GMR

The Original

POLYMER NANOCOMPOSITES FOR BIOSENSING APPLICATIONS: RECENT ADVANCES, CHALLENGES, AND FUTURE PERSPECTIVES

Anjali Pathak[1], Pankaj Kumar Mishra[2]*, Uma Shankar Sharma[3], Chetan Pathak[4], Ayushi Sharma[5], Brijesh Kumar Gupta[6]

[1]Department of Applied Physics, Amity School of Engineering and Technology, Amity University Madhya Pradesh, Maharajpura Dang, Gwalior, India e-mail id : pathakanjali4@gmail.com,
[2]Department of Applied Physics, Amity School of Engineering and Technology, Amity University Madhya Pradesh, Maharajpura Dang, Gwalior, India e-mail id : pmishra@gwa.amity.edu,
[3]Rustamji Institute of Technology BSF Academy, Gwalior (M.P) India e-mail id : ussharma001@gmail.com
[4]Rustamji Institute of Technology BSF Academy, Gwalior (M.P) India e-mail id : cpathak@ec.iitr.ac.in
[5]Rustamji Institute of Technology BSF Academy, Gwalior (M.P) India e-mail id :ayushisharma8770@gmail.com,
[6]Govt Polytechnic college Ashoknagar (MP) India e-mail id : guptabk1507@gmail.com,
*Corresponding Authors: pmishra@gwa.amity.edu

ABSTRACT
Polymer nanocomposites (PNCs) have emerged as a transformative class of materials in biosensing because they combine the flexibility, biocompatibility, and processability of polymers with the exceptional electrical, optical, catalytic, and surface properties of nanomaterials. The integration of nanofillers such as graphene, graphene oxide, carbon nanotubes (CNTs), metal nanoparticles, quantum dots, MXenes, and conductive polymers into polymer matrices has led to highly sensitive, selective, and rapid biosensors capable of detecting biomolecules, pathogens, metabolites, nucleic acids, and disease biomarkers. Recent advances from 2024–2026 have focused on wearable biosensors, flexible electronics, health monitoring devices, electrochemical biosensors, and artificial intelligence-assisted sensing platforms. Polymer nanocomposites now play a central role in personalized medicine, point-of-care diagnostics, environmental monitoring, and healthcare monitoring. This review summarizes the current status of polymer nanocomposite biosensors, their properties, fabrication techniques, sensing mechanisms, biomedical applications, challenges, and future prospects.

KEYWORDS: Polymer nanocomposites (PNCs), biocompatibility, biosensors, metal nanoparticles.

1. INTRODUCTION

Biosensors are defined as instruments that can sense the bio-chemical events in a system in the form of signals and are of great significance in the current era for various fields such as medicine, environment, food safety, and biomedicine. A common biosensor typically comprises three primary elements, which include a biological recognition unit, transducer, and signal processing unit. The biological recognition unit selectively reacts with the target analyte, whereas the transducer transforms this biochemical reaction into an electrical, optical, or mechanical signal. The growing need for quick disease diagnosis, health monitoring, and personalized healthcare has attracted a lot of research towards advanced materials for biosensors possessing superior features. The conventional biosensors have been restricted by several shortcomings, including low sensitivity, lack of stability, non-flexibility, and low amplification. In order to address all these issues, polymer nanocomposites have gained considerable interest because of their capability to integrating the advantages of both the polymers and the nanomaterials (1).

Polymer nanocomposites are composite materials formed by the uniform dispersion of nanomaterials within a polymer matrix. Introduction of nanomaterials improves the physicochemical performance of the composite material due to large surface area, efficient electron transport, biomolecular immobilization, and better signal transduction efficiency. As such, polymer nanocomposites enhance the performance of the biosensor devices in terms of sensitivity, selectivity, response time, and stability. Moreover, due to advancements in nanotechnology and flexible electronics, wearable, stretchable, and implantable biosensors for continuous physiological monitoring can be developed (2).

In recent times, polymer nanomaterials with specially designed structures have gained great popularity, and the development of these nanomaterials has been greatly boosted by using combinatorial synthesis methods (3–5). These innovative nanomaterials exhibit distinct electrical, mechanical, chemical, and surface properties, which enable them to be ideally applied for biosensing and electrochemical sensing purposes. Such unique properties allow diverse electrochemical sensing strategies such as amperometric, potentiometric, and impedimetric sensing, which help in the detection of the desired analytes. The performance of these nanomaterials mainly depends on the interface interactions of the nanomaterial surface with the biological entities. Hence, polymer nanomaterials have been successfully used as versatile sensing platforms for diverse biological and environmental analytes like biomarkers, proteins, nucleic acids, bacteria, viruses, pathogens, and other clinically important analytes (6–9).

Successful design and development of biosensors using polymer nanocomposites calls for optimization of several key performance factors. Such key factors include high sensitivity in analyzing trace amounts of analytes, high selectivity in identifying particular analytes, wide detection range and linearity, lack of hysteresis effect, short reaction and recovery times, and extended stability during operation. Besides analytical performance, other equally important factors, include cost of production, scalability, reproducibility, manufacturability, and commercial potential of the products. Consequently, combining the key factors of improved sensing performance and cost-effective fabrication is an important goal in developing polymer nanocomposite-based biosensors for use in various applications (10–12).

Among different methods developed for the synthesis of biosensors using polymers, electro polymerization has turned out to be one of the most popular techniques because of its simplicity, repeatability, and capability to produce uniformly structured nano-particles right on the surface of electrodes. But one of the limitations of using polymers in electrochemistry is that the electrical conductivity of polymers is rather poor. Efficient charge transport plays an important role in fast signal generation and amplification. That is why there has been much interest in increasing the conductivity of polymer nanomaterials (13–15).

Several methods have been devised to optimize the conductivity and electrochemical properties of polymer nanocomposites (16–18). A commonly used method includes the addition of intrinsically conducting monomers such as pyrrole and aniline that polymerize to form electrically conducting polymers that can be used in biosensors (19). Another commonly used method is that of adding conductive dopants and counter ions such as graphene, MXenes, carbon nanotubes (CNTs), and metal nanoparticles that increase the charge mobility in polymer matrixes. For instance, the polymer Poly(3,4-ethylenedioxythiophene): poly (styrene sulfonate) (PEDOT: PSS) has attracted considerable interest owing to its high conductivity, flexibility, and biocompatibility. Copolymerization methods that utilize both conductive and functional monomers, like Pyrrole-aniline copolymerization, have also been exploited to create a balance between conductivity and surface functionality for immobilization of biomolecules (20).

Moreover, another efficient way to improve sensor characteristics is to combine polymers with conductive nanomaterials. The use of carbon nanotubes, graphene derivatives, MXenes, and metal nanoparticles not only provides additional pathways for electron transport but also increases the surface area available for analyte reactions (21). Moreover, approaches to doped polymers and polymerization on templates involve creating various kinds of structural defects, increased porosity, and ordered structures, which enable better charge transport. Even though all these methods help improve the electrochemical characteristics of polymer nanocomposites, each one involves certain difficulties. For example, doping and copolymerization increase conductivity and chemical functionality but sometimes may require strict control over the process because of the necessity to maintain film integrity and biocompatibility. On the other hand, nanocomposites can improve sensitivity and electron transfer rate significantly; however, there are still problems related to nanoparticle agglomeration and dispersion (22).

As a result, the optimization of appropriate polymer matrices, conductive nanofillers, and mechanisms to enhance conductivity is necessary, depending on the analyte of interest, environment of sensing, fabrication process, and performance of the resulting biosensor. It is anticipated that future improvements in material science, nanofabrication methods, and surface chemistry will result in improved performance of polymer nanocomposite biosensors, thus leading to the development of next-generation sensing devices (23–27).

2. Polymer Nanocomposites Used in Biosensing:

The performance of biosensor systems is highly dependent on the nature of polymer nanocomposites. There exist numerous natural and synthetic polymers that have been used as matrices in biosensors, such as chitosan, cellulose, alginate, polyaniline (PANI), polypyrrole (PPy), polyvinyl alcohol (PVA), etc. The nanofillers, such as carbon nanotubes, graphene derivatives, metallic nanoparticles, quantum dots, and MXenes, provide conductive properties and a high surface area for biomolecule immobilization (1).

Table 1. Common Polymer Nanocomposites Used in Biosensors (1)

Polymer Matrix	Nanofiller	Major Property	Biosensing Application
Chitosan	Gold nanoparticles	Biocompatibility	Glucose sensing
Polyaniline (PANI)	CNTs	Conductivity	Electrochemical sensors
PVA	Graphene oxide	Flexibility	Wearable biosensors
Polypyrrole	Silver nanoparticles	Signal amplification	Pathogen detection
PEG	Quantum dots	Fluorescence	Bioimaging and sensing
Polyurethane	MXenes	High conductivity	Sweat sensors

3. Structure and Working Principle of Polymer Nanocomposite Biosensors:

Polymer nanocomposites-based biosensor is an advanced analytical tool that works based on reactions between biological analytes and the recognition element(s) attached to the sensor matrix. The polymer nanocomposite matrix allows for fast electron transport and signal production. Once the analyte is detected, there will be some changes in electrical current, voltage, resistance, fluorescence, color, or other optical measurements, which are then interpreted into quantitative data (28).

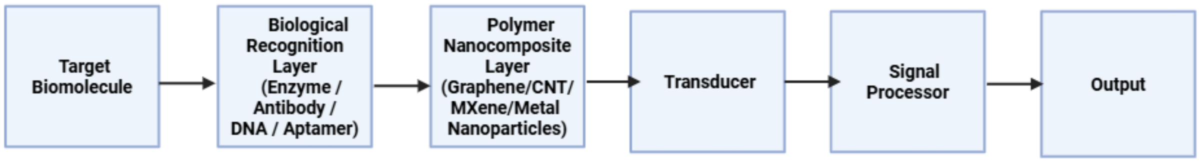


Figure 1. General Structure of a Polymer Nanocomposite Biosensor (28).

4. Important Properties of Polymer Nanocomposites for Biosensing:

Polymer nanocomposites have various unique features that suit their use as biosensors. The high electrical conductivity improves signal transduction, whereas the large surface area increases the capacity for biomolecule loading. Biocompatibility helps achieve biocompatibility, whereas flexibility helps make wearable sensors. Other features include mechanical strength, chemical stability, and biofouling resistance. Multifunctional nanocomposites capable of performing simultaneous sensing, diagnosis, and therapy have been studied recently (2).

Table 2. Key Properties of Polymer Nanocomposites in Biosensing (1).

Property	Contribution to Biosensing
High conductivity	Faster electron transfer
Large surface area	Higher biomolecule loading
Biocompatibility	Safe interaction with biological samples
Mechanical flexibility	Wearable devices
Optical activity	Fluorescent sensing
Catalytic activity	Enhanced sensitivity
Chemical stability	Long sensor lifespan
Stimuli responsiveness	Smart biosensors

5. Carbon Nanotube-Based Polymer Nanocomposite Biosensors:

Carbon nanotubes have become one of the most researched materials for biological sensing. They have high electrical conductivity, high aspect ratio, and large surface area, which makes electron transport easy. Nanocomposites consisting of CNTs and polymers have found application in glucose biosensing, DNA sensing, cancer markers, and neurotransmitter biosensing. Polyaniline and polypyrrole are conducting polymers that, when combined with CNTs, form highly sensitive electrochemical sensors. Recent research showed that biosensors based on CNT-polymer systems could recognize the analytes at picomolar and femtomolar concentration levels (29).

6. Graphene-Based Polymer Nanocomposite Biosensors:

Graphene and its various forms have completely transformed the realm of biosensors thanks to their high electrical conductivity, physical strength, and two-dimensional nature. Graphene-polymer nanocomposites offer fast paths for electron transfer and a large surface area for immobilization of biomolecules. Graphene oxide and reduced graphene oxide are especially promising thanks to their functional groups for biomolecule attachment. The applications include glucose sensors, detection of pathogens, identification of cancer markers, and wearable health monitoring devices. Graphene quantum dots have extended the range of biosensing by means of fluorescent detection methods (30).

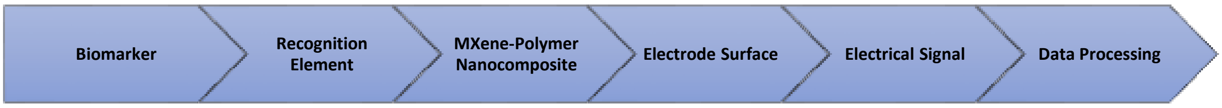
Table 3. Graphene-Based Polymer Nanocomposites for Biosensing (30)

Composite	Target Analyte	Detection Method
Graphene–PANI	Glucose	Electrochemical
GO–Chitosan	DNA	Electrochemical
rGO–PVA	Sweat biomarkers	Wearable sensing
Graphene Quantum Dots–PEG	Cancer markers	Fluorescence

7. MXene-Based Polymer Nanocomposite Biosensors:

The MXene family is amongst the most rapidly emerging families of nanomaterials for biosensing applications. MXenes are two-dimensional transition metal carbides and nitrides, which have high electrical conductivity, hydrophilicity, large surface area, and superior biocompatibility. MXene-polymer nanocomposites are effective biosensors based on electrochemical, optical, wearable, and flexible devices. The abundance of surface groups in MXenes allows for better immobilization of biomolecules and increased sensitivity. It has been reported that MXene biosensors can detect glucose, dopamine, pathogens, proteins, nucleic acids, and cancer biomarkers with high sensitivity (31).

Figure 2. MXene-Based Biosensor Architecture (31).



8. Electrochemical Polymer Nanocomposite Biosensors:

Electrochemical biosensors form the largest group of polymeric nanocomposite sensors. Such biosensors work by measuring electrochemical reactions that result from biological interactions. The use of nanocomposites improves the transfer of electrons and thereby the effectiveness of electrodes. Applications of electrochemical biosensors include blood sugar detection, disease detection, food safety testing, and environmental monitoring. Electrochemical biosensors have advantages such as low cost, quick responses, portability, and sensitivity. New developments include miniature wearable devices and smartphone-based detection systems (32).

9. Wearable and Flexible Biosensors:

Biosensors that can be worn are a game-changer for personal health care. Conductive polymers mixed with carbon nanotubes, graphene, MXenes, and metal nanoparticles allow for flexible and stretchable sensors to monitor physiological data in real time. There has been specific focus on sweat-based biosensors since sweat contains glucose, lactate, cortisol, sodium ions, and other useful biomarkers. The recent developments include wearable patches, fabrics, and flexible electronics (2)

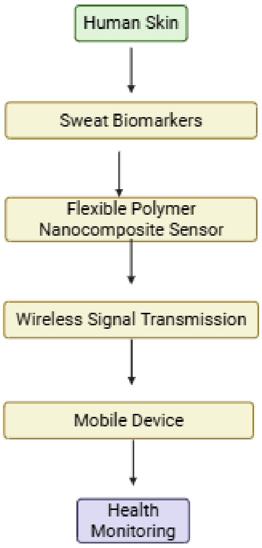


Figure 3. Wearable Biosensing Platform (2).

10. Medical Applications of Polymer Nanocomposite Biosensors:

Polymer nanocomposite biosensors have been used in various medical applications. The glucose biosensors have proved to be a commercially viable application, especially in diabetic patients. The recent polymer nanocomposite glucose biosensors are more sensitive, stable, and accurate than the traditional biosensors. In the field of oncology, biosensors are used to detect cancer biomarkers, circulating tumor cells, and nucleic acids associated with disease progression. Polymer nanocomposite biosensors have been used in the diagnosis of cardiovascular diseases, infectious diseases, and neurological disorders (33).

Table 4. Medical Applications of Polymer Nanocomposite Biosensors (33).

Application	Biomarker
Diabetes monitoring	Glucose
Cancer diagnosis	PSA, CEA, HER2
Cardiovascular disease	Troponin, CRP
Infectious diseases	Viral proteins, DNA
Neurological disorders	Dopamine, neurotransmitters
Wearable health monitoring	Sweat metabolites

11. Challenges and Limitations:

Although there have been notable successes, certain difficulties persist. Agglomeration of nanoparticles may lower the conductivity and the effectiveness of sensors. The stability of nanocomposites over time poses problems, especially when used in wearable medical devices that operate under physiological conditions. It is important to conduct biocompatibility and toxicity studies before applying nanomaterials clinically. MXenes are promising but prone to oxidation and environmental instability (31).

12. Future scope:

Future work in this field is likely to be centered around sensors that incorporate AI technology, self-powered wearables, implantable sensors, and theranostic systems. Self-sensing and drug delivery smart polymer nanocomposites have emerged as one of the most promising fields. It is predicted that the MXene-polymer composite sensors, graphene quantum dots, and bio-inspired nanocomposite sensors will lead future biosensor research. Combination with wireless communication, cloud computing, and machine learning will enable real-time healthcare monitoring and precision medicine (34).

13. CONCLUSION

The emergence of polymer nanocomposites has revolutionized biosensors through the integration of useful features of both polymers and nanomaterials. The high sensitivity, selectivity, flexibility, conductivity, and biocompatibility of these materials have made it possible to make many breakthroughs in the area of diagnosis, wearable health care devices, disease monitoring, and personalized medicine. Materials such as graphene, carbon nanotubes, MXenes, metal nanoparticles, and quantum dots keep inspiring scientists to design better biosensors. Although there are still many issues associated with stability, toxicity, and production, it is expected that polymer nanocomposite biosensors will shape future health care technologies.

Abbreviation

PANI- Polyaniline
PEDOT: PSS- Poly(3,4-ethylenedioxythiophene): Poly (styrene sulfonate)
PPy- Polypyrrole
CNTs- carbon nanotubes
PVA- Polyvinyl Alcohol
DNA- Deoxyribonucleic Acid
GO- Graphene Oxide
rGo- Reduced Graphene Oxide
PEG- Polyethylene Glyco
CRP- C-Reactive Protein
CEA- Carcinoembryonic Antigen
HER2- Human Epidermal Growth Factor Receptor 2
PSA- Prostate-Specific Antigen
AI- Artificial Intelligence

Acknowledgment

The authors are thankful to the department of Applied Physics, Amity School of Applied Science, Amity University Madhya Pradesh, for all the necessary facilities.

Conflict of Interest

There is no conflict of interest.

REFERENCES

1. Natarajan B, Kannan P, Maduraiveeran G, Alnaser AS. Polymer nanocomposite-based biomolecular sensor for healthcare monitoring. *Advances in Colloid and Interface Science*. 2025;343: 103557. https://doi.org/10.1016/J.CIS.2025.103557.

2. Singh L, Jain H, Sharma S, Saini N, Kashyap A, Singh V. Recent advances in conducting polymer nanocomposites for non-invasive sweat-based biosensors: A review. *Nano-Structures & Nano-Objects*. 2026;45: 101609. https://doi.org/10.1016/J.NANOSO.2025.101609.

3. Manivasagan P, Kim J, Reviews EJCC, 2022 undefined. Recent progress in multifunctional conjugated polymer nanomaterial-based synergistic combination phototherapy for microbial infection theranostics. *ElsevierP Manivasagan, J Kim, ES JangCoordination Chemistry Reviews, 2022•Elsevier*. https://www.sciencedirect.com/science/article/pii/S001085452200296X

4. Solangi N, Karri R, … NMAI and, 2024 undefined. Mechanism of polymer composite-based nanomaterial for biomedical applications. *ElsevierNH Solangi, RR Karri, NM Mubarak, SA MazariAdvanced Industrial and Engineering Polymer Research, 2024•Elsevier*. https://www.sciencedirect.com/science/article /pii/S2542504823000544

5. Chi H, chemistry GLF, 2023 undefined. Carbon nanomaterial-based molecularly imprinted polymer sensors for detection of hazardous substances in food: Recent progress and future trends. *ElsevierH Chi, G LiuFood chemistry, 2023•Elsevier*. https://www.sciencedirect.com/science/article/pii/S0308814623007185

6. Kumar H, Kumari N, Review RSEIA, 2020 undefined. Nanocomposites (conducting polymer and nanoparticles) based electrochemical biosensor for the detection of environment pollutant: Its issues and challenges. *ElsevierH Kumar, N Kumari, R Sharma Environmental Impact Assessment Review, 2020•Elsevier*. https://www.sciencedirect.com/ science/article/pii/S0195925520301542

7. Shahbazi M, Jäger H, Ettelaie R, … JCA in C and, 2024 undefined. Dispersion strategies of nanomaterials in polymeric inks for efficient 3D printing of soft and smart 3D structures: A systematic review. *ElsevierM Shahbazi, H Jäger, R Ettelaie, J Chen, PA Kashi, A MohammadiAdvances in Colloid and Interface Science, 2024•Elsevier*. https://www.sciencedirect.com/science/article/pii/S0001868624002082
8. Karimzadeh Z, Mahmoudpour M, … ERA in C and, 2022 undefined. Nanomaterial based PVA nanocomposite hydrogels for biomedical sensing: Advances toward designing the ideal flexible/wearable nanoprobes. *ElsevierZ Karimzadeh, M Mahmoudpour, E Rahimpour, A JouybanAdvances in Colloid and Interface Science, 2022•Elsevier*. https://www.sciencedirect.com/science/article/pii/S0001868622001075
9. Barhoum A, Hamimed S, Slimi H, … AOT in E, 2023 undefined. Modern designs of electrochemical sensor platforms for environmental analyses: Principles, nanofabrication opportunities, and challenges. *ElsevierA Barhoum, S Hamimed, H Slimi, A Othmani, FM Abdel-Haleem, M BechelanyTrends in Environmental Analytical Chemistry, 2023•Elsevier*. https://www.sciencedirect.com/science/article/pii/S2214158823000053
10. Verma A, Sharma G, Wang T, Kumar A, Dhiman P, Verma Y, et al. Graphene oxide/chitosan hydrogels for removal of antibiotics. *Taylor & Francis*. 2025;46(17): 3391–3421. https://doi.org/10.1080/09593330.2025.2464267.
11. Ali N, Khan F, Khan I, Kareem A, Rahman S, Chemosphere AK, et al. Robust polymer hybrid and assembly materials from structure tailoring to efficient catalytic remediation of emerging pollutants. *ElsevierN Ali, F Khan, I Khan, A Kareem, S Rahman, A Khan, F Ali, RA Al Balushi, MM Al-HinaaiChemosphere, 2024•Elsevier*. https://www.sciencedirect.com/science/article/pii/S0045653524013018
12. Qi X, Yan X, Zhao Y, Li L, Chemistry SWTT in A, 2020 undefined. Highly sensitive and specific detection of small molecules using advanced aptasensors based on split aptamers: A review. *ElsevierX Qi, X Yan, Y Zhao, L Li, S WangTrAC Trends in Analytical Chemistry, 2020•Elsevier*. https://www.sciencedirect.com/science/article/ pii/S0165993620302983
13. Jebril S, Fredj Z, Ayman A, Saeed A, Gonçalves AM, Kaur M, et al. Nanomaterial-based electrochemical chemo (bio) sensors for the detection of nanoplastic residues: trends and future prospects. *pubs.rsc.orgS Jebril, Z Fredj, AA Saeed, AM Gonçalves, M Kaur, A Kumar, B SinghRSC Sustainability, 2024•pubs.rsc.org*. 2024; https://doi.org/10.1039/d3su00471f.
14. Fiore L, Mazzaracchio V, Serani A, … GFS and AB, 2023 undefined. Microfluidic paper-based wearable electrochemical biosensor for reliable cortisol detection in sweat. *ElsevierL Fiore, V Mazzaracchio, A Serani, G Fabiani, L Fabiani, G Volpe, D Moscone, GM BiancoSensors and Actuators B: Chemical, 2023•Elsevier*. https://www.sciencedirect.com/science/article/pii/S0925400522019013
15. Shanbhag M, Manasa G, … RMCE, 2023 undefined. Fundamentals of bio-electrochemical sensing. *ElsevierMM Shanbhag, G Manasa, RJ Mascarenhas, K Mondal, NP ShettiChemical Engineering Journal Advances, 2023•Elsevier*. https://www.sciencedirect.com/science/article/pii/S266682112300073X
16. Olorundare F, Sipuka D, … TSS and B, 2023 undefined. An electrochemical immunosensor on a carbon nanofiber/gold nanoparticles platform for the detection of alpha-feto protein cancer biomarker. *ElsevierFOG Olorundare, DS Sipuka, TI Sebokolodi, S Makaluza, N Midzi, T Kodama, OA ArotibaSensing and Bio-Sensing Research, 2023•Elsevier*. https://www.sciencedirect.com/science/article/pii/S2214180423000260
17. Siontorou C, Analytical KGT in E, 2021 undefined. Boosting the advantages of biosensors: Niche applicability and fitness for environmental purpose. *ElsevierCG Siontorou, KN GeorgopoulosTrends in Environmental Analytical Chemistry, 2021•Elsevier*. https://www.sciencedirect.com/science/article/pii/S2214158821000337
18. Meng X, Petrou L, Kenaan A, Khan D, … DOB and, 2024 undefined. Pitfalls and challenges of peptide nucleic acid immobilisation on carbon surfaces for sequence-specific capturing of nucleic acid biomarkers. *Elsevier*. https://www.sciencedirect.com/science/article/pii/S0956566324006407
19. Acar T, Nur Çimen K, Özalp E, Ilıca Ö, Ahlatcıoğlu Özerol E. Recent advances in biosensors based on conducting polymers for biomedical applications. *Wiley Online Library*. 2023;8(30). https://doi.org/10.1002/SLCT.202300819.
20. Sumdani MG, Islam MR, Yahaya ANA, Safie SI. Advancements in MXene-polymer nanocomposites in energy storage and biomedical applications. *mdpi.com*. 2022;62(2): 269–303. https://doi.org/10.1002/PEN.25859.
21. Le C, Sciences HYIJ of M, 2024 undefined. Advances in the use of conducting polymers for healthcare monitoring. *mdpi.com*. https://www.mdpi.com/1422-0067/25/3/1564
22. Fang Y, Chang H, Li J, Li Z, Zhang D. Recent advances in metal nanocomposite-based electrochemical (bio) sensors for pharmaceutical analysis. *Taylor & Francis*. 2024;54(6): 1680–1706. https://doi.org/10.1080/10408347 .2022.2128633.
23. Fopase R, Paramasivam S, … PKJ of E, 2020 undefined. Strategies, challenges and opportunities of enzyme immobilization on porous silicon for biosensing applications. *ElsevierR Fopase, S Paramasivam, P Kale, B ParamasivanJournal of Environmental Chemical Engineering, 2020•Elsevier*. https://www.sciencedirect.com /science/ article/pii/S2213343720306151
24. Pavlenko V, Żółtowska S, Haruna A, … MZMS and, 2022 undefined. A comprehensive review of template-assisted porous carbons: Modern preparation methods and advanced applications. *ElsevierV Pavlenko, S Żółtowska, AB Haruna, M Zahid, Z Mansurov, Z Supiyeva, A GalalMaterials Science and Engineering: R: Reports, 2022•Elsevier*. https://www.sciencedirect.com/science/article/pii/S0927796X22000213
25. Romanholo P, … CRB and, 2021 undefined. Biomimetic electrochemical sensors: New horizons and challenges in biosensing applications. *ElsevierPVV Romanholo, CA Razzino, PA Raymundo-Pereira, TM Prado, SAS Machado, LF SgobbiBiosensors and Bioelectronics, 2021•Elsevier*. https://www.sciencedirect.com/science/article/pii/S0956566321002797

26. Chen G, Zhang S, Ma X, Wilson G, … RZCE, 2024 undefined. Antibody mimics for precise identification of proteins based on molecularly imprinted polymers: Developments and prospects. *ElsevierG Chen, S Zhang, X Ma, G Wilson, R Zong, Q FuChemical Engineering Journal, 2024•Elsevier*. https://www.sciencedirect.com/science/article/pii/S138589472306847X
27. Kant T, Shrivas K, Dewangan K, … AKMT, 2022 undefined. Design and development of conductive nanomaterials for electrochemical sensors: a modern approach. *ElsevierT Kant, K Shrivas, K Dewangan, A Kumar, NK Jaiswal, MK Deb, S PervezMaterials Today Chemistry, 2022•Elsevier*. https://www.sciencedirect.com/science/article/pii/S2468519421003499
28. Mousavi SM, Nezhad FF, Ghahramani Y, Binazadeh M, Javidi Z, Azhdari R, et al. Recent advances in bioactive carbon nanotubes based on polymer composites for biosensor applications. *Wiley Online Library*. 2024;21(7). https://doi.org/10.1002/CBDV.202301288.
29. Raja V, Kour G, katal D, Kaur S, … AMBN for, 2026 undefined. Carbon-Based Nanocomposites for Sensing and Biosensing. *Springer*. 2026; 95–127. https://doi.org/10.1007/978-3-032-10637-7_5.
30. Rasheed PA, Ankitha M, Pillai VK, Alwarappan S. Graphene quantum dots for biosensing and bioimaging. *RSC Advances*. 2024;14(23): 16001–16023. https://doi.org/10.1039/D4RA01431F.
31. *Recent advances in biosensors based on the electrochemical properties of MXenes - Analyst (RSC Publishing) DOI:10.1039/D5AN00235D*. https://pubs.rsc.org/en/content/articlehtml/2025/an/d5an00235d?utm_source=chatgpt.com [Accessed 21st June 2026].
32. Ramesh M, Janani R, Deepa C, Biosensors LR, 2022 undefined. Nanotechnology-enabled biosensors: a review of fundamentals, design principles, materials, and applications. *mdpi.com*. https://www.mdpi.com/2079-6374/13/1/40
33. Sen A. Polymer nanocomposites in diabetes management: advances in biosensors and drug delivery systems. *Discover Materials 2025 5:1*. 2025;5(1): 26-. https://doi.org/10.1007/S43939-025-00210-0.
34. Fakhr MH, Zintzun AIG, Michaelis A, Opitz J, Beshchasna N. Application of MXene-based nanocomposites in electrochemical biosensors. *Applied Surface Science Advances*. 2026;32: 100959. https://doi.org/10.1016/J.APSADV.2026.100959