifedipine, *Electrochim. Acta,* 2015, vol. 168, p. 330.

121. Tığ, G.A., Development of electrochemical sensor for detection of ascorbic acid, dopamine, uric acid and L-tryptophan based on Ag nanoparticles and poly(L-arginine)-graphene oxide composite, *J. Electroanal. Chem.,* 2017, vol. 807, p. 19.

122. Poudyal, D.C., Satpati, A.K., Kumar, S., and Haram, S.K., High sensitive determination of dopamine through catalytic oxidation and preconcentration over gold–multiwall carbon nanotubes composite modified electrode, *Mat. Sci. Eng. C,* 2019, vol.103, p. 109788.

123. Xu, Q., Yuana, H., Dong, X., Zhang, Y., Asif, M., Dong, Z., He, W., Ren, J., Sun, Y., and Xiao, F., Dual nanoenzyme modified microelectrode based on carbon fibre coated with Au–Pd alloy nanoparticles decorated graphene quantum dots assembly for electrochemical detection in clinical cancer samples, *Biosens. Bioelectron.,* 2018, vol. 107, p. 153.

124. Cui, L., Wu, J., and Ju, H., Electrochemical sensing of heavy metal ions with inorganic, organic and bio-materials, *Biosens. Bioelectron.,* 2015, vol. 63, p. 276.

125. Wan, Q., Yu, F., Zhu, L., Wang, X., and Yang, N., Bucky-gel coated glassy carbon electrodes, for voltammetric detection of femtomolar levelled lead ions, *Talanta,* 2010, vol. 82, p. 1820.

126. Cerovac, S., Guzsvány, V., Kónya, Z., Ashrafi, A.M., Švancara, I., Rončević, S., Kukovecz, Á., Dalmacija, B., and Vytřas, K., Trace level voltammetric determination of lead and cadmium in sediment pore water by a bismuth–oxychloride particle-multiwalled carbon nanotube composite modified glassy carbon electrode, *Talanta,* 2015, vol.134, p. 640.

127. Wei, Y., Yang, R., Chen, X., Wang, L., Liu, J.H., and Huang, X.J., A cation trap for anodic stripping voltammetry: NH_3-plasma-treated carbon nanotubes for adsorption and detection of metal ions, *Anal. Chim. Acta,* 2012, vol.755, p. 54.

128. Afkhami, A., Ghaedi, H., Madrakian, T., and Rezaeivala, M., Highly sensitive simultaneous electrochemical determination of trace amounts of Pb(II) and Cd(II) using a carbon paste electrode modified with multi-walled carbon nanotubes and a newly synthesized Schiff base, *Electrochim. Acta,* 2013, vol.89, p. 377.

129. Chang, Y.H., Woi, P.M., and Alias, Y.B., The selective electrochemical detection of dopamine in the presence of ascorbic acid and uric acid using electro-polymerised-β-cyclodextrin incorporated f-MWCNTs/polyaniline modified glassy carbon electrode, *Microchem. J.,* 2019, vol.148, p. 322.

130. Savk, A., Özdil, B., Demirkan, B., Nas, M.S., Calimli, M.H., Alma, M.H., Inamuddin, Asiri, A.M., and Şen, F., Multiwalled carbon nanotube-based nanosensor for ultrasensitive detection of uric acid, dopamine, and ascorbic acid, *Materials Sci. Eng. C,* 2019, vol. 99, p. 248.

131. Wang, H., Xiao, L.-G., Chu, X.-F., Chi, Y.-D., and Yang, X.-T., Rational design of gold nanoparticle/graphene hybrids for simultaneous electrochemical determination of ascorbic acid, dopamine and uric acid, *Chin. J. Anal. Chem.,* 2016, vol. 44, no. 12, p. e1617.

132. Zhu, Q., Bao, J., Huo, D., Yang, M., Wu, H., Hou, C., Zhao, Y., Luo, X., and Fa, H., 3DGH-Fc based electrochemical sensor for the simultaneous determination

of ascorbic acid, dopamine and uric acid, *J. Electroanal. Chem.,* 2017, vol. 799, p. 459.

133. Wang, M., Cui, M., Liu, W., and Liu, X., Highly dispersed conductive polypyrrole hydrogels as sensitive sensor for simultaneous determination of ascorbic acid, dopamine and uric acid, *J. Electroanal. Chem.,* 2019, vol. 832, p. 174.

134. Tukimin, N., Abdullah, J., and Sulaiman, Y., Electrodeposition of poly(3,4-ethylenedioxythiophene)/reduced graphene oxide/manganese dioxide for simultaneous detection of uric acid, dopamine and ascorbic acid, *J. Electroanal. Chem.,* 2018, vol. 820, p. 74.

135. Thangamuthu, R., Senthil Kumar, S.M., and Chandrasekara Pillai, K., Direct amperometric determination of l-ascorbic acid (Vitamin C) at octacyanomolybdate-doped-poly(4-vinylpyridine) modified electrode in fruit juice and pharmaceuticals, *Sens. Actuators B-Chem.,* 2007, vol. 120, p. 745.

136. Ali, A., Jamal, R., Abdiryim, T., and Huang, X., Synthesis of monodispersed PEDOT/Au hollow nanospheres and its application for electrochemical determination of dopamine and uric acid, *J. Electroanal. Chem.,* 2017, vol. 787, p. 110.

137. Zhang, K., Chen, X., Li, Z., Wang, Y., Sun, S., Wang, L., Guo, T., Zhang, D., Xu, Z., Zhou, X., and Lu, X., Au–Pt bimetallic nanoparticles decorated on sulfonated nitrogen sulfur codoped graphene for simultaneous determination of dopamine and uric acid, *Talanta,* 2018, vol. 178, p. 315.

138. Hou, J., Xu, C., Zhao, D., and Zhou, J., Facile fabrication of hierarchical nanoporous AuAg alloy and its highly sensitive detection towards dopamine and uric acid, *Sens. Actuators B-Chem.,* 2016, vol. 225, p. 241.

139. Immanuel, S., Aparna, T.K., and Sivasubramanian, R., A facile preparation of Au–SiO_2 nanocomposite for simultaneous electrochemical detection of dopamine and uric acid, *Surf. Interfaces,* 2019, vol. 14, p. 82.

140. Krishnamoorthy, K., Sudha, V., Kumar, S.M.S., and Thangamuthu, R., Simultaneous determination of dopamine and uric acid using copper oxide nano-rice modified electrode, *J. Alloys Compd.,* 2018, vol. 748, p. 338.

141. Rahman, M.M., Lopa, N.S., Ju, M.J., and Lee, J.-J., Highly sensitive and simultaneous detection of dopamine and uric acid at graphene nanoplatelet-modified fluorine-doped tin oxide electrode in the presence of ascorbic acid, *J. Electroanal. Chem.,* 2017, vol. 792, p. 54.

SPELL: 1. ok