Review

A review on nanosensors to detect diabetes

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Abstract: Diabetes mellitus, a serious disease affecting millions of people worldwide, is a disease characterized by in-creased levels of glucose concentration in the blood. Monitoring blood glucose has been declared a crucial and important tool that makes diabetes management probable. A large number of suitable glucose biosensors have been developed so far. This research has particu-larly focused on covering achieving biocompatible and improved sensing platforms which are evolving with the contribution of novel materials. The motivation for writing this review is to discuss and review the recent advances in enzymatic and non-enzymatic glucose sen-sors evolved in the last few years.

Keywords: diabetes detection; glucose sensors; nanomaterials; en-zymatic glucose sensors; non-enzymatic glucose sensors

1. Introduction

Diabetes is one of the most common and challenging diseases in the 21st century globally. It is now considered a major death cause which seems to be an epidemic in many developing and newly industrialized nations. Complications from diabetes, such as coronary artery and peripheral vascular disease, stroke, diabetic neuropathy, amputations, renal failure, and blindness are resulting in increasing disability, reduced life expectancy, and enormous health costs for virtually every society [1]. Because of those, diabetes management which simply means maintaining a regular blood glucose level has developed rapidly. And monitoring the blood glucose level has turned into one of the most crucial tools in diabetes management. The normal range of blood glucose in a healthy body is found in the range of 4.9–6.9 mm. However, it can be increased by up to 40 mm in diabetic patients after glucose intake [2]. Although various types of glucose sensors have become commercially available, glucose biosensors have also made a huge improvement. Biosensors are devices that can analytically convert a biological response into an electrical signal.

Researchers are being inspired to fabricate affordable, accurate, and user-friendly glucose monitoring instruments by advancements in point-of-care (POC) sensor technologies, microfluidics, nanotechnology, and miniaturization. Accurate on-site and timely detection based on several kinds of glucose sensor platforms has been made possible by the coupling of many glucose sensing techniques with POC biosensors. For patients with abnormalities of glucose metabolism, the incorporation of smartphone-integrated electronic readers into such devices or their enhancement using 3D printing technology shows significant potential. POC biosensors enable people to monitor their blood glucose levels precisely and conveniently without the assistance of expert staff or hospital visit.

The industry has a persistent interest in creating novel glucose sensing devices since there is an enormous need for quick, affordable, and accurate ways to test blood glucose levels. Glucose sensors can be based on different types of transducers such as thermal, optical, electrochemical, acoustic and magnetic. Biosensors can be classified into different groups based on their transducer. Among all of them, the widely investigated one is electrochemical platforms which are divided into two main categories: enzymatic and non-enzymatic (as depicted in **Figure 1**). The categorizing factor is the presence of an enzyme as the sensing material in the biosensor.
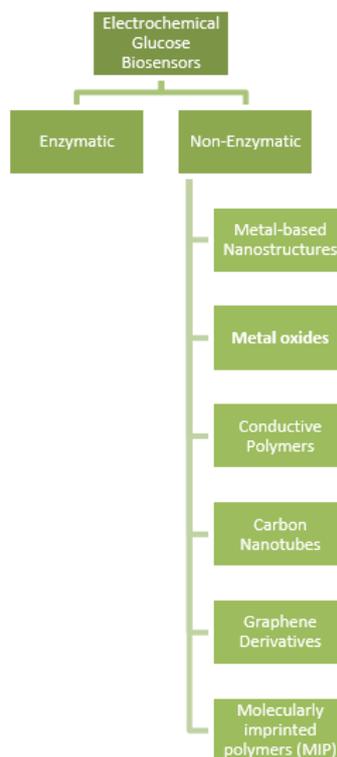

Figure 1. Different glucose biosensors based on their sensing material.

The enzymatic diabetes biosensors have an enzyme that plays a crucial role. A group of these biosensors is glucose oxidase (GOx) depended which uses GOx as the glucose-sensing enzyme. A thin layer of GOx is utilized over an oxygen anode in these electrochemical biosensors, where the oxygen is consumed by the enzyme-catalyzed response. The mechanism of GOx action leads to gluconic acid production (**Figure 2**). To execute this oxidation reaction by GOx, a redox co-factor is needed with the input of flavin adenine dinucleotide (FAD+) which is an electron acceptor. It can be reduced to $FADH_2$ by redox reactions. Subsequent reaction with oxygen that produces H_2O_2 regenerates the FAD+ at the anode, which can sense the number of transferring electrons that are correlated with the amount of H_2O_2 production and hence, the amount of glucose present [3].
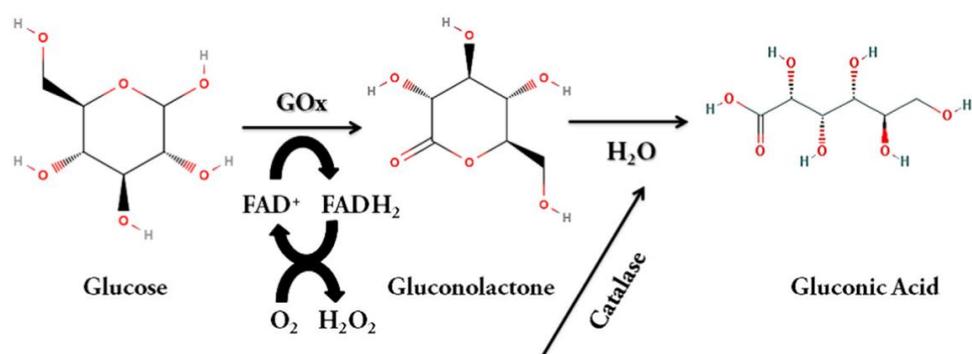
Figure 2. The transition of glucose to gluconic acid using glucose oxidase, reprinted with permission.

Recently, nanomaterials are introduced into enzymatic glucose sensors to enhance electron transfer rates. A wide range of nanomaterials can be used for this purpose, including the nanoparticles of noble and transition metals, the nanostructured metal-oxides or metal sulfides, conductive polymers, carbon nanotubes, and graphene. **Table 1** summarizes the enzymatic biosensors [4].

Table 1. A summary of the enzymatic biosensors for detecting diabetes.

Sensing material	Linear range	Detection limit	References
Ternary-graphene-PANI-TiO$_2$	4–24 mm	–	[5]
3D-NiO-hollow sphere/RGO	0.009–1.129 mm	0.082 nm	[6]
Graphene/MnO$_2$	0.04–2 mm	10 µm	[7]
CHI-Pd@Pt core-shell nanocubes	1–6 mm	0.2 µm	[8]
RGO-Fe$_3$O$_4$	0.05–1 mm	0.1 µm	[9]
PANI-poly (ethylene oxide) nanocomposite	4–6 mm	820 µm	[10]
MnO$_2$/graphene nanoribbons	0.1–1.4 mm	50 µm	[11]
ZnO-nanorods/graphene	0.2–1.6 mm	–	[12]
GO$_x$/RGO	0.01–1 mm	5.8 µm	[13]
GO$_x$/3D graphene film	< 6 mm	200 µm	[14]
MoS$_2$/graphene aerogel	2–20 mm	290 µm	[15]
Pt@ CNOs	2–28 mm	–	[16]
MWCNTs/CSF	0–5 mm	210 µm	[17]
GO$_x$/Au-ZnO/GCE	1–20 mm	20 µm	[18]
GO$_x$/Cu-MOFs	9.1×10^{-3}–36 mm	2.73 µm	[19]
GOx/CHI/GS/PB	8.17×10^{-3}–1 mm	2.45 µm	[20]
Au/NS on carbon fiber	8.17–1 mm	2.45 µm	[21]
CHI-GOx/APTES	0.01–50 mm	10 µm	[22]

PANI: polyaniline, RGO: reduced graphene oxide, CHI: chitosan, GO$_x$: glucose oxidase, MOF: metal-organic frameworks, CNOs: carbon nano-onions, CNT: carbon nanotubes, GCE: glassy carbon electrode, PB: prussian blue, GS: graphene sponge, NS: nanostructures, APTES: (3-Aminopropyl) triethoxysilane, dPIn: dPIn doped-polyindole, CSF: carbonized silk fabric.

2. Non-enzymatic nanobiosensors

Study on non-enzymatic biosensors as an alternative has started mainly due to the limited ranges of pH, temperature, and humidity conditions of the enzymatic

glucose sensors. Metal-based glucose sensors are the sensors using noble (e.g., Au, Pt) and transition (e.g., Ni, Cu) metals for glucose detection as they can facilitate electrocatalytic oxidation of glucose. The metals can be combined to form multi-metallic electrodes for better electrocatalytic performance because of their synergistic activity for glucose electro-oxidation. Nevertheless, the application of transition metal glucose sensors is not attractive enough due to the high cost of transition metals. These metals in oxide form can be a cost-effective alternative. To enhance their electronic conductivity, conductive support materials (e.g., Ni foam, Cu foam, 3D-KSCs) are combined with them. Another large group of non-enzymatic biosensors is a conductive polymer including glucose sensors. These polymers possess high electrical conductivity, as well as electron affinity and redox activity. Their electrocatalytic activity can be even improved by the introduction of metal or metal-oxide nanoparticles, CNTs, and graphene. Carbon nanotubes (CNTs) can be used for sensor applications. Their superior properties, for instance, high aspect ratio, large surface area, as well as remarkable optical and electronic properties, make them promising materials for glucose detection. Similarly, graphene has great properties to be used in electrochemical sensing applications. Besides, all the mentioned materials, molecularly imprinted polymers (MIP) are devised as artificial recognition elements that can recognize and bind target molecules specifically. Their functional monomer is polymerized within a template which is later removed. Glucose imprinted polymer can be utilized for sensor applications [23]. **Table 2** presents a comprehensive comparison between different materials used in electrochemical glucose sensors.

Table 2. A comprehensive overview of different sensing materials used in electrochemical glucose sensors [24–29].

Sensing material	Pros	Cons
Enzyme	Good selectivity Good sensitivity	Limited pH and temperature ranges Affected by humidity Deactivation by ionic detergents
Noble and transition metals	High stability High electrocatalytic activity	Poor sensitivity Poor selectivity High cost
Metal oxides	High stability Low cost	Poor conductivity Alkaline condition needed
Conductive polymers	Facile synthesis Low cost Adjustable properties	Challenging confinement on the electrode Low stability
Carbon nanotubes	High electrocatalytic activity High surface area High stability	Challenging separation process Degradation possibility of nanotubes
Graphene	Enhanced electrical conductivity Biocompatibility	Heterogeneity of samples
MIPs	Low cost Facile synthesis Robustness	Template removal stage

3. Noble and transition metals glucose nanobiosensors

Up to now, metal [13,30–32], metal-alloy [33–35], metal hydrate [36], metal sulfide [37,38], metal nitrides [39,40], and metal oxide [41–43] have been broadly applied as efficient nanostructures for their glucose oxidation ability in neutral and alkaline solutions. Amongst the various metals, Noble (e.g., Au, Pt, Pd) and transition metals (e.g., Ni, Cu, Co) are more commonly used for high-per-formance non-enzymatic glucose monitoring in the last decades. Nanostructured metallic materials with their exclusive physical, chemical, optical and electrical properties such as high surface-to-volume proportion, huge specific surface area, high electrical conductivity, tunable optical property, and high electrocatalytic activity have been widely used in the fabrication of glucose biosensors [44–46].

These metals can be regarded as good electrocatalysts as a result of their capability to be in numerous oxidation states. By absorbing other compounds on their surfaces and acting as catalysts with a high number of surface atoms, intermediates are formed and the reaction process is facilitated by enhancing mass transport property [47]. Since the physicochemical properties of metal nanostructures such as size, shape, architecture, and composition can be varied and controlled, they can be regarded as appealing choices for electrocatalytic glucose sensing [48]. To enhance the performance of detection, by investigating mass transport and electron transfer kinetics of metals, extensive attention has been paid to studying the electrocatalytic properties of metal nanostructures [49,50]. Based on the literature, most metallic nanomaterials used for non-enzymatic glucose sensing are noble metals (i.e., Au, Pd, and Pt) and their bimetallic nanostructures due to their high catalytic activity [51].

Despite the high sensitivity of noble metals towards glucose detection, surface fouling owing to the adsorption of intermediates has remained a challenging issue. Similarly, they do not have desired options for practical application due to their high costs because of inadequate supply. Considering cost-effectiveness, transition metals (such as Ni and Cu) and their bimetallic nano-structures (Cu/Ni) can be considered appropriate alternatives for non-enzymatic glucose sensors [40,52].

Moreover, the benefit of using transition metals instead of noble metals is the ability for oxidizing glucose at a constant potential and therefore simpler operation [53]. For the oxidation of glucose, Ni and Cu-based electrodes are com-monly applied in the alkaline solution. Actually, by electron transferring between multivalent metal redox couples, the oxidation reaction of glucose is catalyzed by the transition metals. By immersing these metal electrodes (M) in an alkaline solution, $M(OH)_2$ compounds are formed at first, furthermore by the further oxidation reaction, MOOH is formed. Consequently, $M(OH)_2$/ MOOH redox couple is the catalytic component in glucose detection [47]. Ni and Cu nanostructures have been used widely as glucose sensors in recent years.

As an alternative solution, to develop the catalytic effect of metallic nanoparticles, bimetal alloy structures were utilized as electrode constituents. They are a novel class of nanomaterials that may have better technological performance compared to individual ones. They are synthesized between one element with filled d-orbitals and the other metal having empty d-orbitals. Their properties could differ along with the

mixing pattern, in particular, their interfaces may play a pivotal role in controlling their behaviors [54].

Moreover, the applicability of these bimetallic nanostructures not only relies on their size and shape but also on the combination of the metals that participated (e.g., composition) and their fine structure. For instance, they can be formed by various hybrids of metals such as (noble/noble), (noble/transition), or both (transition/transition) metals [55,56].

Recently, considerable improvement has been reported on the fabrication of bimetallic nanostructures as electrochemical non-enzymatic glucose sensors owing to the synergistic effect of the two metals which can significantly enhance the electrocatalytic glucose oxidation reaction and minimize the interference and poisoning effect of the electrode [57]. **Table 3** summarized the non-enzymatic Noble and transition metals-based biosensors for detecting diabetes.

Table 3. A summary of the non-enzymatic Noble and transition metals-based biosensors for detecting diabetes.

Sensing material	Linear range	Limit of detection	References
Ni/Cu nanocomposites	4×10^{-3}–5 mm	0.1 µm	[58]
Nafion/Cu (II) GCE	5×10^{-4}–2 mm	0.1 µm	[59]
Pd NPs porous GaN	1×10^{-3}–1 mm	–	[60]
La-Sr-Co-Ni-O nanofibers	0.1–1 mm	83 µm	[61]
bimetallic Co/Zn MOF	0.01–5 mm	6.5 µm	[62]
CuO/ZnO-DSDSHN	500–100 mm	3.575×10^{-1} µm	[63]
Ni-doped SnO$_2$	5×10^{-3}–0.825 mm	0.084 µm	[64]
Cu NPs HNT/PANI	0.01–5 mm	0.27 µm	[65]
NiCo$_2$S$_4$ nanoflakes	0.01–0.25 mm	0.01 µm	[66]
Cu/LAG	0.05–1.5 mm	0.01 µm	[67]
Ni-Cu ANPs/RGO	1×10^{-5}–3×10^{-2} µm	0.005 µm	[68]
Bimetallic Co-Zn-MOFs	0.001–0.255 mm, 0.255–2.53 m	4.7 µm	[69]
MoS$_2$-AuPt	0.005–3 mm	33 µm	[70]
Cu-Co-MOFs/Ni foam	–	23 µm	[70]
Cu-RGO	0.10–12.5 mm	65 µm	[71]
Ni-Co-S/CN/GCE	0.001–0.330 mm, 0.330–4.53 mm	467 µm	[72]

GCE: glassy carbon electrode, NPs: nanoparticles, MOF: metal-organic frameworks, DSDSHN: dumbbell-shaped double-shelled hollow nanoporous, HNT/PANI: halloysite nanotube/polyaniline, LAG: laser-ablated graphene, ANPs/RGO: bimetallic alloy nanoparticles reduced graphene oxide, MoS$_2$-AuPt: gold platinum bimetallic nanoparticles modified molybdenum disulfide nanosheet.

4. Metal oxides

Metal oxides are crystalline solids that contain a metal cation and an oxide anion. These materials show vast varieties of applications as gas sensors, catalysts, solar cells, optoelectronic devices, environmental protectors, and biosensors. Metal oxides have unique functional properties that essentially stem from their crystal structure, composition, indigenous defects, doping, etc. These properties provide them with chemical, optical, mechanical, and electrical characteristics [73]. In recent decades, different materials based on metal oxides such as metal-doped metal oxides, carbon nanotubes nanocomposites of metal oxides, and polymer composites of metal oxides

have been explored broadly due to their cost-effectiveness and high sensitivity. These nanomaterials also show high selectivity when they are coupled with biorecognition molecules in analytical devices [74–77].

As mentioned, utilizing transition and noble metals, despite being desirable materials, has limitations for sensing glucose, because they are not cost-effective. On the other hand, these materials in their oxide form have gained much attention and are considered a good alternative due to the ease of access and low cost. Especially, among these materials, oxides of metal elements of groups 7 to 12 in the Periodic Table have shown excellent performance in non-enzymatic glucose sensing [54]. To enhance the electronic conductivity and obtain higher surface area as well as more active sites, metal oxides are combined with other materials such as Ni foam, Cu foam, and three-dimensional Kenaf stem-derived carbon (3D-KSCs) that act as supports while possessing conductive properties [23].

Concerning the non-enzymatic glucose sensing, in the presence of hydroxide ions, different metal oxides can perform effectively at different pH ranges. The surface of metal oxides is activated by strong hydroxide ions and this process then results in the oxidation of glucose [78–80]. In addition, possessing a wide band gap makes metal oxides promising materials for detecting glucose [81]. Metal oxide-based non-enzymatic biosensors are listed in **Table 4**.

Table 4. A summary of the non-enzymatic metal oxides-based biosensors for detecting diabetes.

Sensing material	Linear range	Limit of detection	References
Nanoporous CuO/ZnO	0.500–100 mm	358 nm	[63]
ZnO QDs on MWCNTs	10^{-5}–2.5×10^{-3} mm	208 nm	[82]
Laser-induced mesoporous NiO on Ni	0.005–1.1 mm	3.31 μm	[83]
NiO/Cu-TCPP	0.002–0.28 mm	0.95 μm	[84]
Co_3O_4 functionalized MoS_2-CNT	< 5.2 mm	0.08 μm	[85]
Ni-Co hydroxide nanosheets	0.002–0.8 mm	3.42 μm	[86]
PPy-CHI-Fe_2O_3	1–16 mm	234 μm	[87]
$NiMnO_3$	0.00005–1 mm	0.014 μm	[86]
CuO/NiO nanosheets	1.20–2.72 mm	0.0667 μm	[88]
MOF-CoO/CuO nanorod arrays	–	11.916 μa μm^{-1}	[89]
AuNPs-CuO NWs/Cu_2O	2.8×10^{-3}–2 mm	1.619 μm	[90]
TiO_2/Cu_2O/CuO CNFs	–	0.25 μm	[91]
CuO/NiO films	0.01–20 mm	1.86 μm	[92]

NF: nanofiber, QDs: quantum dots, MWCNTs: multi-walled carbon nanotube, TCPP: tetrakis (4 carboxyphenyl) porphrin, CNT: carbon nanotube, NWs: nanowires, CNFs: carbon nanofibers, CHI: chitosan, PPy: polypyrrole.
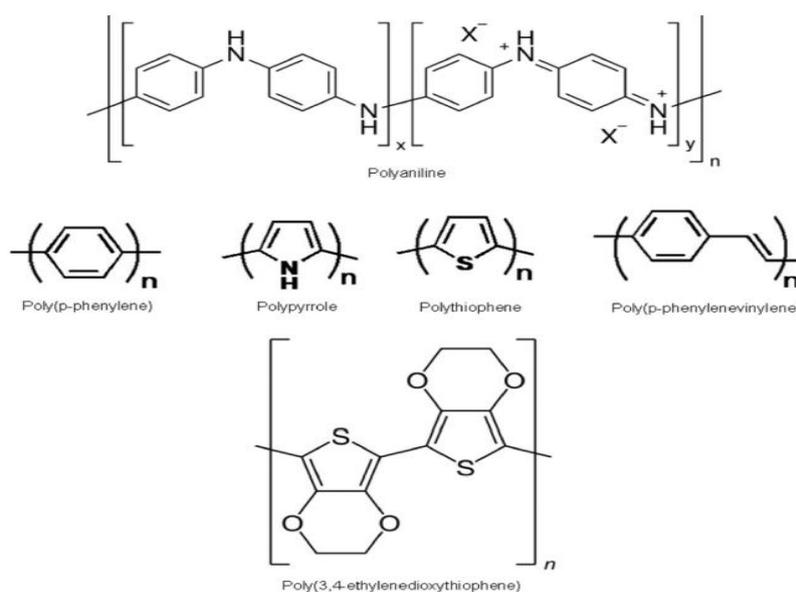
Figure 3. The chemical structures of typical conducting polymers.

5. Conductive polymers

By coupling the electronic properties of semiconductors with the properties of organic polymers, conducting polymers (CPs) emerged as novel compounds attracting great importance nowadays. Since the discovery of CPs in 1977 by Shirakawa et al. [93], they have been utilized in rechargeable batteries [94], membrane separation [95], electrocatalysis [96], solar cells [97], supper capacitors [98], optoelectronic [55] extraction [99] and electrochemical biosensors. In **Figure 3**, some of the most commonly used CPs such as polyaniline (PANI), polypyrrole, and polythiophene have been represented [47].

These are used extensively due to their characteristics such as being cheap, ease of processing, and also facilitating the immobilization procedure [100]. In this type of polymer, alternative single and double bonds exist in the polymer chain, forming p-electron backbones which cause the uncommon properties of CPs. High electrical conductivity, mechanical flexibility, surface areas, electron affinity, electrocatalytic properties, and chemical stability in aqueous solutions, as well as low energy transitions are among the unique properties of these structures [101]. On the other hand, the conductivity of the polymer is affected by the length of conjugation, total chain length, and charge transfer to adjacent molecules [102].

Due to the porous structure of CPs, they are capable of acting as beneficial substrates for the immobilization of nanoparticles. By incorporating nanoparticles into CPs, the conducting polymer-based nanocomposite materials are formed. Additionally, due to the charge transfer which is facilitated between the dispersed nanoparticles, considerable enhancement in the conductivity of the hybrid systems is obtained. The incorporation of nanoparticles into the CPs causes higher performance for both CP and NPs, leading to different physical properties of the hybrid compound compared with the polymer and nanoparticle constituents, separately. **Table 5** summarized recent reports based on the application of conducting polymer-based nanocomposites in non-enzymatic biosensors.

Table 5. A summary of the non-enzymatic conductive polymer-based biosensors for detecting diabetes.

Sensing material	Linear range	Limit of detection	References
Cu NPs/Graphene/PANI	0.5–15 mm	0.16 μm	[103]
Au NPs-PANI nanoarrays	1.026×10^{-3}–10 mm	3.08 μm	[104]
PPy/Co-decorated/2DMoS$_2$-AuNPs/GCE	10^{-7}–8×10^{-6} mm	8×10^{-5} μm	[105]
PPy/GQDs@PB	2×10^{-4}–5×10^{-2} mm	0.1 μm	[106]
NiO/CuO/PANI	2×10^{-4}–2.5×10^{-1} mm	2 μm	[107]
PANI/AuNPs	3×10^{-3}–2×10^{-1} mm	0.5 μm	[108]
PEDOT/IL	2×10^{-4}–3×10^{-2} mm	0.05 μm	[109]
NiNPs/PEDOT/RGO	10^{-3}–5.1 mm	0.8 μm	[110]
Ag-NPs-decorated PmAPNFs	0.1–8 mm	0.062 μm	[111]
CuO/PEDOT-MoS$_2$	3×10^{-2}–1.06 mm	0.046 μm	[112]
PPy@Cu(OH)$_2$NTs	1.78–6.53 mm	0.35 μm	[113]
Ni$_3$S$_2$ NW PEDOT-RGO HFs	1.5×10^{-2}–9.105 mm	0.48 μm	[114]
-NC-(CuS/NSC)	160–11.76 mm	2.72 μm	[115]
PAN/PANI/CuO	0.1–8 mm	0.062 μm	[111]

[*]PANI: polyaniline, PPy: polypyrrole, GQDs: graphene quantum dots, PB: prussian blue, PEDOT: 3,4-ethylenedioxythiophene, PmAPNFs: poly (m-aminophenol) nanofibers, NW: nano worm, RGOHFs: reduced graphene oxide hybrid films, NC: nanocomposite, ITO: indium-tin oxide, PAN: polyacrylonitrile, CHI: chitosan.

6. Carbon nanotubes

A carbon nanotube is an allotrope of carbon that resembles a tube of carbon atoms. Carbon nanotubes are extremely robust. Although it is hard to break them, they are still light. Large surface area, high aspect ratio, excellent thermal and chemical stability, and significant optical and electronic features, caused carbon nanotubes to be one of the most investigated materials [116].

Graphene is known as a single layer consisting of carbon atoms, forming a closely packed hexagonal lattice. Multiwalled carbon nanotubes (MWCNTs) consist of several layers of graphene which are concentrated around the smallest nanotube, while for the synthesis of single walled carbon nanotubes (SWCNTs) only one layer of graphene is needed, which then results in a cylindrical shape with a nanometer-sized diameter [117].

Carbon nanotubes are found in diverse applications as cost-effective materials. They are utilized in energy conversion and storage [118], water filters [119], thin-film electronics [120], and coatings [121]. Due to possessing a large surface area, these materials have shown great performance in pharmacy and medicine to adsorb or conjugate a wide range of medicinal and diagnostic substances [122].

Since CNTs have unique optical, electrical, and structural properties, they are appealing materials for applications such as drug delivery and biosensing [123]. They have efficient capabilities to be used in treating varieties of diseases. These materials also exhibit effective performance when they are utilized for monitoring blood levels as well as other chemical properties of the human body [124,125].

Electronic conductivity and high surface area make CNTs good candidates for detecting glucose electrochemically. It is reported that MWCNTs can act as efficient

support in the process of glucose detection [126]. Also, nanowires can be imported into these materials for amperometric glucose detection [127]. **Table 6** shows a summary of CNTs applications for non-enzy- matic glucose sensing.

Table 6. summarized the non-enzymatic CNT-based biosensors for detecting diabetes.

Sensing material	Linear range	Limit of detection	References
FTO-CNTs	0.07–0.7 mm	7×10^4 μm	[128]
PdSWCNTs-GCE	0.5–17 mm	200 ± 50 μm	[129]
GCE/CNT/MoS$_2$/Ni-NPs	0.05–0.65 mm	200 μm	[130]
CNT	10^{-3}–50×10^{-3} mm	1.708×10^{-6} μm	[131]
β-CD/SPCE/CNTs	10^{-6}–3×10^{-3} mm	5×10^{-4} μm	[132]
Pd-NPs-GNPs/MWCNTs/GCE	2.5×10^{-2}–10 mm, 10–100 mm	83.0 μm	[133]
Ag-NPs-MWCNT	10^{-6}–3.5×10^{-1} mm	3×10^{-4} μm	[126]
Ni(TPA)-MOF	2×10^{-2}–4.4 mm	4.6 μm	[134]
Cu-MWCNTs	< 7.5 mm	1.0 μm	[135]
CHI-(CuS/NSC)	1.6×10^{-1}–11.76 mm	2.72 μm	[115]
Au@Pt-NPs-MWCNTs	5×10^{-5}–0.1 mm	4.2×10^{-2} μm	[136]
Ni-Co-NPs-MWCNT	–	2.6×10^{-1} μm	[137]
QCM-CNT	0.5–120 mm	150 μm	[138]

CNT: carbon nanotubes, FTO: fluorine-doped tin oxide, SWCNTs: single-walled carbon nanotube, GCE: glassy carbon electrode, β-CD: β-cyclodextrin, SPCE: screen printed electrodes, MWCNTs: multi-walled carbon nanotube, (Ni (TPA)) nickel(II)-terephthalic acid MOF: metal-organic framework, QCM: quartz crystal microbalance, CHI: chitosan.

7. Graphene

Various nanoscale compounds such as metal nanowires, nanoparticles, carbon nanotubes, and graphene have been remarkably used as sensing materials in biosensors. Graphene particularly has attracted extensive attention after obtaining its single layer by mechanical exfoliation in 2004 [139]. Furthermore, extra information about the unexpected properties of graphene was discovered as the Nobel prize in 2010 [140]. Graphene is a single atomic layer of carbon atoms with sp^2 hybridization which is organized into a closely packed hexagonal lattice. The exclusive properties of graphene correspond to the pi orbitals of carbon atoms forming π bonds [141].

Graphene demonstrates special mechanical, electrical, thermal, and optical properties. Biocompatibility, high values of thermal conductivity, electron mobility, optical transmittance, and mechanical flexibility along with large specific surface area enable its application in electrochemical sensors [142]. Owing to the atomic thickness of graphene layers, carbon atoms presented in its structure could entirely interact with analytes. Graphene can be regarded as an ideal compound in electrode fabrication because of its high surface area, wide potential window, great flexibility in addition to its robustness, and lower resistance against charge transfer compared to carbon nanotube structures [143].

Apart from carbon nanotubes, graphene also shows high purity as a result of the absence of transition metals like Fe, Ni, etc. [144]. Using graphene in its fabricated or functionalized form (graphene incorporated with metal or metal oxide nanoparticles or conducting polymer such as chitosan) in the modification of the electrode improves the electrochemical performance and detection time of the electrode. The first

graphene-based glucose biosensor was constructed using graphene coupled with ionic liquid functionalized polyethyleneimine-modified electrodes. This biosensor displayed a wide linear range, high stability, and good reproducibility [145].

Additionally, as a result of the reduction of graphene oxide, reduced graphene oxide (RGO) is formed. Before the reduction step, the surface of graphene oxide is fabricated by oxygenated functional groups for instance carboxyl and epoxy groups. With the aid of Van der Waals interactions, these functional groups can affect the solubility of graphene oxide in solvents. The reaction rates are determined by the accessibility of unsaturated bonds presented on the surface of the graphene structure. Owing to the elimination of oxygenated functional groups, the surface of RGO have no free oxygen molecules, facilitating the participation of the surface in any surface activity. RGO can be considered a beneficial choice in electronic components, especially catalytic sensors. This is a result of the presence of oxygen-based functional groups and structural defects such as carbon vacancies.

Recently, extensive studies have been conducted to use nanocomposites in the fabrication of enzymatic or nonenzymatic electrodes for monitoring glucose. In this regard, an effective mixture of graphene with metal oxide nanopowder has been used as the substrate for glucose sensors. This is because of the exclusive properties of carbon atoms, such as conductivity toward heat, great surface area, biocompatibility, high possibility of functionalization, and inertness. Besides, graphene shows high mechanical properties in which sheets are considerably stronger than steel with a thickness of a million times smaller than human hair. In addition, another key property of graphene is its higher electrical conductivity causing a high rate of electron transfer and low resistance against charge transfer. Last but not least, herein, the incompatibility between graphene and metal oxide is not an issue [142].

In the case of metal oxide, excellent selectivity, large surface-to-volume ratio, and outstanding catalytic activities are the key advantages for applying them in non-enzymatic sensors. In this regard, the noble and transition metals and also their alloys are used as nanomaterials in combination with graphene. Nevertheless, the key issue with applying Nobel gases like platinum, gold, or palladium in sensor fabrication is their high prices, so they can be mixed with graphene to improve the efficiency of the sensor and decrease the operating costs. Furthermore, surface poisoning and surface fouling against chloride ions are two probable problems with noble metals, owing to the intermediates absorbed onto the electrode. As a consequence of the negative charge, hydrophilicity, and smooth surface of graphene, this downside of noble metals can be successfully compensated. Accordingly, hydrophilic and negatively charged interference are prevented from the surface of this fabricated sensor.

In contrast, transition metals are cost-effec-tive and present in different oxidation states, the latter means that with the aid of their unpaired d-electrons, they can form more than one ion (for example Fe^{2+} and Fe^{3+}). As a result, improvement of the rate of adsorption and desorption of the analyte on the electrode surface, much more current responses, and also a smaller amount of interferences (experienced by noble metals) are amongst the most remarkable advantages of transition metals [60]. For that reason, transition metals can be considered ideal preferences for sensor fabrication. With the aid of the high electrical conductivity of graphene in combination with Nano-metal oxides, a synergistic effect has been observed, and excellent results for the oxidation

of glucose acquired, compared to both of them individually [146,147]. On the other hand, it should be emphasized that the values of metal oxide used in the electrode fabrication, should be optimized precisely since these metal oxides can cause high resistance and inadequate surface-active sites for glucose oxidation. **Table 7** summarized recent reports on the application of graphene and also its various modification in non-enzymatic biosensors.

Table 7. A summary of the non-enzymatic graphene-based biosensors for detecting diabetes.

Sensing material	Linear range	Limit of detection	References
RGO-Au-CuO-NPs	10^{-3}–12 mm	0.01 μm	[148]
Nafion/Cu-NWs-MOFs-GO	2×10^{-2}–26.6 mm	7 μm	[149]
N-doped graphene	1.3×10^{-5}–14 mm	14.52 μm	[150]
Pt-NPs-MnO$_2$-RGO	2×10^{-3}–133 mm	1 μm	[151]
N-RGO-Mn$_3$O$_4$-NPs	10^{-3}–3.295×10^{-1} mm	0.5 μm	[152]
RGO-Pt-NiO	0.008–14.5 mm	2.67 μm	[153]
Ag-Pt-RGO	0.003–7.72 mm	1.8 μm	[154]
GO-MIP	10^{-7}–10^{-6} mm	10^{-3} μm	[155]
CuO nanoflakes/RGO	10^{-3}–2 mm	0.19 μm	[156]
Co/graphene/IL/SPCE	0.01–13 mm	0.67 μm	[157]
Co/Fe/N-doped graphene	0–32.5 mm	37.7 μm	[158]
PAN-RGO	7.5×10^{-1}–12 mm	600 μm	[159]
NiPcNRs-N-doped RGO	–	1.34 μm	[160]

RGO: reduced graphene oxide, NPs: nanoparticles, NWs: nanowires, MOF: metal-organic framework, GO: graphene oxide, MIP: molecularly imprinted polymers, IL: ionic liquid, SPCE: screen printed electrodes, PAN: polyacrylonitrile, NiPcNRs: nickel phthalocyanine nanorods.

8. MIPs

Molecularly imprinted polymers (MIPs) are a class of polymer materials that are produced by the polymerization of functional monomers and cross-linker molecules. Functional monomers are molecules possessing reactive groups in their structure. They are utilized for synthesizing macromonomers or improving the functionality and performance of polymer chains. These molecules are the major participants in the process of preparing MIPs, due to forming complexes with templates which results in the production of recognition sites in polymers. Cross-linkers are molecules having two or more reactive sites. These reactive sites can be functional groups like primary amines, sulfhydryls, etc. Cross-linkers are involved in a chemical reaction to link the polymer chains.

In the process of producing MIPs, a template which can be an atom or ion, a molecule, a complex, or a macromolecular assembly including micro-organisms, is present as a pure stereochemical compound. By removing the template, cavities are formed in the polymer matrix correlatively to the parent template molecules. MIPs are used as recognition elements to design sensor devices [161,162]. These low-cost materials possess unique properties. They have predictable structures and can specifically recognize the target. Plus, high physical stability, robustness, and ease of preparation are their significant features. Thereby, MIPs have been utilized in diverse applications such as chemical separation [163], selective extraction [164], molecular

sensing [165], drug delivery [166], and catalysis [167]. Compared to other biological receptors, they are more stable at high thermal conditions, and also have other superior properties such as reusability and selectivity.

There are two main methods for the production of MIPs; covalent and non-covalent imprinting. In the covalent imprinting approach, more amounts of cross-linkers are needed to produce an insoluble network with good rigidity. This approach reduces the probable interactions which are not desirable because it results in the production of polymers whose bonding groups are exactly located in the imprinted cavities. MIPs produced by this approach possess higher selectivity than the MIPs prepared by the non-covalent method. Also, it is reported that the distribution of their bonding sites is more homogeneous. Covalent imprinting suits the polymer for acting as a catalyst [168]. The disadvantages of covalent imprinting are the limitation in choosing a functional monomer and template, the need for synthesizing the template monomer before polymerization, and lower efficiency in recognizing target molecules [169].

In non-covalent imprinting, there is a non-covalent bond between the polymer network and the template, so the whole synthetic procedure is demonstrated to be easier. Simple extraction processes used in this approach to remove the template from the polymer network are another advantage of this method. The major disadvantage of non-covalent imprinting is the excess need for functional monomers which are necessary for binding with template molecules. As a result, lots of binding sites are formed while many of them are not needed [170]. MIPs can be utilized for sensor applications including non-enzymatic glucose sensing. In **Table 8**, some examples of MIP-based sensors for detecting glucose are listed.

Table 8. A summary of the non-enzymatic molecularly imprinted polymers-based biosensors for detecting diabetes.

Sensing material	Linear range	Limit of detection	References
EMMIPs	10^{-8}–10^{-6} mm	3×10^{-6} μm	[171]
MI-QCM	1.38×10^{-9}–1.72×10^{-6} mm	2.7×10^{-7} μm	[85]
Nano-MIP/SPPE	5×10^{-8}–2×10^{-6} mm	8.1×10^{-8} μm	[172]
MIP-cryogel/MWCNTs/Au	5×10^{-11}–1.40×10^{-9} mm	3.3×10^{-8} μm	[173]
MIP/nCD	5×10^{-6}–4×10^{-5}, 5×10^{-5}–6×10^{-4} mm	0.09 μm	[174]
GO-MIP	10^{-5}–6×10^{-3} mm	0.02 μm	[175]
MIP-coated microwave	8.32×10^{-11} mm	2.7×10^{3}–2.22×10^{-4} μm	[176]
MIP-Au-SPE	3.32×10^{-6} mm	24.15–2415 μm	[177]
MIP	19.4×10^{-6} mm	19.4–330 μm	[178]
MIP-PANI	1.0048×10^{-3} mm	2.2×10^{3}–1.11×10^{4} μm	[179]
PPy-MIP	1.25×10^{-8} mm	10^{-5}–10^{3} μm	[180]
MIP-CS/Co$_3$O$_4$	4.01×10^{-6} mm	12.17–2.3×10^{3} μm	[181]

EMMIPs: electromagnetic molecularly imprinted polymers, QCM: quartz crystal microbalance, NanoMIP: molecularly imprinted polymer nanoparticles, SPPE: screen printed platinum electrode, nCD: nano-carbon-dots, GO-MIP: graphene oxide, olecular imprinted polymer, SPE: screen printed electrode, PANI: polyaniline, PPy: poly-pyrrole, CHI: chitosan.

9. Conclusions

In this paper, the recent trends in enzymatic and non-enzymatic glucose sensor applications have been thoroughly reviewed and discussed. Among the different types of glucose sensors, enzymatic sensors have pH, temperature, and humidity limitations, however, they possess high sensitivity and specificity. So, non-enzymatic glucose sensors have been developed to cover their weaknesses. They function as the electrode material on which the glucose is oxidized. Recent efforts have been focused on exploiting different materials and fabrication processes for these electrodes, such as metal-based nanostructures, metal oxides, conductive polymers, carbon nano- tubes, graphene derivatives, and molecularly imprinted polymers.

Unique nanostructures and approaches have been created to modernize glucose sensors as a result of the recent rise in nanotechnology research. Metals or metal oxides with nanostructures provide a higher surface area for the oxidation of glucose. The utilization of carbon nanotubes and graphene has also attracted a lot of interest because the high conductivity of these materials boosts the electron transfer rate and hence enhances their sensitivity. The majority of nanotechnology research has been concentrated on the creation and integration of nanomaterials to enhance the performance of electrochemical glucose sensors. Before these approaches may be commercialized, there are still several obstacles to overcome with regard to their application to the human body. Due to their poor biocompatibility, high cost, and labor-intensive preparation procedures, the majority of glucose sensors based on novel materials have been restricted. Thus, the challenge of developing materials with high selectivity, low detection limit, a wide detection range, and quick response time still exists when attempting to prepare these sensors for continuous glucose measurement. Future research is expected to continue toward detecting infinitesimally small concentrations of glucose in forming sensors that are capable of being incorporated into small portable devices.

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References

1. Meuleneire F. Management of diabetic foot ulcers using dressings with safetac: A review of case studies. Wounds UK 2008; 4(4): 16–30.
2. Metkar SK, Girigoswami K. Diagnostic biosensors in medicine—A review. Biocatalysis and Agricultural Biotechnology 2019; 17: 271–283. doi: 10.1016/j.bcab.2018.11.029.
3. Lv Y, Jin S, Wang Y, et al. Recent advances in the application of nanomaterials in enzymatic glucose sensors. Journal of the Iranian Chemical Society 2016; 13: 1767–1776. doi: 10.1007/s13738-016-0894-y.
4. Martinkova P, Pohanka M. Biosensors for blood glucose and diabetes diagnosis: Evolution, construction, and current status. Analytical Letters 2015; 48(16): 2509–2532. doi: 10.1080/00032719.2015.1043661.
5. Kashmery HA, Inamuddin. Ternary graphene@polyaniline—TiO$_2$ composite for glucose biofuel cell anode application. International Journal of Hydrogen Energy 2019; 44(39): 22173–22180. doi: 10.1016/j.ijhydene.2019.06.153.
6. Huang W, Ding S, Chen Y, et al. 3D NiO hollow sphere/reduced graphene oxide composite for high-performance glucose biosensor. Scientific Reports 2017; 7(1): 5220. doi: 10.1038/s41598-017-05528-1.
7. Liu Y, Zhang X, He D, et al. An amperometric glucose biosensor based on a MnO$_2$/graphene composite modified electrode. RSC advances 2016; 6(22): 18654–18661. doi: 10.1039/C6RA02680J.
8. Krishnan SK, Prokhorov Y, Bahena D, et al. Chitosan-covered Pd@Pt core-shell nanocubes for direct electron transfer in electrochemical enzymatic glucose biosensor. ACS Omega 2017; 2(5): 1896–1904. doi: 10.1021/acsomega.7b00060.

9. Pakapongpan S, Poo-arporn RP. Self-assembly of glucose oxidase on reduced graphene oxide-magnetic nanoparticles nanocomposite-based direct electrochemistry for reagentless glucose biosensor. Materials Science and Engineering C 2017; 76: 398–405. doi: 10.1016/j.msec.2017.03.031.

10. Hansen B, Hocevar MA, Ferreira CA. A facile and simple polyaniline-poly (ethylene oxide) based glucose biosensor. Synthetic Metals 2016; 222: 224–231. doi: 10.1016/j.synthmet.2016.10.028.

11. Vukojević V, Djurdjic S, Ognjanovic M, et al. Enzymatic glucose biosensor based on manganese dioxide nanoparticles decorated on graphene nanoribbons. Journal of Electroanalytical Chemistry 2018; 823: 610–616. doi: 10.1016/j.jelechem.2018.07.013.

12. Zhao Y, Li W, Pan L, et al. ZnO-nanorods/graphene heterostructure: A direct electron transfer glucose biosensor. Scientific Reports 2016; 6(1): 32327. doi: 10.1038/srep32327.

13. Vijayaraj K, Hong S, Jin SH, et al. Fabrication of a novel disposable glucose biosensor using an electrochemically reduced graphene oxide-glucose oxidase biocomposite. Analytical Methods 2016; 8(38): 6974–6981. doi: 10.1039/c6ay02032a.

14. Mansouri N, Babadi AA, Bagheri S, et al. Immobilization of glucose oxidase on 3D graphene thin film: Novel glucose bioanalytical sensing platform. International Journal of Hydrogen Energy 2017; 42(2): 1337–1343. doi: 10.1016/j.ijhydene.2016.10.002.

15. Jeong JM, Yang MH, Kim DS, et al. High performance electrochemical glucose sensor based on three-dimensional MoS_2/graphene aerogel. Journal of Colloid and Interface Science 2017; 506: 379–385. doi: 10.1016/j.jcis.2017.07.061.

16. Mohapatra J, Ananthoju B, Nair V, et al. Enzymatic and non-enzymatic electrochemical glucose sensor based on carbon nano-onions. Applied Surface Science 2018; 442: 332–341. doi: 10.1016/j.apsusc.2018.02.124.

17. Chen C, Ran R, Yang Z, et al. An efficient flexible electrochemical glucose sensor based on carbon nanotubes/carbonized silk fabrics decorated with Pt microspheres. Sensors and Actuators B: Chemical 2018; 256: 63–70. doi: 10.1016./j.snb.2017.10.067.

18. Fang L, Liu B, Liu L, et al. Direct electrochemistry of glucose oxidase immobilized on Au nanoparticles—Functionalized 3D hierarchically ZnO nanostructures and its application to bioelectrochemical glucose sensor. Sensors and Actuators B: Chemical 2016; 222: 1096–1102. doi: 100.1016./J.SNB.2015.08.032.

19. He J, Yang H, Zhang Y, et al. Smart nanocomposites of Cu-hemin metal-organic frameworks for electrochemical glucose biosensing. Scientific Reports 2016; 6(1): 36637. doi: 10.1038/srep36637.

20. Li B, Wu X, Shi C, et al. Flexible enzymatic biosensor based on graphene sponge for glucose detection in human sweat. Surfaces and Interfaces 2023; 36: 102525. doi: 10.1016./j.surfin.2022.102525.

21. Bi R, Ma X, Miao K, et al. Enzymatic biosensor based on dendritic gold nanostructure and enzyme precipitation coating for glucose sensing and detection. Enzyme and Microbial Technology 2023; 162: 110132. doi: 10.1016/j.enzmictec.2022.110132.

22. Phasuksom K, Sirivat A. Chronoampermetric detection of enzymatic glucose sensor based on doped polyindole/MWCNT composites modified onto screen-printed carbon electrode as portable sensing device for diabetes. RSC Advances 2022; 12(44): 28505–28518. doi: 10.1039/D2RA04947C.

23. Sehit E, Altintas Z. Significance of nanomaterials in electrochemical glucose sensors: An updated review (2016–2020). Biosensors and Bioelectronics 2020; 159: 112165. doi: 10.1016/j.bios.2020.112165.

24. Park S, Boo H, Chung TD, et al. Electrochemical non-enzymatic glucose sensors. Analytica Chimica Acta 2006; 556(1): 46–57. doi: 10.1016/j.aca.2005.05.080.

25. Wilson R, Turner APF. Glucose oxidase: An ideal enzyme. Biosensors and Bioelectronics 1992; 7(3): 165–185. doi: 10.1016/0956-5663(92)87013-F.

26. Kim DM, Moon JM, Lee WC, et al. A potentiometric non-enzymatic glucose sensor using a molecularly imprinted layer bonded on a conducting polymer. Biosensors and Bioelectronics 2017; 91: 276–283. doi: 10.1016/j.bios.2016.12.046.

27. He G, Tian L, Cai Y. et al. Sensitive nonenzymatic electrochemical glucose detection based on hollow porous NiO. Nanoscale Research Letters 2018; 13: 1–10. doi: 10.1186/s11671-017-2406-0.

28. Chen C, Xie Q, Yang D, et al. Recent advances in electrochemical glucose biosensors: A review. Rsc Advances 2013; 3(14): 4473–4491. doi: 10.1039/C2RA22351A.

29. Nambiar S, Yeow JT. Conductive polymer-based sensors for biomedical applications. Biosensors and Bioelectronics 2011; 26(5): 1825–1832. doi: 10.1016/j.bios.2010.09.046.

30. Heli H, Amirizadeh O. Non-enzymatic glucose biosensor based on hyperbranched pine-like gold nanostructure. Marerials Science and Engineering: C 2016; 63: 150–154. doi: 10.1016/j.msec.2016.02.068.

31. Li C, Su Y, Lv X, et al. Controllable anchoring of gold nanoparticles to polypyrrole nanofibers by hydrogen bonding and their application in nonenzymatic glucose sensors. Biosensors and Bioelectronics 2012; 38(1): 402–406. doi: 10.1016/j.bios.2012.04.049.

32. Zhong G, Zhang W, Sun Y, et al. A nonenzymatic amperometric glucose sensor based on three dimensional nanostructure gold electrode. Sensors and Actuators B: Chemical 2015; 212: 72–77. doi: 10.1016/j.snb.2015.02.003.

33. Wang C, Ma D, Sun Y, et al. Ag-Pt hollow nanoparticles anchored reduced graphene oxide composites for non-enzymatic glucose biosensor. Journal of Materials Science: Materials in Electronics 2016; 27(9): 9370–9378. doi: 10.1007/s10854-016-4979-2.

34. Liu S, Zhang C, Yuan L, et al. Component-controlled synthesis of small-sized Pd-Ag bimetallic alloy nanocrystals and their application in a non-enzymatic glucose biosensor. Particle and Particle Systems Characterization 2013; 30(6): 549–556. doi: 10.1002/ppsc.201200150.

35. Liu P, Zhang M, Xie S, et al. Non-enzymatic glucose biosensor based on palladium-copper oxide nanocomposites synthesized via galvanic replacement reaction. Sensors and Actuators B: Chemical 2017; 253: 552–558. doi: 10.1016/j.snb.2017.07.010.

36. Xia C, Ning W. A novel non-enzymatic electrochemical glucose sensor modified with FeOOH nanowire. Electrochemistry Communications 2010; 12(11): 1581–1584. doi: 10.1016/j.elecom.2010.09.002.

37. Zhao C, Wu X, Zhang X, et al. Facile synthesis of layered CuS/RGO/CuS nanocomposite on Cu foam for ultrasensitive nonenzymatic detection of glucose. Journal of Electroanalytical Chemistry 2017; 785: 172–179. doi: 10.1016/j.jelechem.2016.12.039.

38. Sridhar V, Park H. Carbon encapsulated cobalt sulfide nano-particles anchored on reduced graphene oxide as high capacity anodes for sodium-ion batteries and glucose sensor. Journal of Alloys and Compounds 2018; 764: 490–497. doi: 10.1016/j.jallcom.2018.06.098.

39. Chen J, Yin H, Zhou J, et al. Hybrid Ni_3N-nitrogen-doped carbon microspheres ($Ni_3N@C$) in situ derived from Ni-MOFs as sensitive non-enzymatic glucose sensors. Materials Technology 2021; 36(5): 286–295. doi: 10.1080/10667857.2020.1751471.

40. Xie F, Cao X, Qu F, et al. Cobalt nitride nanowire array as an efficient electrochemical sensor for glucose and H_2O_2 detection. Sensors and Actuators B Chemical 2018; 255: 1254–1261. doi: 10.1016/j.snb.2017.08.098.

41. Li Y, Guan P, Yu F, et al. CeO_2 nanorods embedded in $Ni(OH)_2$ matrix for the non-enzymatic detection of glucose. Nanomaterials 2017; 7(8): 205. doi: 10.3390/nano7080205.

42. Chen H, Rim YS, Wang IC, et al. Quasi-two-dimensional metal oxide semiconductors based ultrasensitive potentiometric biosensors. ACS Nano 2017; 11(5): 4710–4718.

43. Dong Q, Song D, Huang Y, et al. High-temperature annealing enabled iridium oxide nanofibers for both non-enzymatic glucose and solid-state pH sensing. Electrochimica Acta 2018; 281: 117–126. doi: 10.1016/j.electacta.2018.04.205.

44. Huang Y, Kim JS. Synthesis and self-assembly of highly monodispersed quasispherical gold nanoparticles. Langmuir 2011; 27(22): 13861–13867. doi: 10.1021/la203143k.

45. Wei L, Fan Y, Wang H, et al. Electrochemically shape-controlled synthesis in deep eutectic solvents of Pt nanoflowers with enhanced activity for ethanol oxidation. Electrochimica Acta 2012; 76: 468–474. doi: 10.1016/j.electacta.2012.05.063.

46. Zeng J. A simple eco-friendly solution phase reduction method for the synthesis of polyhedra platinum nanoparticles with high catalytic activity for methanol electrooxidation. Journal of Material Chemistry 2012; 22(7): 3170–3176. doi: 10.1039/C1JM14413H.

47. Si P, Huang Y, Wang T, et al. Nanomaterials for electrochemical non-enzymatic glucose biosensors. RSC Advances 2013; 3(11): 3487–3502. doi: 10.1039/c2ra22360k.

48. Govindhan M, Adhikari BR, Chen A, et al. Nanomaterials-based electrochemical detection of chemical contaminants. RSC Advances 2014; 4(109): 63741–63760. doi: 10.1039/C4RA10399H.

49. Kimmel DW, LeBlanc G, Meschievitz ME, et al. Electrochemical sensors and biosensors. Analytical Chemistry 2012; 84(2): 685–707. doi: 10.1021/ac202878q.

50. Zhu C, Yang G, Li H, et al. Electrochemical sensors and biosensors based on nanomaterials and nanostructures. Analytical Chemistry 2015; 87(1): 230–249. doi: 10.1021/ac5039863.

51. Tee SY, Teng C, Ye E, et al. Metal nanostructures for non-enzymatic glucose sensing. Material Science and Engineering C 2017; 70: 1018–1030. doi: 10.1016/j.msec.2016.04.009.

52. Sun CL, Cheng W, Hsu TK, et al. Ultrasensitive and highly stable nonenzymatic glucose sensor by a CuO/graphene-modified screen-printed carbon electrode integrated with flow-injection analysis. Electrochemistry Communications 2013; 30: 91–94. doi: 10.1016/j.elecom.2013.02.015.

53. Liu H, Su X, Tian X, et al. Preparation and electrocatalytic performance of functionalized copper-based nanoparticles supported on the gold surface. Electroanalysis 2006; 18(21): 2055–2060. doi: 10.1002/elan.200603598.

54. Dong Q, Ryu H, Lei Y. Metal oxide based non-enzymatic electrochemical sensors for glucose detection. Electrochimica Acta 2021; 370: 137744. doi: 10.1016/j.electacta.2021.137744.

55. Xia Y, Sun K, Ouyang J. Solution-processed metallic conducting polymer films as transparent electrode of optoelectronic devices. Advanced Materials 2012; 24(18): 2436–2440. doi: 10.1002/adma.201104795.

56. Guisbiers G, Mejia-Rosales S, Khanal S, et al. Gold-copper nano-alloy, "tumbaga", in the era of nano: Phase diagram and segregation. Nano Letters 2014; 14(11): 6718–6726. doi: 10.1021/nl503584q.

57. Ferrando R, Jellinek J, Johnston RL. Nanoalloys: From theory to applications of alloy clusters and nanoparticles. Chemical Reviews 2008; 108(3): 845–910. doi: 10.1021/cr040090g.

58. Zhang M, Liu Y, Wang J, et al. Photodeposition of palladium nanoparticles on a porous gallium nitride electrode for nonenzymatic electrochemical sensing of glucose. Microchimica Acta 2019; 186 (2): 1–8. doi: 10.1007/s00604-018-3172-0.

59. Shamsipur M, Tabrizi MA, Karimi Z, et al. Highly sensitive non-enzymatic electrochemical glucose sensor by Nafion/SBA-15-Cu (II) modified glassy carbon electrode. Journal of Electroanalytical Chemistry 2017; 799: 406–412. doi: 10.1016/j.jelechem.2017.06.029.

60. Gong X, Gu Y, Zhang F, et al. High-performance non-enzymatic glucose sensors based on CoNiCu alloy nanotubes arrays prepared by electrodeposition. Frontiers in Materials 2019; 6: 3. doi: 10.3389/fmats.2019.00003.

61. Pelucarte KD, Hatchell TA, Georga G, et al. Electrospun porous La-Sr-Co-Ni-O nanofibers for highly sensitive non-enzymatic glucose detection. Matericals Advances 2022; 3(4): 2096–2103. doi: 10.1039/D1MA00984B.

62. Li X, Dong H, Fan Q, et al. One-pot, rapid microwave-assisted synthesis of bimetallic metal-organic framework for efficient enzyme-free glucose detection. Microchemical Journal 2022; 179: 107468. doi: 10.1016/j.microc.2022.107468.

63. Haghparas Z, Kordrostami Z, Sorouri M, et al. Highly sensitive non-enzymatic electrochemical glucose sensor based on dumbbell-shaped double-shelled hollow nanoporous CuO/ZnO microstructures. Scientific Reports 2021; 11(1): 1–12. doi: 10.1038/s41598-020-79460-2.

64. Chakraborty P, Deka N, Patra DC, et al. Salivary glucose sensing using highly sensitive and selective non-enzymatic porous NiO nanostructured electrodes. Surfaces and Interfaces 2021; 26: 101324. doi: 10.1016/j.surfin.2021.101324.

65. Luo Y, Liu W, Huang M, et al. Copper nanoparticles decorated halloysite nanotube/polyaniline composites for high performance non-enzymatic glucose sensor. Electrochemical Society 2021; 168(8): 086504. doi: 10.1149/1945-7111/ac1b4d.

66. Rabbani SS, Nisar A, Zafar A, et al. Mesoporous $NiCo_2S_4$ nanoflakes as an efficient and durable electrocatalyst for non-enzymatic detection of cholesterol. Nanotechnology 2022; 33(37): 375502. doi: 10.1088/1361-6528/ac75fb.

67. Yang D, Yin R, Gao Y, et al. Fabrication of Cu/graphene layer via laser direct writing for flexible non-enzymatic glucose electrode. In: Wei W, Yue Y (editors). Proceedings of International Conference on Biometrics, Microelectronic Sensors, and Artificial Intelligence (BMSAI); 2022 March 25–27; Guangzhou. Washington: SPIE; 2022. p. 85–90. doi: 10.1117/12.2640279.

68. Xu X, Tan R, Lv X, et al. Non-enzymatic electrochemical detection of glucose using Ni-Cu bimetallic alloy nanoparticles loaded on reduced graphene oxide through a one-step synthesis strategy. Analytical Methods 2021; 13(46): 5628–5637. doi: 10.1039/D1AY01357B.

69. Kachouei MA, Shahrokhian S, Ezzati M, et al. Bimetallic CoZn-MOFs easily derived from CoZn-LDHs, as a suitable platform in fabrication of a non-enzymatic electrochemical sensor for detecting glucose in human fluids. Sensors and Actuators B: Chemical 2021; 344: 130254. doi: 10.1016/j.snb.2021.130254.

70. Xiao H, Cao L, Qin H, et al. Non-enzymatic lactic acid sensor based on AuPtNPs functionalized MoS_2 nanosheet as electrode modified materials. Journal of Electroanalytical Chemistry 2021; 903: 115806. doi: 10.1016/j.jelechem.2021.115806.

71. Phetsang S, Kidkhunthod P, Chanlek N, et al. Copper/reduced graphene oxide film modified electrode for non-enzymatic glucose sensing application. Scientific Reports 2021; 11(1): 1–13. doi: 10.1038/s41598-021-88747-x.

72. Kachouei MA, Hekmat F, Wang H, et al. Direct decoration of carbon nanohorns with binary nickel-cobalt sulfide nanosheets towards non-enzymatic glucose sensing in human fluids. Electrochimica Acta 2022; 428: 140952. doi: 10.1016/jelectacta.2022.140952.

73. Grilli ML. Metal oxides. Metals 2020; 10(6): 820. doi: 10.3390/met10060820.

74. Liu A. Towards development of chemosensors and biosensors with metal-oxide-based nanowires or nanotubes. Biosensors and Bioelectronics 2008; 24(2): 167–177. doi: 10.1016/j.bios.2008.04.014.

75. Zhai T, Fang X, Liao M, et al. A comprehensive review of one-dimensional metal-oxide nanostructure photodetectors. Sensors 2009; 9(8): 6504–6529. doi: 10.3390/s90806504.

76. Huang J, Wan Q. Gas sensors based on semiconducting metal oxide one-dimensional nanostructures. Sensors 2009; 9(12): 9903–9924. doi: 10.3390/s912.9903.

77. Saleh Ahammad A, Lee JJ, Rahman MA, et al. Electrochemical sensors based on carbon nanotubes. Sensors 2009; 9(4): 2289–2319. doi: 10.3390/s904022898.

78. Ding Y, Wang Y, Su L, et al. Electrospun Co_3O_4 nanofibers for sensitive and selective glucose detection. Biosensors and Bioelectronics 2010; 26(2): 542–548. doi: 10.1016/j.bios.2010.07.050.

79. Li C, Su Li, Zhang S, et al. An improved sensitivity nonenzymatic glucose biosensor based on a Cu_xO modified electrode. Biosensors and Bioelectronics 2010; 26(2): 903–907. doi: 10.1016/j.bios.2010.07.007.

80. Wang J, Xu L, Lu Y, et al. Engineered IrO_2@NiO core-shell nanowires for sensitive non-enzymatic detection of trace glucose in saliva. Analytical Chemistry 2016; 88(24): 12346–12353. doi: 10.1021/acs.anaichem.6b03558.

81. Wang X, Zhao M, Li H, et al. Introducing Schottky interface as a novel strategy for ultrasensitive nonenzymatic glucose detection. Journal of Electroanalytical Chemistry 2017; 801: 251–257. doi: 10.1016/j.jelechem.2017.07.026.

82. Vinoth V, Subramaniyam G, Anandan S, et al. Non-enzymatic glucose sensor and photocurrent performance of zinc oxide quantum dots supported multi-walled carbon nanotubes. Materials Science and Engineering: B 2021; 265: 115036. doi: 10.1016/j.mseb.2020.115036.

83. Sedaghat S, Piepenburg C, Qi Z, et al. Laser-induced mesoporous nickel oxide as a highly sensitive nonenzymatic glucose sensor. ACS Applied Nano Materials 2020; 3(6): 5260–5270. doi: 10.1021/acsanm.0c00659.

84. Li S, Bai W, Zhang X, et al. NiO/Cu-TCPP hybrid nanosheets as an efficient substrate for supercapacitor and sensing applications. Journal of The Electrochemical Society 2020; 167(2): 027534. doi: 10.1149/1945-7111/ab6d4c.

85. Maghsoudi S, Mohammadi A. Reduced graphene oxide nanosheets decorated with cobalt oxide nanoparticles: A nonenzymatic electrochemical approach for glucose detection. Synthetic Metals 2020; 269: 116543. doi: 10.1016/j.synthmet.2020.116543.

86. Balasubramanian P, Annalakshmi M, Chen S, Chen TW. Ultrasensitive non-enzymatic electrochemical sensing of glucose in noninvasive samples using interconnected nanosheets-like $NiMnO_3$ as a promising electrocatalyst. Sensors and Actuators B: Chemical 2019; 299: 126974. doi: 10.1016/j.snb.2019.126974.

87. Al-Mokaram AMAAA, Yahya R, Abdi MM. One-step electrochemical deposition of Polypyrrole-Chitosan-Iron oxide nanocomposite films for non-enzymatic glucose biosensor. Materials Letters 2016; 183: 90–93. doi: 10.1016/j.matlet.2016.07.049.

88. Zhang L, Ye C, Li X, et al. A CuNi/C nanosheet array based on a metal-organic framework derivate as a supersensitive non-enzymatic glucose sensor. Nano-Micro Letters 2018; 10: 1–10. doi: 10.1007/s40820-017-0178-9.

89. Wei C, Li X, Xiang W, et al. MOF derived seaweed-like CoCu oxides nanorod arrays for electrochemical non-enzymatic glucose sensing with ultrahigh sensitivity. Sensors and Actuators B: Chemical 2020; 324: 128773. doi: 10.1016/j.snb.2020.128773.

90. Zhao Z, Li Q, Sun Y, et al. Highly sensitive and portable electrochemical detection system based on AuNPs@CuO NWs/Cu_2O/CF hierarchical nanostructures for enzymeless glucose sensing. Sensors and Actuators B: Chemical 2021; 345: 130379. doi: 10.1016/j.snb.2021.130379.

91. Hou S, Lu N, Zhu Y, et al. Photoinduced phase-transition on CuO electrospun nanofibers over the TiO_2 photosensitizer for enhancing non-enzymatic glucose-sensing performance. Journal of Alloys and Compounds 2022; 900: 163409. doi: 10.1016/j.jallcom.2021.163409.

92. Barbee B, Muchharla B, Adedeji A, et al. Cu and Ni co-sputtered heteroatomic thin film for enhanced nonenzymatic glucose detection. Scientific Reports 2022; 12(1): 7507. doi: 10.1038/s41598-022-11563-4.

93. Liu A, Liu E, Yang G, et al. Non-enzymatic glucose detection using nitrogen-doped diamond-like carbon electrodes modified with gold nanoclusters. Pure and Applied Chemistry 2010; 82(11): 2217–2229. doi: 10.1351/PAC-CON-09-11-11.

94. Guerfi A, Trottier J, Boyano I, et al. High cycling stability of zinc-anode/conducting polymer rechargeable battery with non-aqueous electrolyte. Journal of Power Sources 2014; 248: 1099–1104. doi: 10.1016/j.jpowsour.2013.09.082.

95. Halali MA. Electrically conductive membranes for water and wastewater treatment: Their surface properties, antifouling mechanisms, and applications [PhD thesis]. Hamilton: McMaster University; 2021.

96. Dutta K, Das S, Rana D, et al. Enhancements of catalyst distribution and functioning upon utilization of conducting polymers as supporting matrices in DMFCs: A review. Polymer Reviews 2015; 55(1): 1–56. doi: 10.1080/15583724.2014.958771.

97. Saranya K, Rameez M, Subramania A. Developments in conducting polymer based counter electrodes for dye-sensitized solar cells—An overview. European Polymer Journal 2015; 66: 207–227. doi: 10.1016/j.eurpolymj.2015.01.049.

98. Naseri M, Fotouhi L, Ehsani A, et al. Novel electroactive nanocomposite of POAP for highly efficient energy storage and electrocatalyst: Electrosynthesis and electrochemical performance. Journal of Colloid and Interface Science 2016; 484: 308–313. doi: 10.1016/j.jcis.2016.08.071.

99. Bagheri H, Ayazi Z, Naderi M. Conductive polymer-based microextraction methods: A review. Analytica Chimica Acta 2013; 767: 1–13. doi: 10.1016/j.aca.2012.12.013.

100. Prehn R, Cortina-Puig M, Muñoz FX. A non-enzymatic glucose sensor based on the use of gold micropillar array electrodes. Journal of The Electrochemical Society 2012; 159(5): F134. doi: 10.1149/2.018206jes.

101. Li T, Zhu K, He S, et al. Sensitive detection of glucose based on gold nanoparticles assisted silver mirror reaction. Analyst 2011; 136(14): 2893–2896. doi: 10.1039/C1AN15256D.

102. Kyomihumbo HD, Feleni U. Electroconductive green metal-polyaniline nanocomposites: Synthesis and application in sensors. Electroanalysis 2022; 35(2): e202100636. doi: 10.1002/elan.202100636.

103. Gopalan AI, Muthuchamy N, Komathi S, et al. A novel multicomponent redox polymer nanobead based high performance non-enzymatic glucose sensor. Biosensors and Bioelectronics 2016; 84: 53–63. doi: 10.1016/j.bios.2015.10.079.

104. Xu M, Song Y, Ye Y, et al. A novel flexible electrochemical glucose sensor based on gold nanoparticles/polyaniline arrays/carbon cloth electrode. Sensors and Actuators B: Chemical 2017; 252: 1187–1193. doi: 10.1016/j.snb.2017.07.147.

105. Ma K, Sinha A, Dang X, et al. Electrochemical preparation of gold nanoparticles-polypyrrole co-decorated 2D MoS_2 nanocomposite sensor for sensitive detection of glucose. Journal of The Electrochemical Society 2019; 166(2): B147. doi: 10.1149/2.1231902jes.

106. Wang L, Tricard S, Yue P, et al. Polypyrrole and graphene quantum dots@Prussian Blue hybrid film on graphite felt electrodes: Application for amperometric determination of l-cysteine. Biosensors and Bioelectronics 2016; 77: 1112–1118. doi: 10.1016/j.bios.2015.10.088.

107. Miao Z, Wang P, Zhong A, et al. Development of a glucose biosensor based on electrodeposited gold nanoparticles-polyvinylpyrrolidone-polyan- iline nanocomposites. Journal of Electroanalytical Chemistry 2015; 756: 153–160. doi: 10.1016/j.jelechem.2015.08.025.

108. Ghanbari K, Babaei Z. Fabrication and characterization of non-enzymatic glucose sensor based on ternary NiO/CuO/polyaniline nanocomposite. Analytical Biochemistry 2016; 498: 37–46. doi: 10.1016/j.ab.2016.01.006.

109. Sheng G, Xu G, Xu S, et al. Cost-effective preparation and sensing application of conducting polymer PEDOT/ionic liquid nanocomposite with excellent electrochemical properties. RSC Advances 2015; 5(27): 20741–20746. doi: 10.1039/C4RA15755A.

110. Hui N, Wang S, Xie H, et al. Nickel nanoparticles modified conducting polymer composite of reduced graphene oxide doped poly (3, 4-ethylenedioxythiophene) for enhanced nonenzymatic glucose sensing. Sensors and Actuators B: Chemical 2015; 221: 606–613. doi: 10.1016/j.snb.2015.07.011.

111. Ahmad MW, Verma SK, Yang DJ, et al. Synthesis of silver nanoparticles-decorated poly (m-aminophenol) nanofibers and their application in a non-enzymatic glucose biosensor. Journal of Macromolecular Science, Part A Pure and Applied Chemistry 2021; 58(7): 461–471. doi: 10601325.2021.1886585.

112. Medhi A, Mohanta D. Deciphering highly sensitive non-enzymatic glucose sensor based on nanoscale CuO/PEDOT-MoS_2 electrodes in chronoamperometry. ESC Advances 2022; 1(4): 046504. doi: 10.1149/2754-2734/ac9324.

113. Manafi-Yeldaghermani R, Shahrokhian S, Kahnamouei MH. Facile preparation of a highly sensitive non-enzymatic glucose sensor based on the composite of $Cu(OH)_2$ nanotubes arrays and conductive polypyrrole. Microchemical Journal 2021; 169: 106636. doi: 10.1016/j.microc.2021.106636.

114. Meng A, Hong X, Zhang H, et al. Nickel sulfide nanoworm network architecture as a binder-free high-performance non-enzymatic glucose sensor. Microchica Acta 2021; 188(2): 1–9. doi: 10.1007/s00604-020-04665-1.

115. Sharma KP, Shin M, Awasthi GP, et al. Chitosan polymer matrix-derived nanocomposite (CuS/NSC) for non-enzymatic electrochemical glucose sensor. International Journal of Biological Macromolecules 2022; 206: 708–717. doi: 10.1016/j.ijbiomac.2022.02.142.

116. Pirzada M, Altintas Z. Nanomaterials for healthcare biosensing applications. Sensors 2019; 19(23): 5311. doi: 10.3390/s19235311.

117. Jain N, Gupta E, Kanu NJ, et al. Plethora of carbon nanotubes applications in various fields—A state-of-the-art-review. Smart Science 2022; 10(1): 1–24. doi: 10.1080/23080477.2021.0940752.

118. Kumar S, Nehra M, Kedia D, et al. Carbon nanotubes: A potential material for energy conversion and storage. Progress in Energy and Combustion Science 2018; 64: 219–253. doi: 10.1016/j.pecs.2017.10.005.

119. Liu X, Zhang S, Pan B, et al. Potential of carbon nanotubes in water treatment. Recent Progress in Carbon Nanotube Research 2012; 201110(5772): 51332. doi: 10.5772/51332.

120. Si J, Xu L, Zhu M, et al. Advances in high-performance carbon-nanotube thin-film electronics. Advanced Electronic Materials 2019; 5(8): 1900122. doi: 10.1002/aelm.201900122.

121. De Volder MFL, Tawfick SH, Baughman RH, et al. Carbon nanotubes: Present and future commercial applications. Science 2013; 339(6119): 535–539. doi: 10.1126/science.1222453.

122. He H, Pham-Huy LA, Dramou P, et al. Carbon nanotubes: Applications in pharmacy and medicine. BioMed Research International 2013; 2013. doi: 10.1155/2013/578290.

123. Sireesha M, Jagadeesh BV, Kranthi Kiran AS, et al. A review on carbon nanotubes in biosensor devices and their applications in medicine. Nanocomposites 2018; 4(2): 36–57. doi: 10.1080/20550324.2018.1478765.

124. Li G, Liao JM, Hu GQ, et al. Study of carbon nanotube modified biosensor for monitoring total cholesterol in blood. Biosensors and Bioelectronics 2005; 20(10): 2140–2144. doi: 10.1016/j.bios.2004.09.005.

125. Rasheed T, Hassan AA, Kausar F, et al. Carbon nanotubes assisted analytical detection—Sensing/delivery cues for environmental and biomedical monitoring. TrAC Trends in Analytical Chemistry 2020; 132: 116066. doi: 10.1016/J.TRAC.2020.116066.

126. Baghayeri M, Amiri A, Farhadi S. Development of non-enzymatic glucose sensor based on efficient loading Ag nanoparticles on functionalized carbon nanotubes. Sensors and Actuators B: Chemical 2016; 225: 354–362. doi: 10.1016/j.snb.2015.11.003.

127. Ramachandran K, Babu K, Raj Kumar T, et al. Ni-Co bimetal nanowires filled multiwalled carbon nanotubes for the highly sensitive and selective non-enzymatic glucose sensor applications. Scientific Reports 2016; 6(1): 1–12. doi: 10.1016/j.snb.2015.11.003.

128. Lin MH, Gupta S, Chang C, et al. Carbon nanotubes/polyethylenimine/glucose oxidase as a non-invasive electrochemical biosensor performs high sensitivity for detecting glucose in saliva. Microchemical Journal 2022; 180: 107547. doi: 10.1016/j.microc.2022.107547.

129. Meng L, Jin J, Yang G, et al. Nonenzymatic electrochemical detection of glucose based on palladium-single-walled carbon nanotube hybrid nanostructures. Analytical Chemistry 2009; 81(17): 7271–7280. doi: 10.1021/ac901005p.

130. Fall B, Sall DD, Hémadi M, et al. Highly efficient non-enzymatic electrochemical glucose sensor based on carbon nanotubes functionalized by molybdenum disulfide and decorated with nickel nanoparticles (GCE/CNT/MoS$_2$/NiNPs). Sensors and Actuators Reports 2023; 5: 100136. doi: 10.1016/j.snr.2022.100136.

131. Yang J, Lee H, Cho M, et al. Nonenzymatic cholesterol sensor based on spontaneous deposition of platinum nanoparticles on layer-by-layer assembled CNT thin film. Sensors and Actuators B: Chemical 2012; 171: 374–379. doi: 10.1016/j.snb.20212.04.070.

132. Nawaz MAH, Majdinasab M, Latif U, et al. Development of a disposable electrochemical sensor for detection of cholesterol using differential pulse voltammetry. Journal of Pharmaceutical and Biomedical Analysis 2018; 159: 398–405. doi: 10.1016/j.jpba.2018.07.005.

133. Promsuwan K, Kachatong N, Limbut W. Simple flow injection system for non-enzymatic glucose sensing based on an electrode modified with palladium nanoparticles-graphene nanoplatelets/mullti-walled carbon nanotubes. Electrochimica Acta 2019; 320: 134621. doi: 10.1016/j.electacta.2019.134621.

134. Wang F, Chen X, Chen L, et al. High-performance non-enzymatic glucose sensor by hierarchical flower-like nickel(II)-based MOF/carbon nanotubes composite. Materials Science and Engineering: C 2019; 96: 41–50. doi: 10.1016./j.msec.2018.11.004.

135. Yang J, Zhang W, Gunasekaran S. An amperometric non-enzymatic glucose sensor by electrodepositing copper nanocubes onto vertically well-aligned multi-walled carbon nanotube arrays. Biosensors and Bioelectronics 2010; 26(1): 279–284. doi: 10.1016/j.bios.2010.06.014.

136. Wang R, Liu X, Zhao Y, et al. Novel electrochemical non-enzymatic glucose sensor based on 3D Au@Pt core-shell nanoparticles decorated graphene oxide/multi-walled carbon nanotubes composite. Microchemical Journal 2022; 174: 107061. doi: 10.1016/j.microc.2021.107061.

137. Arikan K, Burhan H, Bayat R, et al. Glucose nano biosensor with non-enzymatic excellent sensitivity prepared with nickel-cobalt nanocomposites on f-MWCNT. Chemosphere 2022; 291: 132720. doi: 10.1016/j.chemosphere.2021.132720.

138. Liu N, Xiang X, Sun M, et al. Flexible hydrogel non-enzymatic QCM sensor for continuous glucose monitoring. Biosensors and Bioelectronics: X 2022; 10: 100110. doi: 10.1016/j.biosx.2022.100110.

139. Xu B, Huang J, Ding L, et al. Graphene oxide-functionalized long period fiber grating for ultrafast label-free glucose biosensor. Materials Science and Engineering: C 2020; 107: 110329. doi: 10.1016/j.msec.2019.110329.

140. Geim AK. Graphene: Status and prospects. Science 2009; 324(5934): 1530–1534. doi: 10.1126/science.1158877.

141. Allen MJ, Tung VC, Kaner RB. Honeycomb carbon: A review of graphene. Chemical Reviews 2010; 110(1): 132–145. doi: 10.1021/cr900070d.

142. Panda P, Pal K, Chakroborty S. Smart advancements of key challenges in graphene-assembly glucose sensor technologies: A mini review. Materials Letters 2021; 303: 130508. doi: 10.1016/j.matlet.2021.130508.

143. Reghunath devi K, Singh KK. Recent advances in graphene based electrochemical glucose sensor. Nano-Structures & Nano-Objects 2021; 26: 100750. doi: 10.1016/j.nanoso.2021.100750.

144. Banks CE, Crossley A, Salter C, et al. Carbon nanotubes contain metal impurities which are responsible for the "electrocatalysis" seen at some nanotube-modified electrodes. Angewandte Chemie International Edition 2006; 45(16): 2533–2537. doi: 10.1002/anie.200600033.

145. Alwarappan S, Liu C, Kumar A, Li CZ. Enzyme-doped graphene nanosheets for enhanced glucose biosensing. Analytical Chemistry 2010; 114(30): 12920–12924. doi: 10.1021/jp103273z.

146. Fu X, Chen Z, Shen S, et al. Highly sensitive nonenzymatic glucose sensor based on reduced graphene oxide/ultrasmall Pt nanowire nanocomposites. International Journal of Electrochemical Science 2018; 13(5): 4817–4826. doi: 10.20964/2018.05.46.

147. Batool R, Rhouati A, Nawaz MH, et al. A review of the construction of nano-hybrids for electrochemical biosensing of glucose. Biosensors 2019; 9(1): 46. doi: 10.3390/bios9010046.

148. Dhara K, Ramachandran T, Nair BG, Babu TGS. Single step synthesis of Au-CuO nanoparticles decorated reduced graphene oxide for high performance disposable nonenzymatic glucose sensor. Journal of Electroanalytical Chemistry 2015; 743: 1–9. doi: 10.1016/j.jelechem.2015.02.005.

149. Zang Z, Hao W, Li X, et al. Copper nanowires-MOFs-graphene oxide hybrid nanocomposite targeting glucose electro-oxidation in neutral medium. Electrochimica Acta 2018; 277: 176–184. doi: 10.1016/j.electacta.2018.05.016.

150. Rahsepar M, Foroughi F, Kim H. A new enzyme-free biosensor based on nitrogen-doped graphene with high sensing performance for electrochemical detection of glucose at biological pH value. Sensors and Actuators B: Chemical 2019; 282: 322–330. doi: 10.1016/j.snb.2018.11.078.

151. Xiao F, Li Y, Zan X, et al. Growth of metal-metal oxide nanostructures on freestanding graphene paper for flexible biosensors. Advanced Functional Materials 2012; 22(12): 2487–2494. doi: 10.1002/adfm.201200191.

152. Yang S, Liu L, Wang G, et al. One-pot synthesis of Mn_3O_4 nanoparticles decorated with nitrogen-doped reduced graphene oxide for sensitive nonenzymatic glucose sensing. Journal of Electroanalytical Chemistry 2015; 755: 15–21. doi: 10.1016/j.jelechem.2015.07.021.

153. Wang L, Lu X, Wen C, et al. One-step synthesis of Pt-NiO nanoplate array/reduced graphene oxide nanocomposites for nonenzymatic glucose sensing. Journal of Materials Chemistry A 2015; 3(2): 608–616. doi: 10.1039/C4TA04724A.

154. Lakshmi G, Sharma A, Solanki PR, Avasthi DK. Mesoporous polyaniline nanofiber decorated graphene micro-flowers for enzyme-less cholesterol biosensors. Nanotechnology 2016; 27(34): 345101. doi: 10.1088/0957-4484/27/34/345101.

155. Alexander S, Baraneedharan P, Balasubrahmanyan S, Ramaprabhu S. Modified graphene based molecular imprinted polymer for electrochemical non-enzymatic cholesterol biosensor. European Polymer Journal 2017; 86: 106–116. doi: 10.1016/j.eurpolymj.2016.11.024.

156. Yan X, Gu Y, Li C, et al. A non-enzymatic glucose sensor based on the CuS nanoflakes-reduced graphene oxide nanocomposite. Analytical Methods 2018; 10(3): 381–388. doi: 10.1039/C7AY02290E.

157. Chaiyo S, Mehmeti E, Siangproh W, et al. Non-enzymatic electrochemical detection of glucose with a disposable paper-based sensor using a cobalt phthalocyanine-ionic liquid-graphene composite. Biosensors and Bioelectronics 2018; 102: 113–120. doi: 10.1016/j.bios.2017.11.015.

158. Janyasupab M, Promptmas C. Development of non-enzymatic N-doped graphene supported cobalt/iron amperometric based sensor for glucose detection in urine. In: Proceedig of the 2018 IEEE–EMBS Conference on Biomedical Engineering and Sciences (IECBES); 2018 Dec 3–6; Sarawak. New York: IEEE; 2019.

159. Karakuş S, Taşaltın C, Gürol İ, et al. Design of the polyacrylonitrile-reduced graphene oxide nanocomposite-based non-enzymatic electrochemical biosensor for glucose detection. Journal of Materials Science: Materials in Electronics 2022; 33(23): 18400–18409. doi: 10.1007/s10854-022-08694-9.

160. Adeniyi O, Nwahara N, Mwanza D, et al. High-performance non-enzymatic glucose sensing on nanocomposite electrocatalysts of nickel phthalocyanine nanorods and nitrogen doped-reduced graphene oxide nanosheets. Applied Surface Science 2022; 609: 155234. doi: 10.1016/j.apsusc.2022.155234.

161. Altintas Z, Takiden A, Utesch T, et al. Integrated approaches toward high-affinity artificial protein binders obtained via computationally simulated epitopes for protein recognition. Advanced Functional Materials 2019; 29(15): 1807332. doi: 10.1002/adfm.201807332.

162. Waffo AFT, Yesildag C, Caserta G, et al. Fully electrochemical MIP sensor for artemisinin. Sensors and Actuators B: Chemical 2018; 275: 163–173. doi: 10.1016/j.snb.2018.08.018.

163. Cheong WJ, Yang SH, Ali F. Molecular imprinted polymers for separation science: A review of reviews. Journal of Separation Science 2013; 36(3): 609–628. doi: 10.1002/jssc.201200784.

164. Beltran A, Borrull F, Marcé RM, Cormack PAG. Molecularly-imprinted polymers: Useful sorbents for selective extractions. TrAC Trends in Analytical Chemistry 2010; 29(11): 1363–1375. doi: 10.1016/j.trac.2010.07.020.

165. Schirhagl R. Bioapplications for molecularly imprinted polymers. Analytical Chemistry 2014; 86(1): 250–261. doi: 10.1021/ac401251j.

166. He S, Zhang L, Bai S, et al. Advances of molecularly imprinted polymers (MIP) and the application in drug delivery. European Polymer Journal 2021; 143: 110179. doi: 10.1016/j.eurpolymj.2020.110179.

167. Ramström O, Mosbach K. Synthesis and catalysis by molecularly imprinted materials. Current Opinion in Chemical Biology 1999; 3(6): 759–764. doi: 10.1016/S1367-5931(99)00037-X.

168. Haupt K, Mosbach K. Molecularly imprinted polymers and their use in biomimetic sensors. Chemical Reviews 2000; 100(7): 2495–2504. doi: 10.1021/cr990099w.

169. Wulff G. Enzyme-like catalysis by molecularly imprinted polymers. Chemical Reviews 2002; 102(1): 1–28. doi: 10.1021/cr980039a.

170. Arshady R, Mosbach K. Synthesis of substrate-selective polymers by host-guest polymerization. Die Makromolekulare Chemie: Macromolecular Chemistry and Physics 1981; 182(2): 687–692. doi: 10.1002/macp.1981.021820240.

171. Zhu W, Xu L, Zhu C, et al. Magnetically controlled electrochemical sensing membrane based on multifunctional molecularly imprinted polymers for detection of insulin. Electrochimica Acta 2016; 218: 91–100. doi: 10.1016/j.electacta.2016.09.108.

172. Gui R, Jin H, Guo H, Wang Z. Recent advances and future prospects in molecularly imprinted polymers-based electrochemical biosensors. Biosensors and Bioelectronics 2018; 100: 56–70. doi: 10.1016/j.bios.2017.08.058.

173. Wardani NI, Kangkamano T, Wannapob R, et al. Electrochemical sensor based on molecularly imprinted polymer cryogel and multiwalled carbon nanotubes for direct insulin detection. Talanta 2023; 254: 124137. doi: 10.1016/j.talanta.2022.124137.

174. Zheng W, Wu H, Jiang Y, et al. A molecularly-imprinted-electrochemical-sensor modified with nano-carbon-dots with high sensitivity and selectivity for rapid determination of glucose. Analytical Biochemistry 2018; 555: 42–49. doi: 10.1016/j.ab.2018.06.004.

175. Alexander S, Baraneedharan P, Balasubrahmanyan S, Ramaprabhu S. Highly sensitive and selective non enzymatic electrochemical glucose sensors based on graphene oxide-molecular imprinted polymer. Materials Science and Engineering: C 2017; 78: 124–129. doi: 10.1016/j.msec.2017.04.045.

176. Omidvar AH, Shahri AA, Serrano ALC, et al. A highly sensitive molecularly imprinted polymer (MIP)-coated microwave glucose sensor. Sensors 2022; 22(22): 8648. doi: 10.3390/s22228648.

177. Diouf A, Bouchikhi B, El Bari N. A nonenzymatic electrochemical glucose sensor based on molecularly imprinted polymer and its application in measuring saliva glucose. Materials Science and Engineering: C 2019; 98: 1196–1209. doi: 10.1016/j.msec.2019.01.001.

178. Caldara M, Lowdon JW, Rogosic R, et al. Thermal detection of glucose in urine using a molecularly imprinted polymer as a recognition element. ACS Sensors 2021; 6(12): 4515–4525. doi: 10.1021/acssensors.1c02223.

179. Chen Z, Wright C, Dincel O, et al. A low-cost paper glucose sensor with molecularly imprinted polyaniline electrode. Sensors 2020; 20(4): 1098. doi: 10.3390/s20041098.

180. Roy S, Nagabooshanam S, Chauhan N, et al. Design and development of a novel flexible molecularly imprinted electroanalytical sensor for the monitoring of diabetic foot ulcers. Surfaces and Interfaces 2021; 26: 101310. doi: 10.1016/j.surfin.2021.101310.

181. Peng C, Miao L, Qiu D, Chen S. Co_3O_4-chitosan/biomass-derived porous carbon molecularly imprinted polymer integrated electrode for selective detection of glucose. Ceramics International 2022; 48(16): 23137–23144. doi: 10.1016/j.ceramint.2022.04.294.