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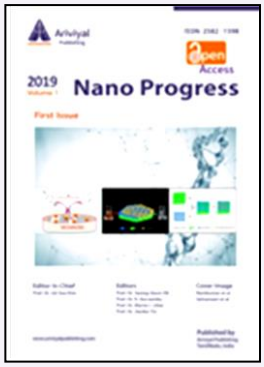

Carbon Based Nanocomposites for Electrochemical Sensing of Adenine and Guanine Purine Bases: A Review

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Abstract: Electrochemical sensing (ECS) is one of the most preferred detection techniques for the analysis of biomolecules such as purine bases (PB) which is based on transducing of biochemical reactions to electric signal (impedance, current, voltage, etc.). The sensitivity and fast signal responding nature of ECS technique to quantify PB, depends on the surface characteristics of working electrodes (WE), since all electrochemical reactions during sensing of PB is generally detected on the surface of WE. In this context, carbon electrodes have been widely studied and used WEin ECS techniques because of their promising electrochemical properties. Moreover, the modification of carbon electrode surfaces with carbon based nanocomposites (CNC) has displayed effective outcomes with good reproducibility, stability, and improved sensitivity in PB quantification via electrochemical methods. CNC including carbon nanomaterials, metal/ metal oxides nanoparticles and polymers, are frequently used electrode modifier due to their extraordinary conductivity and surface to volume ratio. This review provides a critical analysis of the CNC electrochemical sensor with examination of more suitable/efficient sensors for the quantitative detection of PB. Among various PB, the adenine and guanine bases are overviewed in the present review for their electrochemical quantification. In addition, the recent progress in CNC for WE surface modification used in ECS of Adenine and Guanine is also discussed.

Keywords: Transducer; Purine bases; Electrochemical sensing; Sweep and pulse voltammetry; Carbon based nanocomposites

1. Introduction

Purines, the nitrogenous aromatic bases are known to play crucial roles in life processes as they contain one pyrimidine ring fused to an imidazole ring. They are weak bases with core formula $C_5H_4N_4$ and exhibit lower oxidation potential than pyrimidine bases.[1] This redox property of purine bases (PB) is found to be very helpful for easy electrochemical analysis of PB than other bases present in DNA and RNA. Adenine (Ad) and Guanine (Gu) are two important PB, present in nucleosides and hence serve as building blocks for both DNA and RNA.[2] Ad and Gu has contributed in cell signaling processes and also play key role in the storage of genetic information as well as in the determination of hereditary characteristics. Interactions of DNA and RNA with foreign compounds may cause the variation in PB (Ad and Gu) structure and this results some kinds of damage in structure of DNA and RNA.[3] Consequently, they give rise to different type of diseases and extensively affected the adenylate cyclase activity, control of blood flow as well as inhibition of neurotransmitter release.[4-7] The concentration levels of Ad and Guare considered as an important indicator for diagnosis of different diseases. Therefore, the qualitative and quantitative estimation of PB in pharmaceuticals and biological fluids must be required, as they have significant impacts on bioscience and clinical diagnosis.[8] For the estimation of PB various sensitive detection methods such as capillary electrophoresis[9,10] chemiluminescence,[11] spectrometry[12] and liquid chromatography[13,14] have been used in past few years. These analytical methods provide a good accuracy and sensitivity but have some drawbacks due to their time-consuming nature, high cost, tough to handle, slow response and consist a complicated setup that required a skilled person to handle it.[15,16] Electrochemical techniques have become the promising candidate for the sensing of PB as these techniques directly transform the biological changes into an electrical signal.[17-19] This type of sensing in which electrochemical methods are used for the estimation of biological molecules, called electrochemical sensing (ECS). ECS is mainly electrode-based technique because working electrodes (WE) play crucial role to determine the performance of ECS. The main advantages of using ECS, are its low cost, rapid response, simplicity, high sensitivity and it is a user- friendly technique that required a semi- skilled person to operate.[20] Basically, ECS consist a WE (also known as electrochemical transducer) or detector system with a molecular recognition element (MRE) immobilized on its surface and this MRE

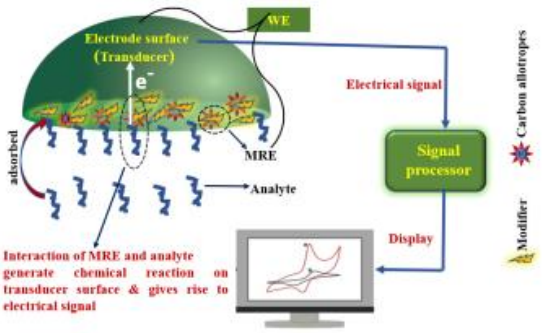

Fig. 1. Simplified diagram for ECS elements.

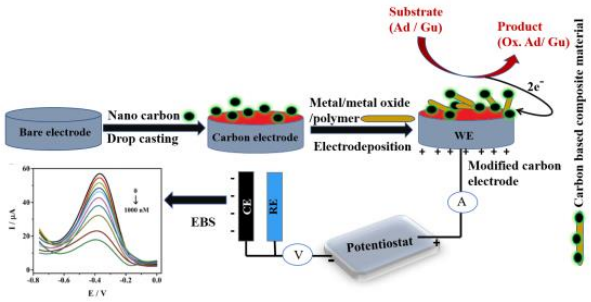

Fig. 2. Three electrode assembly to show voltammetry performance of Ad and Gu with fabrication of WE

has capability to detect desired molecule (analyte) present in the sample (Fig. 1).[21-23] The binding nature of MRE with analyte can result various electrochemical changes on WE surface and some redox reactions also observed on WE surface due to electrochemical behaviour of analyte. These chemical activities on WE surface (transducer) is transformed into electrical signal (impedance, current, voltage, etc.) and finally displayed on a screen by signal processor.[22] Since concentration of analyte is determined by the quantifications of electrical signal, the various approaches i.e. amperometry, voltammetry, conductometry, impedimetry, or potentiometry are adopted for the quantification of electrical signal.[24] Amperometry is a transduction method used to estimate the concentration of analyte which is directly proportional to peak current generated by redox reactions between MRE and analyte on WE surface at constant potential.[25,26] Potentiometry and impedimetric is used to detect the accumulation of a charge potential and impedance (both resistance and reactance) respectively, at the WE compared to the reference electrode (RE) when zero or no significant current flows between them.[27-29] Conductometry measure the ability of an analyte to conduct an electrical current between electrodes. Among these, voltammetry (sweep or pulse) is one of the most widely used ECS techniques for the PB sensing. Cyclic voltammetry (CV) and linear sweep voltammetry (LSV) comes under sweep voltammetry whereas square wave voltammetry (SWV) and differential pulse voltammetry (DPV) is a part of pulse voltammetry.[25] CV and SWV are widely used quantitative method to evaluate redox potential and for the quantification of electrical signal due to electrochemical reaction between PB and MRE. Voltammetric measurement is performed under an electrochemical cell based on two-or three-electrode assembly that is connected with a potentiostat where the resultant impedance, voltage and current can be measured (Fig. 2).

Basically, three electrode systems, widely used for ECS, contain Ag/ AgCl or calomel electrode as reference electrode (RE), Pt wire as counter electrode (CE) and metal substrate with some material coating is performed as WE. Performance of ECS can be improved by surface modification of WE because it has been observed that all the redox reactions due to oxidation or reduction of Ad andGu are detected on, WE surface.[30,31] Hence, WE play crucial role in the detection of PB present in biological substances. Binding capacity of WE material with PB also affected the efficiency of ECS, larger surface area of electrode material can provide the greater sites for sensing molecules to bind with it and hence greater sensing ability of that particular electrode. Weak electron transfer capacity and poor binding capacity of Ad and Gu with bare or traditional electrodes, loss the bioactivity behaviour of Ad and Gu and also limit the use of these electrodes at high scale for PB sensing.[32] In past few years, carbon materials such as graphite (Gr), grapheme,[33,34] fullerene, carbon nanotubes (CNT)[35] single walled carbon nanohorns (SWCNH), graphene oxide (GO) based electrodes have gain much attention for sensing of PB due to their wide potential window range, good electrical and structural properties.[36-38]

The good redox behaviour of Ad and Gu on carbon allotrope electrodes has been reported via ECS technique, showing sharp individual Ad and Gu oxidation peaks on voltammogram. The allotropes of carbon have larger surface area and hence, much sites are available for PB binding on WE surface which make these electrodes highly sensitive and electrochemically active.[39] However, some problems related with these carbon allotropes WE have also been reported[40] e.g. hydrophobicity of Gr and less dispersion of carbon-based compounds in common solvents decreases the widespread use of ECS at some levels.[41] Therefore, for better performance of carbon electrodes, carbon based nanocomposites (CNC) have been proposed as potential candidate for WE used in ECS.[42]

CNC consisted two or more materials in which unique properties of carbon nanoparticles (NPs) is combined with other components to fabricate a composite with enhanced performance. Each individual component in CNC does not lose its original identity but as a whole CNC have distinctive chemical, mechanical and physical peculiarities. In this review, we present the recent developments in the composite materials domain that contain at least one carbon-based component for the development of WE used in ECS technique. We comprise here about the performance of various composite materials for sensing of PB (Ad and Gu) and application of PB sensing is also discussed. CNC may be of following types: carbon–carbon composite, carbon/metal oxide composite, carbon/polymer composite and carbon/polymer-metal oxide composite materials and this study elaborates these all composite materials that have been developed as electrode material for quantitative estimation of Ad and Gu.

2. CNC for ECS for Ad and Gu Sensing

CNC modified electrode is highly useful for the better performance of ECS against the traditional carbon-based WE since these electrodes enhance the oxidation current due to good electrochemical activity of PB on CNC modified electrode.[43] Simultaneous detection of Gu

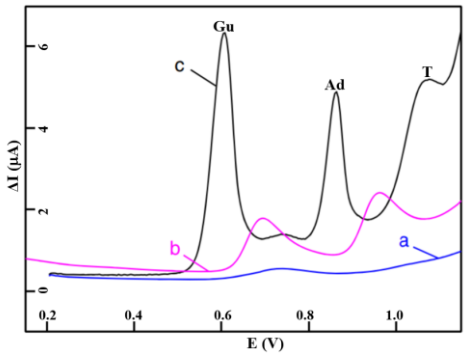

Fig. 3. DPV of a mixture of Gu (50 μM), Ad (50 μM) and T (100 μM) at GCE (a), GCE/GNP (b) and GCE/GMC (c) in PB (neutral pH). Reproduced from ref.[43] by permission of The Royal Society of Chemistry

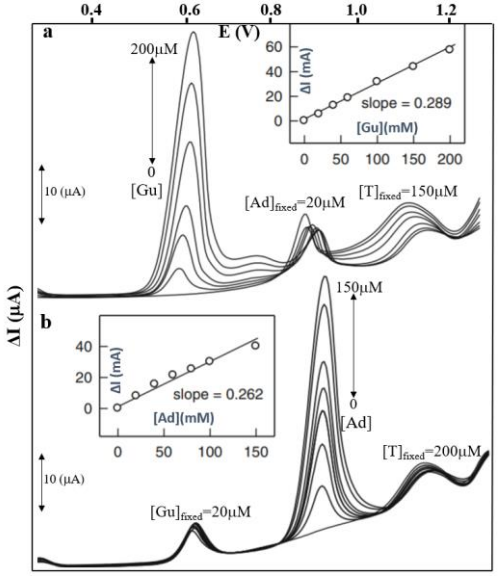

Fig. 4. DPV for simultaneous detection of G, A and T with respect to one another using GCE/GMC in PB (neutral pH). Inset: calibration curve (Ip vs. [analyte]) Reproduced from ref.[43] by permission of The Royal Society of Chemistry

and Ad through DPV is shown in Fig. 3, which represents the electron transfer reactions of Ad and Gu was carried out on bare glassy carbon electrode (GCE), GCE modified with graphitized mesoporous carbon (GCE/GMC) and Gr nano powder modified GCE (GCE/GrNP). All DPV measurements was evaluated under 50 mV amplitude, potential of 4 mV, pulse width of 0.05 s and 0.5 s pulse period parameters. The GCE/GMC offered a more sensitive response with well-defined peak separation between the nucleobase peaks compared to bare GCE and GCE/GrNP that verifies the well suitability of GCE/GMC for quantitative analysis of Gu and Ad. It is also observed that GMC enhanced the electroanalytical activity of GCE surface for better detection of PB. To find the voltammetric oxidation peaks of Ad and Gu in the presence of T, the DPV of one base was recorded in the presence of other two fixed concentrations (Fig. 4a, b). The linear calibration plot was displayed the high sensitivity of GCE/GMC towards Gu (0.29±0.011 μA/μM) and Ad (0.26±0.019 μA/μM) with concentration range 25 to 200 μM and 25– 150 μM, respectively (inset Fig. 4). LOD was found to be 0.76, 0.63 μM for Gu and Ad, respectively by using calibration equations values.

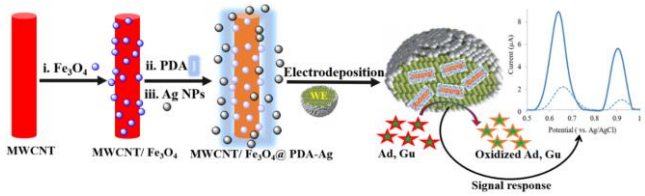

Fig. 5. Fabrication of WE with MWCNT/ Fe_3O_4@PDA-Ag composite material.[49]

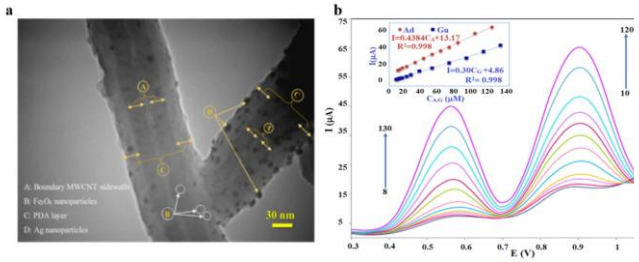

Fig. 6. TEM image of MWCNT/ Fe_3O_4@PDA-Ag. **b** DPV of G (8–130 μM) and A (10–120 μM) at MWCNT-Fe_3O_4@PDA-Ag/CPE, in PB (pH 4.0).[49]

3. Carbon-metal/metal oxide nanocomposites

Inorganic nanomaterials such as noble metals or metal oxides have been reported for their easy absorbance on carbon material surface and are considered as a promising candidate for ECS of biological molecules since they exhibit highest conductivity and high surface area.[44-47] Ag and Fe_3O_4 based composite material with multiwalled carbon nanotube (MWCNT) served as a versatile WE with excellent electrochemical activity for Ad and Gu sensing. MWCNT-Fe_3O_4@PDA-Ag composite material was synthesised by a simple method and hence serves as low-cost sensor for PB (Ad and Gu) in fish sperm DNA sample.[48] polydopamine (PDA) was dispersed on MWCNT-Fe_3O_4 composite material to form MWCNT-Fe_3O_4@PDA nanocomposite and then Ag NPs was embedded on the surface of PDA (Fig. 5).

The TEM image of MWCNT-Fe_3O_4@PDA-Ag nanocomposite in Fig. 6a. displayed the homogeneous coating of Fe_3O_4 NPs on MWCNTs side wall (about 10 nm diameter) with Ag NPs 5–15 nm) embedded onto the PDA surface. PDA formed a grey layer (10 nm diameter) around MWCNT- Fe_3O_4 with core shell structure. DPV of Ad and Gu showed the satisfactory electrochemical behavior of PB on MWCNT- Fe_3O_4@PDA-Ag sensing element and strong interaction of PB with Ag NPs offered rapid electroanalytical response with sharp oxidation peaks separation @0.35 V (Fig. 6b). The linear relationship between DPV signals of Ad and Gu provided optimum limit of detections (LODs) 1.47 and 5.66 μM simultaneously under concentration range of 8–130 μM and 10–120 μM, respectively (inset Fig. 6b).

The combination of Ag NPs with Gr can improve the performance of composite material to synthesize a highly potentiometric transducer in electrochemical sensor. The green reduction of Gr and Ag NPs via β-cyclodextrin (β-CD) provide Ag NPs-β-CD-Gr nanocomposite for the sensing of Gu and Ad with linear ranges of 0.3–200 and 0.5–250 μM and detection limits of 0.09 and 0.15 μM, respectively.[49] SnO_2 NPs on combination with Gr developed a more electroconductive MRE which could provide a highly sensitive transducer, use to design the cost effective and versatile electrochemical sensor for analysis of Ad and Gu.[50] The conductive

properties of SnO_2 is responsible for the better performance of electrochemical sensor that used SnO_2-carbon composite material.[51] Modified carbon paste electrode (CPE) with SnO_2/Gr was developed for the estimation of Ad and all electrochemical measurements were explored by DPV in acetate buffer solution @ 30 mV/s and 50 mV under 0.2-1.45 V potential range for the detection of adenine oxidation signal.[52] TiO_2-graphene composite material was prepared by the immobilisation of TiO_2 NPs on graphene surface through in situ hydrothermal treatment. The prepared composite material fabricated a modified TiO_2-graphene/ GCE with good electrochemical activity and high sensitivity for Ad and Gu sensing. Results show that modified TiO_2-graphene/ GCE offers a low detection limit (0.10 and 0.15 µM) for redox activity of Ad and Gu respectively, in a wide linear range (0.5–200 µM).[53]

Magnetic NPs also play vital role in ECS since they have unique characteristics like rapid electroanalysis response, larger electroactive surface area and exhibit low resistance for mass transfer.[54] MWCNT/$NiFe_2O_4$ magnetic composite material was developed by sol-gel method for the modification of GCE and the immobilisation of magnetic composite material display the satisfactory electrochemical results for Ad and Gu sensing. The modified MWCNT/$NiFe_2O_4$-GCE show synergic effect on redox activity of Ad and Gu that enhanced oxidation peaks currents dramatically but reduces the peaks potential.[55]

L-cysteine (LC) can easily embedded onto the surface of carbon materials like Gr and also incorporated the metal oxide NPs that provide better performance to electrochemical transducer to detect the concentration of Ad and Gu.[56,57] The combination of two metal oxides can improve the sensitivity of electrochemical sensor owing to their enormous characteristics such as their porous nanorods structure and formation of p-n junction between two metal oxide NPs.[58] It was reported that LC was electropolymerized on the surface of Gr as poly L-cysteine (PLC) in the presence of a phosphate buffer solution that contain copper oxide nanofibers (CuO) along with zinc oxide NPs (ZnO). These two metal oxides were incorporated into the PLC matrix such that they developed PLC/ZnO–CuO nanocomposite which further modified the Gr electrode to produce PLC/ZnO–CuO /GE modified electrode. The as developed modified electrode was detected the high oxidation peaks for Ad and Gu individually as well as simultaneously with wide linear concentration range (0.05–6.78 and 0.01–3.87 µM) and low detection limit (12.48 and 1.25 nM) was reported for Gu and Ad, respectively by DPV techniques.[59]

An iron (Fe) impurity was doped in nafion (Nf) embedded MWCNT by in situ electro assisted derivatization and a hybrid system was referred as Nf-MWCNT- Fe which on further treated with 2,2'-bipyridine ligand (bpy) ligand and provide an electroactive Nf-MWCNT-*$Fe(bpy)_3^{2+}$ complex composite material. Prepared composite material was used to modify the GCE electrode to perform electrochemical analysis of Ad and Gu in buffer solution (pH=7). Electrochemical potential cyclisation of GCE/Nf-MWCNT-$Fe(bpy)_3^{2+}$ electrode, estimated the DNA's PB, Ad and Gu at different oxidative potentials i.e. 1 V (Ad and Gu) and 0.7 V vs Ag/AgCl (Gu).[60] NiAl-LDH/GO hybrids was developed by ultrasonic irradiation of NiAl-layered double hydroxide (NiAl-LDH) with GO and dispersion of this hybrid with MWCNT in ethanol provided an efficient MWCNTs/NiAl-LDH/GO sensing material, coated on GCE to modify it. The redox activities of Ad and Gu at the surface of MWCNTs/NiAl-LDH/GO/ GCE were investigated by LSV technique and oxidation peak potentials under linear ranges 0.010-45 µM and 0.08-45 µM with LOD 0.003 µM and 0.02 µM for Gu and Ad were reported, respectively.[61]

PbO_2 play vital role in the field of electrochemistry because of its chemical stability, fast oxygen transfer response and good electrical conductivity as shown by other metal oxides. The interaction of its unique properties with carbon allotropes used for the development of new composite material that exhibit the properties of both materials.[62]

A novel carbon composite material proposed by the combination of PbO_2 and MWCNT which was further incorporated with room temperature ionic liquid (RTIL) i.e., 1-butyl-3-methylimidazolium hexafluorophosphate (BMIMPF6) to develop a composite film on GCE and finally a modified WE (PbO_2–MWCNT–RTIL/GCE) investigated the individual and simultaneous oxidative detection of Ad and Gu via DPV technique. The peak separation was found to be 0.29 V in neutral PB (0.1 M) and detection limit was 0.006 and 0.0003 mM for Gu and Ad, respectively. It was also reported that, synergistic effect of PbO_2, MWNT and RTIL could facilitate the electron transfer of Ad and Gu with improved oxidation peak current and reduced the oxidative potential.[63] Gold NPs (GNP) comprised with MWCNT and IL (i.e. 1-octyl-3-methylimidazolium hexafluorophosphate, OMIMPF6) to prepare an electrochemical composite film with high sensing ability for Ad and Gu in milk, plasma and urine samples that displayed simultaneous determination of well separated anodic peaks of Ad and Gu. The composite film offered the low electron transfer resistance that could help electrode in the detection of Ad and Gu at lower limit with linear curve of oxidative peak current.[64]

CNT doped with boron (CNB) are investigated for their wide applications in carbon electrode modification due to the presence of unique characteristics in CNB such as wide potential window, good antifouling property and high electron transfer rate could facilitate the electrochemical activity of carbon electrode. The electrodeposition of CNB on GCE offered a promising platform for simultaneous determination of purine as well as pyrimidine bases with large peak separation, low detection limit and high oxidative linear peak via DPV technique.[65]

The microwave assisted combined properties of lanthanum hydroxide ($La(OH)_3$) with CNT was observed to determine the redox activities of Ad and Gu via CV technique that demonstrated fast oxidative response towards CNT/$La(OH)_3$ modified electrode with detection limits 0.22 (Ad) and 0.26 µM (Gu).[66]

4. Carbon-polymer NC for Ad and Gu Sensing

The combination of conductive polymers with carbon NPs, due to their excellent electrical conductivity are well reported as promising sensing elements in electrochemical sensors. In this regard, high conductive nature and good catalytic property of Poly(3,4-ethylendioxythiophene) (PEDOT) have been reported for its wide application in detection of biological compounds and hence serves as good electroactive sensing material to increased efficiency of transducer in sensors.[67] Electro- deposition of PEDOT on Gr fabricated a PEDOT/GR composite material to modify GCE and to

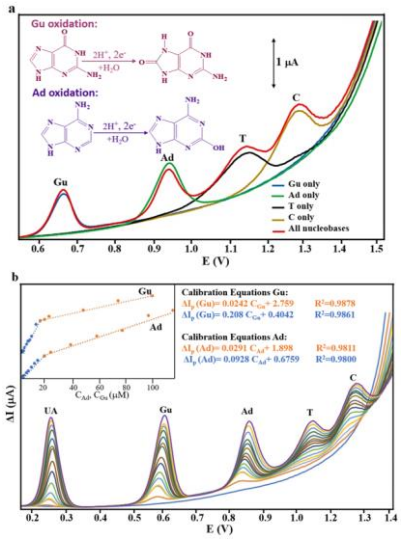

Fig. 7. DPV for individual and simultaneous detection of Ad (12.5 µM), T (147.5 µM), C (97.5 µM), and Gu (10 µM) in PB (0.2 M). (b**)** Calibration curves for simultaneous detection of UA, Gu, Ad, T, and C using GCE/GO-MWCNT-CHT. Inset: calibration graphs and equations for Ad and Gu.[83]

investigate electrooxidation response of PB. The modified electrode PEDOT/GR/GCE showed large potential peak separation, low detection limit and increased oxidation current due to the synergic effect of Gr and PEDOT that improved the electrochemical activity of GCE and increased sensing ability of PEDOT/GR for detection.[68]

CNC include ionic liquids (ILs)/ poly(ionic liquids) (PILs), based on imidazolium ring provides an attractive means for ECS of Ad and Gu since imidazolium ring have excellent ability to bind with carbon nanomaterial via interaction between positive charge of imidazolium ring and p orbital of carbon nanomaterial.[69-71] As a result, the prepared composite materials have broad electrochemical window and high ionic conductivity which may useful for sensing of biological compounds. MWCNT was dispersed in aqueous solution of Imidazolium-based cationic (PILs) e.g. poly(1ethyl-3-vinylimidazolium bromide) and poly(1-butyl-3-vinylimidazolium bromide) to synthesise a composite material PILs/MWCNT that modify a screen printed electrodes (SPEs). Such modification of SPEs remarkably increases its electrochemical activity due to the combination of synergistic effect of MWCNT and ionic amphiphilicity of PILs. PILs/MWCNT modified SPEs reported the oxidation peaks between 0.5–50µM and 5–500 µM corresponding to Ad and Gu for the determination of dsDNA.[72] IL, an electrolyte or green solvent, is reported as the modifier of carbon electrode and due to wide potential window and high ionic mobility of IL, the electron transfer reaction rates on carbon surface is increased.[73]

Owing to an excellent film-forming-ability and high mechanical strength of CHT biopolymer, hydrophobicity of graphene sheets (GS) can be reduced and this unique application of CHT for GS could be further utilize for the synthesis of an electroactive carbon composite.[74] These unusual properties of ILs and CHT was jointly used with GS to fabricate GS/IL/CHT modified electrode and this electrode was successfully applied for individual and simultaneous detection of electrocatalytic activities of Ad and Gu via CV and DPV technique. The results revealed that GS/IL/CHT electrode used two electrons for oxidation/reduction of Gu and Ad with charge transfer coefficient (a) 0.58 and 0.51, respectively, therefore the modified electrode followed the two electron- two proton transfer process.[75]

Polypyrrole (PPy) was dispersed onto GO to develop PPy/Gr conductive nanocomposite and deposited on bare GCE to evaluate their electrochemically measurements through CV @ 1.8 V. The obtained modified PPy/Gr/GCE was used for simultaneous quantitative estimation of Ad and Gu by LSV technique with high linear range covering (60-10^5µM and 40–10^5 µM, respectively) at low detection limit (0.02 µM and 0.01 µM, respectively)) and it was reported that PPy/Gr act as good electrocatalytic sensing element because it provides a large surface area for the adsorption of Ad and Gu through p-p electrostatic interaction.[76]

PB biosensor based on epoxy composite materials was also reported, where epoxy resin develops an insulating phase and carbon allotropes generates a conductive phase in composite electrode to achieve highly sensitive electrochemical sensor with good mechanical properties.[77] Epoxy resin with Gr composite is developed to detect the oxidation of Guanine monophosphate and adenine monophosphate by SWV under the optimal conditions.[78] Perfluorosulfonic acid polymer in combination with graphene is used to facilitate the electron transfer of PB. It is well reported that graphene does not disperse in aqueous solution properly due to its reaggregate ability via p-p and van der Waal's interactions, this characteristic makes graphene's sheets unable to separate out in aqueous solution.[79]

Researchers have been found out that the individual sheets of graphene are responsible for all type of properties exhibited by graphene. An electroactive composite film of Nf with graphene on GCE to study the electrooxidative properties of Ad and Gu was developed, showing that negatively charged Nf enhanced the oxidative current due to easy adsorption of positive charged Ad and Gu on GCE electrode. The peak separation of Ad and Gu determined simultaneously at 0.364 V and detection limit 0.75 (Ad) and 0.58 µM (Gu) via DPV technique was reported, satisfactorily.[80] MWCNT with poly (new fuchsin) (PFu) comprises a composite material MWCNT–PFuto fabricate a conductive film on GCE for simultaneous quantitative estimation of Ad and Gu by DPV technique. Electrochemical studies on MWCNT–PFu revealed a well separated voltammetric peaks at 320.3 mV for Ad and Gu with high sensitivity 218.18 (Ad), 12.62 mA $M^{-1}cm^{-2}$ (Gu) display that MWCNT–PFu provide a highly sensitive electrochemical PB sensor.[81]

5. Carbon-carbon NC for Ad and Gu Sensing

The combination of MWCNT with GO produce a novel class of carbon composite that possess an excellent electrochemical ability to fabricate a high response sensor because p-p interaction between MWCNT and GO induce GO-MWCNT dispersion.[82] GCE/GO-MWCNT-CHT electrode material was developed by using GO-MWCNT carbon composite dispersed in CHT on the surface of GCE to determine the electroanalytical behavior of DNA bases simultaneously. GCE/GO-MWCNT-CHT examined the redox nature of Gu and Ad with enhanced oxidation peaks due to the presence of CHT and wide concentration linear ranges with low detection limit (0.12, 0.44 µM, respectively) under optimum controlled conditions was also evaluated.[83] Fig. 7a represents the individual (blue, green, black and

Table 1. Recent advances on electrochemical detection of Gu and Ad by various CNC (as sensing elements)

Sensing element	Sample	Method	LOD (µM)		Linear range (µM)		Ref.
			Gu	Ad	Gu	Ad	
PIL/MWCNT	dsDNA	DPV	-	-	5-500	0.5-50	[72]
GCE/GO-MWCNT-CHT	Human serum/ Human saliva/ Artificial saliva	DPV	0.12	0.44	1-78	1-79.5	[84]
NC/SWCNH	Fish sperm DNA	LSV	0.17	1.4	0.74-6.4	7.4-210	[90]
SWCNT-Borondipyrromethene	Calf thymus DNA	DPV	1.07	2.91	4-60	4.0-80	[92]
SWCNT/1-docosyloxylmethyl-pyrene, (DomP)	Fish sperm DNA	DPV	0.25	0.5	140-440	100-360	[93]
Nitrogen-doped reduced GO (N-rGO)	U87 cells	LSV	-	0.138	-	0.41- 371	[94]
MoS_2-pencil Gr electrode	Calf thymus DNA	DPV	0.76	2.38	15-120	15-120	[95]
MnO_2nanosheets/ionic liquid functionalized graphene/PDA	Fetal bovine serum, mice whole blood	DPV	0.25	0.15	10-300	10-300	[96]
GO nanoribbons /CHT	Single nucleotide, dsDNA	DPV	0.002	0.023	0.05-256	0.05-172	[97]
GO quantum dots /MWCNT	BALB/3T3 cells, MCF-7 cells	DPV	-	-	-	-	[98]
Copper−nickel@nitrogen, boron−doped reduced GO	Calf thymus DNA	DPV	0.118	0.134	1-160	1-120	[99]
Cu-MOF/GO nanohybrid	Herring sperm DNA/Urine	DPV	0.012	0.002	0.02−10	20-100	[100]
Prussian blue@palladium/ N-rGO	Rabbit serum, human urine	DPV	0.0026	-	0.01-85	-	[101]
NH_2-rGO/ molybdenum disulfide	Herring sperm DNA	DPV	0.51	0.44	0.5-150	1.0-280	[102]

brown lines) and simultaneous (red) DPV detections of Gu, Ad, thymine (T) and cytosine (C) in PB (0.2 M) at neutral pH using GCE/GO-MWCNT-CHT electrode, that reported the negligible variations in oxidations peaks of each base on comparing simultaneous and individual detection measurements. The peak potential for Gu, Ad, T and C were reported at 0.65, 0.93, 1.13, 1.27 V, respectively. Fig. 7b elucidates the calibration curve of Uric acid (UA) and all DNA bases by using simultaneous DPV detection. Calibration graph in inset Fig. 7b, validates the linear dependency of Current peaks (I_p) on the concentration of Gu and Ad. The concentration range 2-78 and 2-79.5 µM were used to detect Gu and Ad, respectively and two calibration equations (line segments) were found for each base in this linear range, which is shown in Fig. 7b. Blue segment show the calibration equations under 2-13 µM (Gu) and 2-19.5 µM (Ad), while 13-78 µM and 14.5- 79.5 µM concentration range represent the red segment for linear response of Gu and Ad, respectively. These calibration equations were used to evaluate the LOD for Gu (0.11 µM) and Ad (0.43 µM). Drop casting of MWCNT NPs on Gr surface developed a modified WE to investigate electrooxidative properties of Gu by DPV technique that reported good working potential window and high charge transfer resistance with reduced cathodic current.[84]

The combination of Gr with ILs of N-butylpyridiniumhexafluorophosphate ($BPPF_6$) offered a carbon ionic liquid electrode (CILE) with increased oxidation peak and a negative shift in oxidation potential for Ad and Gu was also reported. CV technique displayed the well-defined electrochemical calculations performed by CILE to detect Ad and Gu at high oxidative peak separation (0.304 V).[85] β-CD presents host-guest mechanism due to the presence of torus- shaped cavity in which a proper sized biological molecule (guest) can trapped easily. CNT can bind to the β-CD to propose a β-CD-CNT modified electrode for simultaneous or individual oxidative estimation of Gu and Ad via DPV technique with detection limit 100 and 200 µM under optimum condition of +0.79 and +1.09 V in acetate buffer (pH=4.5).[86]

Boron doped diamond (BDD), a carbonaceous material has some advantages that allow to study the voltammetric response of PB at large potential range that is not as much suitable for other carbon composite materials. BDD offer wide positive potential window range, low background current, good biocompatibility, high electrochemical stability, high resistance against fouling, these properties are found to be helpful to construct an electrochemical transducer.[87,88] Human placenta and fish sperm were investigated for the direct quantification of DNA via oxidation of its bases (Ad and Gu), using BDD electrode. DP voltammogram technique used to display electrocatalytic activities of PB on BDD electrode individually and simultaneously as well. The results showed that oxidation potential is 1.15 and 1.35 V with simultaneous and individual determination of LOD 37, 19 and 15.8, 67 µM in concentration range 210–23×10^3 120–25×$10^3$and 300–19 ×10^3, 300–19 ×10^3 µM for Gu and Ad, respectively.[89] Nano cellulose (NC) and SWCNH based material are promising for sensing different biological molecules as they exhibit high porosity, good conductivity, less toxicity and high biodegradability. NC-SWCNH/GCE modified electrode presented good catalytic activity with low detection limit (0.17 and 0.14 µM) for Gu and Ad, respectively via LSV technique.[90]

A composite material graphene/COOH which contains carboxylic acid (COOH) and graphene was synthesised on GCE to investigate electrochemical oxidative activities of Ad and Gu via DPV technique and results showed that graphene/COOH-GCE modified electrode determined the oxidative peaks separation of Ad and Gu @ 0.334 V with detection limit 0.05, 0.025 µM, respectively.[91] Besides, above discussed studies some recent developments based on CNC modified electrode for PB sensing are given in table 1.

6. Conclusions

As we have discussed in this review, CNC is emerged as a promising candidate for the development of electroactive transducer to design an efficient and highly sensitive ECS technique for Ad and Gu. Compared to other composites, carbon-based composites provide an effective electrode surface with unique characteristics that enhance the electrochemical signal generated from the biological reaction between PB and electrode material. Although, it has been demonstrated that CNC is emerged as an alternate over others with satisfactory results in the field of PB sensing, still there is a need of

some improvements to enhance the physiological activities of PB on electrode surface during analyte/electrode surface interaction. The conventional carbon materials such as Gr, graphene, GO, CNT, fullerenes utilized in the development of CNC are costly and introduces toxicity in CNC. Moreover, the application of CNC as a transducer for ECS of Ad and Gu is not so environmentally effective. Biocarbons derived from biomass could be a better replacement of conventional carbon nano materials in development of cost effective ecofriendly CNC. Biocarbons have rich physiochemical properties and has ability to use as precursor for synthesis of conventional carbon nanomaterials that possess improved properties and may utilize for design a sustainable sensor that could help to detect the Ad and Gu.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1 Blanco G.; Blanco A. *Medical Biochemistry*. Academic Press. 2017. [Link]
2 Rosenberg E. *It's in Your DNA: From Discovery to Structure, Function and Role in Evolution, Cancer and Aging*. Academic Press. 2017. [Link]
3 Shen CH. Diagnostic Molecular Biology. Academic Press, 2019. [Link]
4 Ali-Sisto T.; Tolmunen T.; Toffol E.; Viinamäki H.; Mäntyselkä P.; Valkonen-Korhonen M.; Lehto S.M. Purine Metabolism is Dysregulated in Patients with Major Depressive Disorder. *Psychoneuroendocrinology*, 2016, **70**, 25-32. [CrossRef]
5 Barnes R.P.; Fouquerel E.; Opresko P.L. The Impact of Oxidative DNA Damage and Stress on Telomere Homeostasis. *Mech. Ageing Dev.*, 2019, **177,** 37-45. [CrossRef]
6 Nicolae I.; Ene C. D.; Mitran C.I.; Mitran M.I.; Sarbu M.I.; Matei C.; Georgescu S.R. Correlations between Related-Purine Derivatives and Renal Disorders in Patients with Psoriasis Vulgaris. *Exp. Ther. Med.*, 2019, **17**, 1012-1019. [CrossRef]
7 Reichert S.; Stier A. Does Oxidative Stress Shorten Telomeres in vivo? A Review. *Biol. Lett.*, 2017, **13**, 20170463. [CrossRef]
8 Monostori P.; Klinke G.; Hauke J.; Richter S.; Bierau J.; Garbade S.F.; Okun J.G. Extended Diagnosis of purine and Pyrimidine Disorders from Urine: LC MS/MS Assay Development and Clinical Validation. *PloS one*, 2019, **14**, e0212458. [CrossRef]
9 Martín Gonzàlez A. Separation and Characterization of MicroRNAs by Capillary Electrophoresis with Ultraviolet Detection and Mass Spectrometry. 2019. [Link]
10 Roychoudhury A.; Francis K.A.; Patel J.; Jha S.K.; Basu S. A Decoupler-Free Simple Paper Microchip Capillary Electrophoresis Device for Simultaneous Detection of Dopamine, Epinephrine and Serotonin. *RSC Adv.*, 2020, **104**, 25487-25495. [CrossRef]
11 Shi B.; Su Y.; Duan Y.; Chen S.; Zuo W. A Nanocomposite Prepared From Copper (II) and Nitrogen-Doped Graphene Quantum Dots with Peroxidase Mimicking Properties For Chemiluminescent Determination of Uric Acid. *MicrochimicaActa*, 2019, **186**, 397. [CrossRef]
12 Wang Y.Y.; Cheng H.W.; Chang K.W.; Shiue J.; Wang J.K.; Wang Y.L.; Huang N.T. A Particle-Based Microfluidic Molecular Separation Integrating Surface-Enhanced Raman Scattering Sensing for Purine Derivatives Analysis. *Microfluid. Nanofluid.*, 2019, **23**, 48. [CrossRef]
13 Rong S.; Zou L.; Zhang Y.; Zhang G.; Li X.; Li M.; Guo Y. Determination of purine contents in different parts of pork and beef by high performance liquid chromatography. *Food Chem.*, 2015, **170**, 303-307. [CrossRef]
14 Szterk A.; Roszko M. Simultaneous Determination of Free Amino Acids, L-Carnosine, Purine, Pyrimidine, and Nucleosides in Meat by Liquid Chromatography/Single Quadrupole Mass Spectrometry. *J. Liq. Chromatogr. Relat. Technol.*, 2014, **37**, 664-680. [CrossRef]
15 Agyei D.; Pan S.; Acquah C.; Bekhit A.E.D.A.; Danquah M.K. Structure-Informed Detection and Quantification of Peptides in Food and Biological Fluids. *J. Food Biochem.*, 2019, **43**, e12482. [CrossRef]
16 Zhang C.; Woolfork A.G.; Suh K.; Ovbude S.; Bi C.; Elzoeiry M.; Hage D.S. Clinical and Pharmaceutical Applications of Affinity Ligands in Capillary Electrophoresis: A Review. *J. Pharm. Biomed. Anal.*, 2020, **177**, 112882. [CrossRef]
17 Mathew M.R.; Kumar K.G. Poly (Amino Hydroxy Naphthalene Sulphonic Acid) Modified Glassy Carbon Electrode; an Effective Sensing Platform for the Simultaneous Determination of Xanthine and Hypoxanthine. *J. Electrochem. Soc.*, 2020, **167**, 047519. [CrossRef]
18 Li H.; Liu X.; Li L.; Mu X.; Genov R.; Mason A.J. CMOS Electrochemical Instrumentation for Biosensor Microsystems: A Review. *Sensors*, 2017, **17**, 74. [CrossRef]
19 Rikhari R.; Saklani B.; Bisht A.; Mehtab S.; Zaidi M.; Haider G. Graphene Oxide Assisted Modification in Electrical and Electrochemical Characteristics of Polypyrrole. *Sens. Lett.*, 2019, **17**, 511-515. [CrossRef]
20 Sharma S.; Joshi P.; Mehtab S.; Zaidi M.G.H.; Singhal K.; Siddiqi T.I. Development of Non-enzymatic Cholesterol Electrochemical Sensor Based on Polyindole/Tungsten Carbide Nanocomposite. *J. Anal. Test.*, 2020, **4**, 13-22. [CrossRef]
21 Zainul R.; Isa I. M.; Hashim N.; Prima B. Electrochemical Sensors: Principles and Applications, 2019. [CrossRef]
22 Rafique B.; Iqbal M.; Mehmood T.; Shaheen M.A. Electrochemical DNA Biosensors: A Review. *Sens. Rev.*, 2019, **39,** 34–50. [CrossRef]
23 Mehtab S.; Zaidi M.G.H.; Joshi P. Metal Nanoparticles Based Electrochemical Biosensors for Cholesterol. *J. Nanomed. Nanotechnol.*, 2020, **11**, 540-541. [Link]
24 Cho I.H.; Kim D.H.; Park S. Electrochemical Biosensors: Perspective on Functional Nanomaterials for On-Site Analysis. *Biomater. Res.*, 2020, **24**, 1-12. [CrossRef]
25 Yu Y.; Nyein H.Y.Y.; Gao W.; Javey A. Flexible Electrochemical Bioelectronics: The Rise of In Situ Bioanalysis. *Adv. Mater.*, 2020, **32**, 1902083. [CrossRef]
26 Tan S.T.M.; Giovannitti A.; Melianas A.; Moser M.; Cotts B.L.; Singh D.; Salleo A. Chemical to Electrical Transduction using Fuel Cell Powered Organic Electrochemical Transistors, 2020. [CrossRef]
27 Gualandi I.; Tessarolo M.; Mariani F.; Tonelli D.; Fraboni B.; Scavetta E. Organic Electrochemical Transistors As Versatile Analytical Potentiometric Sensors. *Front. Bioeng. Biotechnol.*, 2019, **7**, 354. [CrossRef]
28 Sun M.; Li Z.; Xia Y.; Zhao C.; Liu H. Concentration cell-based potentiometric analysis for point-of-care testing with minimum background. *Anal. Chim. Acta*, 2019, **1046**, 110-114. [CrossRef]
29 Reich P., Preuß JA., Bahner N., Bahnemann J. Impedimetric Aptamer-Based Biosensors: Principles and Techniques. In: Urmann K.; Walter JG. (eds) Aptamers in Biotechnology. Advances in Biochemical Engineering/Biotechnology, 2020, **174**. Springer, Cham. [CrossRef]
30 Katz E.; Willner I. Probing Biomolecular Interactions at Conductive and Semiconductive Surfaces by Impedance Spectroscopy: Routes to Impedimetricimmunosensors, DNA-Sensors, and Enzyme Biosensors. *Electroanalysis*, 2003, **15**, 913-947. [CrossRef]
31 Goncalves L.M.; Batchelor-McAuley C.; Barros A.A.; Compton, R.G. Electrochemical Oxidation of Adenine: A Mixed Adsorption and Diffusion Response on an Edge-Plane Pyrolytic Graphite Electrode. *J. Phys. Chem. C*, 2010, **114**, 14213-14219. [CrossRef]
32 Sun W.; Liu, J.; Ju X.; Zhang L.; Qi X.; Hui N. Highly Sensitive Electrochemical Detection of Adenine on a Graphene-Modified Carbon Ionic Liquid Electrode. *Ionics*, 2013, **19**, 657-663. [CrossRef]
33 Batool R.; Rhouati A.; Nawaz M.H.; Hayat A.; Marty J.L. A Review of the Construction of Nano-Hybrids for Electrochemical Biosensing of Glucose. *Biosensors*, 2019, **9**, 46. [CrossRef]

34 Shan C.; Yang H.; Han D.; Zhang Q.; Ivaska A.; Niu L. Electrochemical Determination of NADH and Ethanol based on Ionic Liquid-Functionalized Graphene. *Biosens. Bioelectron.*, 2010, **25**, 1504-1508. [CrossRef]
35 Kang X.; Wang J.; Wu H.; Aksay I.A.; Liu J.; Lin Y. Glucose Oxidase–Graphene–Chitosan Modified Electrode for Direct Electrochemistry and Glucose Sensing. *Biosens. Bioelectron.*, 2009, **25**, 901-905. [CrossRef]
36 Kang X.; Mai Z.; Zou X.; Cai P.; Mo J. A Sensitive Nonenzymatic Glucose Sensor in Alkaline Media with a Copper Nanocluster/Multiwall Carbon Nanotube-Modified Glassy Carbon Electrode. *Anal. Biochem.*, 2007, **363**, 143-150. [CrossRef]
37 Tu Y.; Lin Y.; Yantasee W.; Ren Z. Carbon Nanotubes Based Nanoelectrode Arrays: Fabrication, Evaluation, and Application in Voltammetric Analysis. *Electroanalysis*, 2005, **17**, 79-84. [CrossRef]
38 Mehtab S.; Zaidi M.G.H.; Singhal K.; Arya B.; Siddiqui T.I. Polyindole Based Nanocomposites and Their Applications: A Review. *Mater. Sci. Res. India*, 2019, **16**, 97-102. [CrossRef]
39 Pumera M.; Merkoçi A.; Alegret S. Carbon Nanotube-Epoxy Composites for Electrochemical Sensing. *Sens. Actuators B: Chem.*, 2006, **113**, 617-622. [CrossRef]
40 Adhikari B.R.; Govindhan M.; Chen A. Carbon Nanomaterials Based Electrochemical Sensors/Biosensors for the Sensitive Detection of Pharmaceutical and Biological Compounds. *Sensors*, 2015, **15**, 22490-22508. [CrossRef]
41 Joshi P.; Mehtab S.; Zaidi M.G.H.; Tyagi T.; Bisht A. Development of Polyindole/Tungsten Carbide Nanocomposite-Modified Electrodes for Electrochemical Quantification of Chlorpyrifos. *J. Nanostruct. Chem.*, 2020, ***10***, 33-45. [CrossRef]
42 Kharissova O.V.; Oliva González C.M.; Kharisov B.I. Solubilization and Dispersion of Carbon Allotropes in Water and Non-Aqueous Solvents. *Ind. Eng. Chem. Res.*, 2018, **57**, 12624-12645. [CrossRef]
43 Ramírez-García S.; Alegret S.; Céspedes F.; Forster R.J. Carbon Composite Electrodes: Surface and Electrochemical Properties. *Analyst*, 2002, **127**, 1512-1519. [CrossRef]
44 Thangaraj R.; Kumar A.S. Simultaneous Detection of Guanine and Adenine in DNA and Meat Samples using Graphitized Mesoporous Carbon Modified Electrode. *J. Solid State Electrochem.*, 2013, **17**, 583-590. [CrossRef]
45 Arvand M.; Ghodsi N.; Zanjanchi M.A. A New Microplatform Based on Titanium Dioxide Nanofibers/Graphene Oxide Nanosheets Nanocomposite Modified Screen Printed Carbon Electrode for Electrochemical Determination of Adenine in the Presence of Guanine. *Biosens. Bioelectron.*, 2016, **77**, 837-844. [CrossRef]
46 Georgakilas V.; Gournis D.; Tzitzios V.; Pasquato L.; Guldi D. M.; Prato M. Decorating Carbon Nanotubes With Metal Or Semiconductor Nanoparticles. *J. Mater. Chem.*, 2007, **17**, 2679-2694. [CrossRef]
47 Ge J.; Yu J.H.; Yang H.; Yang D.; Cai R. Human Serum Albumin Templated Mno_2 Nanosheets as an Efficient Biomimetic Oxidase for Biomolecule Sensing. *J. Mater. Chem. B,* 2020, **8**, 11090-11095. [CrossRef]
48 Yang L.; Ren X.; Tang F.; Zhang L. A Practical Glucose Biosensor Based on Fe_3O_4 Nanoparticles and Chitosan/Nafion Composite Film. *Biosens. Bioelectron.*, 2009, **25**, 889-895. [CrossRef]
49 Yari A.; Derki S. New MWCNT-Fe_3O_4@ PDA-Ag Nanocomposite as a Novel Sensing Element of an Electrochemical Sensor for Determination of Guanine and Adenine Contents of DNA. *Sens. Actuators B: Chem.*, 2016, **227**, 456-466. [CrossRef]
50 Jia N.; Zhou Q.; Liu L.; Yan M.; Jiang Z. Direct Electrochemistry and Electrocatalysis of Horseradish Peroxidase Immobilized in Sol–Gel-Derived Tin Oxide/Gelatin Composite Films. *J. Electroanal. Chem.*, 2005, **580**, 213-221. [CrossRef]
51 Ansari A.A.; Kaushik A.; Solanki P.R.; Malhotra B.E. Electrochemical Cholesterol Sensor Based On Tin Oxide-Chitosan Nanobiocomposite Film. *Electroanalysis*, 2009, **21**, 965-972. [CrossRef]
52 Muti M.; Erdem A.; Caliskan A.; Sınag A.; Yumak T. Electrochemical Behaviour of Carbon Paste Electrodes Enriched with Tin Oxide Nanoparticles using Voltammetry and Electrochemical Impedance Spectroscopy. *Colloids Surf. B*, 2011, **86**, 154-157. [CrossRef]
53 Fan Y.; Huang K.J.; Niu D.J.; Yang C.P.; Jing Q.S. Tio_2-Graphene Nanocomposite for Electrochemical Sensing of Adenine and Guanine. *Electrochim. Acta*, 2011, **56**, 4685-4690. [CrossRef]
54 Raffaelle R.P.; Landi B.J.; Harris J.D.; Bailey S.G.; Hepp A.F. Carbon Nanotubes for Power Applications. *Mater. Sci. Eng.: B*, 2005, **116**, 233-243. [CrossRef]
55 Ensafi A.A.; Jafari-Asl M.; Rezaei B.; Allafchian A.R. Simultaneous Determination of Guanine and Adenine in DNA based on $NiFe_2O_4$ Magnetic Nanoparticles Decorated MWCNTs as a Novel Electrochemical Sensor using Adsorptive Stripping Voltammetry. *Sens. Actuators B: Chem.*, 2013, **177**, 634-642. [CrossRef]
56 Zhou W.; Li C.; Sun C.; Yang X. Simultaneously Determination of Trace Cd^{2+} and Pb^{2+} Based on L-Cysteine/Graphene Modified Glassy Carbon Electrode. *Food Chem.*, 2016, **192**, 351-357. [CrossRef]
57 Zhang K.; Luo P.; Wu J.; Wang W.; Ye B. Highly Sensitive Determination of Sunset Yellow in Drink using a Poly (L-Cysteine) Modified Glassy Carbon Electrode. *Anal. Methods*, 2013, **5**, 5044-5050. [CrossRef]
58 Wang L.; Kang Y.; Wang Y.; Zhu B.; Zhang S.; Huang W.; Wang S. CuO Nanoparticle Decorated Zno Nanorod Sensor for Low-Temperature H_2S Detection. *Mater. Sci. Eng.: C*, 2012, **32**, 2079-2085. [CrossRef]
59 Arvand M.; Ardaki M.S. Poly-L-Cysteine/Electrospun Copper Oxide Nanofibers-Zinc Oxide Nanoparticles Nanocomposite as Sensing Element of an Electrochemical Sensor For Simultaneous Determination of Adenine and Guanine In Biological Samples and Evaluation of Damage to dsDna and DNA Purine Bases by UV Radiation. *Anal. Chim. Acta*, 2017, **986**, 25-41. [CrossRef]
60 Mayuri P.; Senthil Kumar A. In Situ Derivatization of an Intrinsic Iron Impurity as a Surface-Confined Iron(II) tris (2,2′-bipyridine) Complex on MWCNT and its Application to Selective Electrochemical Sensing of DNA's Purine Bases. *Langmuir*, 2015, **31**, 5945-5951. [CrossRef]
61 Rezaei B.; Khosropour H.; Ensafi A.A.; Dinari M.; Nabiyan A. A New Electrochemical Sensor for the Simultaneous Determination of Guanine and Adenine: Using a Nial-Layered Double Hydroxide/Graphene Oxide-Multi Wall Carbon Nanotube Modified Glassy Carbon Electrode. *RSC Adv.*, 2015, **5**, 75756-75765. [CrossRef]
62 Feng L.J.; Zhang X.H.; Liu P.; Xiong H.Y.; Wang S.F. An Electrochemical Sensor Based on Single-Stranded DNA–Poly (Sulfosalicylic Acid) Composite Film for Simultaneous Determination of Adenine, Guanine, and Thymine. *Anal. Biochem.*, 2011, **419**, 71-75. [CrossRef]
63 Liu T.; Zhu X.; Cui L.; Ju P.; Qu X.; Ai S. Simultaneous Determination of Adenine and Guanine Utilizing PbO_2-Carbon Nanotubes-Ionic Liquid Composite Film Modified Glassy Carbon Electrode. *J. Electroanal. Chem.*, 2011, **651**, 216-221. [CrossRef]
64 Xiao F.; Zhao F.; Li J.; Liu L.; Zeng B. Characterization of Hydrophobic Ionic Liquid-Carbon Nanotubes–Gold Nanoparticles Composite Film Coated Electrode and the Simultaneous Voltammetric Determination of Guanine and Adenine. *Electrochim. Acta*, 2008**, 53,** 7781-7788. [CrossRef]
65 Deng C.; Xia Y.; Xiao C.; Nie, Z.; Yang M.; Si S. Electrochemical Oxidation of Purine and Pyrimidine Bases Based on the Boron-Doped Nanotubes Modified Electrode. *Biosens. Bioelectron.*, 2012, **31**, 469-474. [CrossRef]
66 Fang B.; Zhang W.; Wang G.; Liu H.; Wei S. Microwave-Assisted Preparation of a Carbon Nanotube/La $(OH)_3$ Nanocomposite, and its Application to Electrochemical Determination of Adenine and Guanine. *Microchim. Acta*, 2008, **162**, 175-180. [CrossRef]
67 Kros A.; Sommerdijk N.A.; Nolte R.J. Poly (Pyrrole) Versus Poly (3, 4-Ethylenedioxythiophene): Implications for Biosensor Applications. *Sens. Actuators B: Chem.*, 2005, **106**, 289-295. [CrossRef]
68 Ouyang X.; Luo L.; Ding Y.; Liu B.; Xu D. Simultaneous Determination of Purine and Pyrimidine bases in DNA using Poly (3, 4-ethylenedioxythiophene)/Graphene Composite Film. *J. Electroanal. Chem.*, 2014, **735**, 51-56. [CrossRef]
69 Men Y.; Li X.H.; Antonietti M.; Yuan J. Poly (Tetrabutylphosphonium 4-Styrenesulfonate): A Poly (Ionic Liquid) Stabilizer for Graphene Being Multi-Responsive. *Polym. Chem.*, 2012, **3**, 871-873. [CrossRef]
70 Fukushima T.; Kosaka A.; Ishimura Y.; Yamamoto T.; Takigawa T.; Ishii N.; Aida T. Molecular Ordering of Organic Molten Salts Triggered by Single-Walled Carbon Nanotubes. *Science*, 2003, **300**, 2072-2074. [CrossRef]

71 Yuan J.; Mecerreyes D.; Antonietti M. Poly (Ionic Liquid)s: An Update. *Prog. Polym. Sci.*, 2013, **38**, 1009-1036. [CrossRef]
72 Sigolaeva L.V.; Bulko T.V.; Kozin M.S.; Zhang W.; Köhler M.; Romanenko I.; Shumyantseva V.V. Long-Term Stable Poly (Ionic Liquid)/MWCNTs Inks Enable Enhanced Surface Modification for Electrooxidative Detection and Quantification of dsDNA. *Polymer*, 2019, **168**, 95-103. [CrossRef]
73 Sun W.; Qin P.; Zhao R.; Jiao K. Direct Electrochemistry and Electrocatalysis of Hemoglobin on Gold Nanoparticle Decorated Carbon Ionic Liquid Electrode. *Talanta*, 2010, **80**, 2177-2181. [CrossRef]
74 Wu J.F.; Xu M.Q.; Zhao G.C. Graphene-Based Modified Electrode for the Direct Electron Transfer of Cytochrome C and Biosensing. *Electrochem. Commun.*, 2010, **12**, 175-177. [CrossRef]
75 Niu X.; Yang W.; Ren J.; Guo H.; Long S.; Chen J.; Gao J. Electrochemical Behaviors and Simultaneous Determination of Guanine and Adenine based on Graphene–Ionic Liquid–Chitosan Composite Film Modified Glassy Carbon Electrode. *Electrochim. Acta*, 2012, **80**, 346-353. [CrossRef]
76 Gao Y.S.; Xu J.K.; Lu L.M.; Wu L.P.; Zhang K.X.; Nie T.; Wu Y. Overoxidized Polypyrrole/Graphene Nanocomposite with Good Electrochemical Performance as Novel Electrode Material for the Detection of Adenine and Guanine. *Biosens. Bioelectron.*, 2014, **62**, 261-267. [CrossRef]
77 Zacco E.; Pividori M.I.; Llopis X.; Del Valle M.; Alegret S. Renewable Protein a Modified Graphite-Epoxy Composite for Electrochemical Immunosensing. *J. immunol. Methods*, 2004, **286**, 35-46. [CrossRef]
78 Tamayo A.I.B.; Riso L.S.; Gramatges A.P.; Farías P.A.M.; Guas A.M.E. Electrochemical Characterization a New Epoxy Graphite Composite Electrode as Transducer for Biosensor. *Sens. Transducers*, 2016, **202**, 59-65. [Link]
79 Pu N.W.; Wang C.A.; Liu Y.M.; Sung Y.; Wang D.S.; Ger M.D. Dispersion of Graphene in Aqueous Solutions with Different Types of Surfactants and the Production of Graphene Films by Spray or Drop Coating. *J. Taiwan Inst. Chem. Eng.*, 2012, **43**, 140-146. [CrossRef]
80 Yin H.; Zhou Y.; Ma Q.; Ai S.; Ju P.; Zhu L.; Lu L. Electrochemical Oxidation Behavior of Guanine and Adenine on Graphene–Nafion Composite Film Modified Glassy Carbon Electrode and the Simultaneous Determination. *Process Biochem.*, 2010, **45**, 1707-1712. [CrossRef]
81 Tang C.; Yogeswaran U.; Chen S.M. Simultaneous Determination of Adenine Guanine and Thymine at Multi-Walled Carbon Nanotubes Incorporated with Poly (New Fuchsin) Composite Film. *Analyticachim. Acta*, 2009, **636**, 19-27. [CrossRef]
82 Kong H.X. Hybrids of Carbon Nanotubes and Graphene/Graphene Oxide. *Curr. Opin. Solid State Mater. Sci.*, 2013, **17**, 31-37. [CrossRef]
83 Wang S.; Ferrag C.; Noroozifar M.; Kerman K. Simultaneous Determination of Four DNA bases at Graphene Oxide/Multi-Walled Carbon Nanotube Nanocomposite-Modified Electrode. *Micromachines*, 2020, **11**, 294. [CrossRef]
84 Gayathri S.B.; Kamaraj P.; Arthanareeswari M.; Kala S.D. Electrochemical Characterization Of Guanine And Guanosine Based Biosensors Over Multi-Walled Carbon Nanotube Modified Graphite Electrode. *Chem. Sci. Trans.*, 2014, **3**, 1446-1454. [Link]
85 Sun W.; Li Y.; Duan Y.; Jiao K. Direct Electrocatalytic Oxidation of Adenine and Guanine on Carbon Ionic Liquid Electrode and the Simultaneous Determination. *Biosens. Bioelectron*, 2008, **24**, 988-993. [CrossRef]
86 Wang Z.; Xiao S.; Chen Y. β-Cyclodextrin Incorporated Carbon Nanotubes-Modified Electrodes for Simultaneous Determination of Adenine and Guanine. *J. Electroanal. Chem.*, 2006, **589**, 237-242. [CrossRef]
87 Yardım Y.; Gülcan M.; Şentürk Z. Determination of Vanillin in Commercial Food Product by Adsorptive Stripping Voltammetry using a Boron-Doped Diamond Electrode. *Food Chem.*, 2013, **141**, 1821-1827. [CrossRef]
88 Ardila J.A.; Sartori E.R.; Rocha-Filho R.C.; Fatibello-Filho O. Square-Wave Voltammetric Determination of Bezafibrate in Pharmaceutical Formulations using a Cathodically Pretreated Boron-Doped Diamond Electrode. *Talanta*, 2013, **103**, 201-206. [CrossRef]
89 Švorc Ľ.; Kalcher K. Modification-Free Electrochemical Approach for Sensitive Monitoring of Purine DNA Bases: Simultaneous Determination of Guanine and Adenine in Biological Samples Using Boron-Doped Diamond Electrode. *Sens. Actuators B: Chem.*, 2014, **194**, 332-342. [CrossRef]
90 Ortolani T.S.; Pereira T.S.; Assumpção M.H.; Vicentini F.C.; de Oliveira G.G.; Janegitz B.C. Electrochemical Sensing of Purines Guanine and Adenine using Single-Walled Carbon Nanohorns and Nanocellulose. *Electrochim. Acta*, 2019, **298**, 893-900. [CrossRef]
91 Huang K.J.; Niu D.J.; Sun J.Y.; Han C.H.; Wu Z.W.; Li Y.L.; Xiong X.Q. Novel Electrochemical Sensor Based on Functionalized Graphene for Simultaneous Determination of Adenine and Guanine in DNA. *Colloids Surf. B*, 2011, **82**, 543-549. [CrossRef]
92 Sarıoğulları H.; Şenocak A.; Basova T.; Demirbaş E.; Durmuş M. Effect of Different SWCNT-BODIPY Hybrid Materials for Selective and Sensitive Electrochemical Detection of Guanine and Adenine. *J. Electroanal. Chem.*, 2019, **840**, 10-20. [CrossRef]
93 Ji L.; Yu S.; Zhou X.; Bao Y.; Yang F.; Kang W.; Zhang X. Modification of Electron Structure on the Semiconducting Single-Walled Carbon Nanotubes for Effectively Electrosensing Guanine and Adenine. *Analyticachim. Acta*, 2019, **1079**, 86-93. [CrossRef]
94 Song G.; Zhang R.; Jiang X.; Liu F.; Liu X. Nitrogen-Doped Reduced Graphene Oxide as a Sensing Platform for Detection of Guanine and Application in Cell Necrosis. *Chem. Papers*, 2020, **74**, 89-98. [CrossRef]
95 Vishnu N.; Badhulika S. Single Step Grown MoS_2 on Pencil Graphite as an Electrochemical Sensor for Guanine and Adenine: A Novel and Low Cost electrode for DNA Studies. *Biosens. Bioelectron.*, 2019, **124**, 122-128. [CrossRef]
96 Zhang S.; Zhuang X.; Chen D.; Luan F.; He T.; Tian C.; Chen L. Simultaneous Voltammetric Determination of Guanine and Adenine using MnO_2 Nanosheets and Ionic Liquid-Functionalized Graphene Combined with a Permeation-Selective Polydopamine Membrane. *Microchim. Acta*, 2019, **186**, 450. [CrossRef]
97 Zhou J.; Li S.; Noroozifar M.; Kerman K. Graphene Oxide Nanoribbons in Chitosan for Simultaneous Electrochemical Detection of Guanine, Adenine, Thymine and Cytosine. *Biosensors*, 2020, **10**, 30. [CrossRef]
98 Zhou S.; Guo X.; Meng L.; Cui J.; Li J.; Yuan X.; Wu D. A Miniature Electrochemical Detection System Based on GOQDs/MWCNTs/SPCE* for Determination the Purine in Cells. *Anal. Biochem.*, 2019, **577**, 67-72. [CrossRef]
99 Lei P.; Zhou Y.; Zhu R.; Liu Y.; Dong C.; Shuang S. Novel Strategy of Electrochemical Analysis of DNA Bases with Enhanced Performance Based on Copper− Nickel Nanosphere Decorated N, B− Doped Reduced Graphene Oxide. *Biosens. Bioelectron.*, 2020, **147**, 111735. [CrossRef]
100 Wang X.; Zhang J.; Wei Y.; Xing T.; Cao T.; Wu S.; Zhu F. A Copper-Based Metal–Organic Framework/Graphene Nanocomposite for the Sensitive and Stable Electrochemical Detection of DNA Bases. *Analyst*, 2020, **145**, 1933-1942. [CrossRef]
101 Li J.; Jiang J.; Zhao D.; Xu Z.; Liu M.; Liu X.; Qian D. Novel Hierarchical Sea Urchin-Like Prussian Blue@ Palladium Core–Shell Heterostructures Supported on Nitrogen-Doped Reduced Graphene Oxide: Facile Synthesis and Excellent Guanine Sensing Performance. *Electrochim. Acta*, 2020, **330**, 135196. [CrossRef]
102 Zhao X.; Guo H.; Xue R.; Wang M.; Guan Q.; Fan T.; Yang W.; Yang W. Electrochemical Sensing and Simultaneous Determination of Guanine and Adenine Based on Covalent Organic Frameworks/NH_2-rG/MoS_2 Modified Glassy Carbon Electrode. *Microchem. J.*, 2021, **160**, 105759. [CrossRef]