NanoWorld Journal

https://doi.org/10.17756/nwj.2023-s5-060

Review Article

Open Access

Nanotechnology Integration for Enhanced Performance of Wearable IoT Devices

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Received: October 20, 2023
Accepted: December 22, 2023
Published: December 28, 2023

Citation: Kumar A, Singh KU, Raja L, Kumar P, Sharma S, et al. 2023. Nanotechnology Integration for Enhanced Performance of Wearable IoT Devices. *NanoWorld J* 9(S5): S333-S340.

Published by United Scientific Group

Abstract

Sensors that are driven by microtechnology and nanotechnology have revolutionized the biomedical and environmental landscapes, which in turn has revolutionized the detection and quantification of analytes. In the field of biomedicine, the introduction of these sensors has catalyzed illness detection, sped the process of drug development, and enabled point-of-care diagnostics. Together, they have been helpful in determining the quality of the air, water, and soil, which has resulted in comprehensive monitoring of the environment and protection of the food supply. Despite the incredible progress that has been made, there are still many obstacles to overcome. This review paper offers a comprehensive analysis of current developments in sensors enabled by microtechnology and nanotechnology, with a focus on their applications in the fields of biomedicine and environmental science. By elucidating the cutting-edge techniques and methodologies, the review underscores the need for continuous research to enhance sensor capabilities, sensitivity, selectivity, wireless integration, and energy efficiency. The call for optimizing material selection, automated components, and advanced fabrication and characterization techniques encapsulates the vision for the future of sensor technology. With the march of technology paralleling the evolution of hu-man lifestyles, the demand for convenience and ease has grown fervently. This tendency culminates in the merging of Internet of Things (IoT) enabled wearable sensors with nanotechnology, igniting a revolutionary wave in the field of sensor technology. Real-time, location independent identification of pollutants, illnesses, and toxins is made possible by this paradigm change, providing previously unheard-of accessibility and efficiency. The limitations and constraints that come with this fusion also invite discussion about the opportunities and roadblocks that lie at the nexus of nanotechnology and IoT. This featured article carefully gathers up-to-date knowledge about wearable sensors with nanotechnology capabilities within the IoT framework. In addition to giving an outline of their existing and future applications, it also explores the upcoming problems that call for creative solutions and focused research efforts.

Keywords

Internet of things, Nanotechnology, Sensor, Fusion, Wearable device

Introduction

Individual health is a vital life facet, yet healthcare centers often grapple with technology limitations, constraining patient treatment. The burgeoning realm of IoT offers multifaceted solutions to these constraints. IoT is revolutionizing healthcare, encompassing disease detection, treatment, and monitoring. Wearable IoT devices, facilitating precise patient care, hold promise [1]. While conventional networks for human applications encounter latency and computing constraints, the advent of 5G heralds transformative potential, offering unparalleled connectivity for the impending IoT era. Leveraging 5G's prowess, healthcare stands to gain treatment breakthroughs, data analytics, diagnostics, and imaging enhancements.

This comprehensive review delves into IoT, IoT-based wearables, and 5G's pivotal role in healthcare IoT. Wearable devices' role in healthcare, spanning detection, monitoring, and curing, is explored. Despite these advancements, this review also accentuates the ongoing challenges in IoT architecture and wearables, propelling future research. Advancing technology parallels evolving human lifestyles, demanding convenience. Nano-enabled wearable sensors for IoT epitomize this evolution, enabling convenient, real-time diagnosis of pollutants, diseases, and contaminants [2]. While the fusion of nanotechnology and IoT promises a dynamic future, inherent limitations and challenges persist. This featured article assimilates contemporary insights into nano-enabled wearable sensors for IoT, offering a discourse on their future trajectories and challenges.

Micro and nanotechnology fueled sensors have revolutionized biomedicine and environmental monitoring, revolutionizing analyte detection. In biomedicine, these sensors drive disease diagnosis, drug discovery, and point-of-care solutions. Concurrently, environmental monitoring benefits from these sensors, enhancing air, water, and soil quality assessments, and ensuring food safety. Yet, while strides have been made, challenges endure. This review article [3] delves into the latest micro- and nanotechnology-enabled sensor developments in biomedical and environmental contexts. It underscores the need for ongoing research to enhance sensor capabilities, sensitivity, selectivity, wireless communication integration, and energy-harvesting solutions. The review culminates in a call for optimizing sensor design, fabrication, and characterization through material selection, automated components, and refined sample preparation.

Nanomaterials for wearable IoT

Combining nanotechnology with the IoT has created an environment conducive to the development of game-changing advancements in a variety of different fields. Among these, the integration of nanomaterials into wearable devices for IoT applications stands as a remarkable advancement, promising to revolutionize healthcare, environmental monitoring, communication, and beyond. This convergence of nanotechnology and IoT, often referred to as the Internet of Nano-Things (IoNT), has garnered immense interest due to its potential to enhance device performance, enable novel functionalities, and address existing limitations.

Nanomaterials, characterized by their nanoscale dimensions and unique properties, have unlocked new horizons for wearable IoT devices [4]. This interdisciplinary domain brings together materials science, electronics, and communication technologies to create smart devices that seamlessly interface with the human body and the environment. In this exploration, we delve into the diverse applications, benefits, challenges, and future prospects of nanomaterials in wearable IoT devices.

Integration of nanomaterials in wearable IoT

The integration of nanomaterials has extended the capabilities of wearable IoT devices across a range of applications:

- Healthcare and medical monitoring: Nanomaterial-based sensors can detect biological markers, monitor vital signs, and track health conditions in real-time. For instance, wearable biosensors incorporating nanomaterials enable continuous glucose monitoring for diabetes patients, enhancing disease management and improving their quality of life.
- Environmental sensing: Nanomaterials exhibit high sensitivity to environmental pollutants, enabling the creation of wearable sensors for air quality monitoring. These devices can detect harmful gases, particulate matter, and volatile organic compounds, providing valuable data for public health and environmental conservation efforts.
- Smart textiles: Nanomaterials can be seamlessly integrated into fabrics, creating smart textiles with diverse functionalities. These textiles can monitor physiological parameters, adapt to changing environmental conditions, and even generate energy from body movement.
- Communication and connectivity: Nanomaterials facilitate the development of efficient antennas and communication modules for wearable devices. These advancements enhance data transfer rates and connectivity, enabling seamless communication between wearables and other IoT devices (Figure 1).

Benefits of nanomaterials in wearable IoT

The incorporation of nanomaterials brings several advantages to wearable IoT devices:

- Enhanced sensing: Nanomaterials offer high sensitivity and selectivity, enabling accurate detection of analytes. This is crucial for applications like disease diagnosis and

Figure 1: Nanomaterials based IoT wearable device.

environmental monitoring, where precise measurements are paramount.

- Miniaturization: Nanomaterials can be engineered to exhibit unique properties at the nanoscale, allowing the creation of compact, lightweight wearable devices that do not compromise functionality.
- Energy efficiency: Nanomaterials can enhance the energy efficiency of wearable devices. They enable low-power operation, prolonging battery life and reducing the need for frequent recharging.
- Biocompatibility: Many nanomaterials are biocompatible and can interface seamlessly with biological systems. This is crucial for applications involving direct contact with the human body, such as health monitoring and medical diagnostics.
- Functional diversity: Nanomaterials offer a wide range of functionalities, from conductive properties for efficient energy storage to catalytic properties for chemical sensing. This versatility enables the creation of multifunctional wearable devices.

Challenges and considerations

Despite the promise of nanomaterials in wearable IoT, several challenges and considerations must be addressed:

- Safety: The potential health and environmental impacts of nanomaterials need thorough assessment to ensure their safe integration into wearable devices and their interaction with the human body.
- Scalability: The scalable production of nanomaterials with consistent properties is essential for large-scale manufacturing of wearable devices. Cost-effective and sustainable synthesis methods are crucial.
- Integration complexity: Integrating nanomaterials into wearable devices requires precise engineering to maintain their unique properties. Compatibility with other device components and fabrication processes must be ensured.
- Standardization: The diverse nature of nanomaterials poses challenges in establishing standardized testing protocols, performance metrics, and safety guidelines for wearable IoT devices.
- Power management: While nanomaterials enhance energy efficiency, power management remains a critical consideration. Efficient energy harvesting and storage solutions are needed to ensure continuous device operation.

Application of nanotechnology in wearable IoT

The future of nanomaterials in wearable IoT holds tremendous potential for groundbreaking innovations:

- Advanced sensing: Continued research into novel nanomaterials and their integration techniques will lead to enhanced sensing capabilities, enabling real-time detection of an even broader range of analytes.
- Flexible and stretchable electronics: Nanomaterials can enable flexible and stretchable electronic components, paving the way for wearable devices that conform to the body's movements and shapes.
- Energy harvesting: Nanomaterials with piezoelectric or thermoelectric properties can be used to harvest energy from body movements or temperature differentials, further extending battery life or eliminating the need for batteries altogether.
- Bio-integration: Nanomaterials with tailored biocompatibility will enable seamless integration between wearable devices and the human body, creating a symbiotic relationship that enhances both health monitoring and device performance.

The integration of nanomaterials into wearable IoT devices has opened up a realm of possibilities, from healthcare to environmental monitoring and communication [5]. While challenges exist, ongoing research and innovation will likely address these hurdles, propelling nanomaterial based wearable IoT devices into the forefront of technological advancement. It is becoming more apparent that wearable gadgets will play an increasingly crucial role in determining the future of personalized health, smart surroundings, and connectivity as the synergy between nanotechnology and the internet of things continues to expand.

Literature Review

This comprehensive review meticulously examines the integration of nanomaterial-enabled wearable sensors within the healthcare realm. Diving into an array of sensor types such as temperature, electrophysiological, strain, tactile, electrochemical, and environmental sensors, the paper presents a panoramic view of their potential applications. The wearable IoT devices discussed in this review offer not only innovative diagnostic tools but also promise enhanced patient care and treatment efficacy. By delving into the intricacies of these nanomaterial-enabled sensors [6]. The review contemplates a future where healthcare is revolutionized through seamless and personalized monitoring and treatment strategies.

Recent strides in micro- and nano-technology have sparked a paradigm shift in sensor technology, especially in addressing biomedical and environmental challenges. This comprehensive review [7] systematically traverses the landscape of these advancements, emphasizing the integration of nanotechnology to enhance conventional sensing techniques. The paper [8] underscores the pivotal role nanomaterials play in revolutionizing sensor performance, sensitivities, and selectivity's. From elucidating the workings of biosensors to highlighting their applications in both biomedical diagnostics and environmental monitoring, the review encapsulates the transformative impact of nanotechnology on modern sensor systems.

Unraveling the latent potential of nanomaterial-enabled sensors, this review casts its spotlight on environmental monitoring, particularly the detection of contaminants. The paper [9] surveys the landscape of facile, low-cost technologies that leverage nanomaterials to detect pollutants, heavy metals, pesticides, and pathogens. It high-lights the significance of these field-deployable sensors in understanding and safe-guarding the environment. By discussing both the advantages and challenges of these nanomaterial-based sensors, the review contributes to a more profound understanding of how nanotechnology can be harnessed for environmental protection and preservation [10].

The burgeoning intersection of nanotechnology and wireless sensing networks unfolds in this review, underscoring its potential to reshape security measures. By tapping into nanomaterial-enhanced sensors, the review envisages a future where mobile sensing and wireless sensor networks are pivotal components of national security and public safety strategies [11]. With a keen focus on the innovative ways nanotechnology can amplify sensor capabilities, the paper positions these developments as a promising avenue for ensuring societal well-being and safeguarding critical infrastructures.

Nano-polymers are at the forefront of this review's exploration, which delves into their potential applications within biomedical contexts. By examining the various classes of nanomaterials and their distinctive sensing mechanisms, the paper [12] presents a comprehensive analysis of nano-polymers as enabling components in sensor systems. It discusses knowledge gaps, potential challenges, and offers a roadmap for future research to harness these materials for innovative biomedical sensing applications.

This review comprehensively addresses the realm of biosensors [13], illuminating their pivotal role in disease diagnosis, drug discovery, and environmental monitoring. It navigates the diverse landscape of biosensor signal transduction methods, uncovering the intricate mechanisms that underlie their operation. By outlining applications spanning healthcare, environmental assessments, and agriculture, the paper under-scores the versatility of biosensors while providing a valuable reference for under-standing and advancing these transformative devices.

Within the scope of this study, the integration of nanoscience principles into chemical sensors is thoroughly explored. The review peels back the layers of sensor systems and the underlying facets of modern nanoscience, elucidating their symbiotic relationship [14]. By delving into the intricate details of sensor design and fabrication, the paper equips readers with insights into the transformative potential of nanoscience in shaping the future of chemical sensing technologies.

The landscape of nanostructured gas sensors finds comprehensive exploration in this review, delving into their manifold applications and the challenges they address. By casting a spotlight on environmental monitoring, the paper envisions a future where these sensors contribute to commercial solutions for assessing air quality and safety [15]. The review's emphasis on the transformative potential of these sensors under-scores their role in driving advancements in environmental monitoring.

A deep dive into the world of nanowire-based sensors characterizes this review, focusing on their applications in biological and medical domains. It magnifies their inherent advantages, such as ultra-sensitivity and ease of fabrication, while exploring re-cent advances that amplify their performance. By charting the trajectory of these sensors, the paper presents a compelling narrative of their growing importance in advancing healthcare diagnostics and biomedical research [16].

The fusion of nanotechnology and the IoT unfolds in this review, spotlighting nano-enabled wearable sensors. The discussion revolves around their unique advantages and formidable challenges, offering insights into their potential for revolutionizing data acquisition and analysis. The paper delves into the anticipated future aspects of this technology, envisioning a landscape where nano-enabled wearables seamlessly integrate with the IoT ecosystem [17].

Within the framework of this review, the journey towards enhanced sensing capabilities takes center stage, driven by the integration of nanowires. The review elaborates on various types of nanowires and their potential applications as sensor materials or templates [18]. It identifies key obstacles and proposes future directions to unlock the potential of nanosensors rooted in nanowire technology.

The review envisions a landscape where nanomaterial-enabled detection strategies redefine pathogen monitoring. By delving into the opportunities that nano-enabled biosensors present for environmental surveillance, the paper highlights their capacity to safeguard ecosystems and public health [19]. This comprehensive analysis positions nanotechnology at the forefront of biosensor advancements.

The transformative influence of nanotechnology on sensors finds meticulous examination in this review. It traces how nanoscale features revolutionize sensing systems, and how advancements in thin film techniques and chemical synthesis empower tailored material properties. This paper [20] insights underscore the essential role nanotechnology plays in shaping sensor capabilities and driving the evolution of micro- and nano-sensor systems. Recent strides in nanomaterials-based sensors for environmental monitoring unfold in this comprehensive review. By spotlighting the diverse capabilities of nanomaterials such as carbon nanotubes (CNTs), gold nanoparticles (AuNPs), silicon nanowires, and quantum dots, the paper envisions a future where these sensors address critical challenges in detecting toxic metal ions, gases, pesticides, and hazardous chemicals. Nanoparticle-based environmental sensors take the stage in this review, heralding a new era of enhanced pollutant detection. The review underscores their advantages over conventional methods, including heightened selectivity, sensitivity, stability, and cost-effectiveness [21]. By exploring their applications in detecting tox-ins, heavy metals, and organic pollutants, the paper envisions a landscape where nanoparticle-based sensors play a pivotal role in safeguarding environmental health.

Nanotechnology-enabled biosensors step into the spotlight of this review, emphasizing their unique attributes such as high surface-area-to-volume ratio and versatile detection mechanisms. The paper traverses' applications spanning healthcare, environmental monitoring, pathogenic bacteria detection, and agriculture, painting a comprehensive picture of how nanotechnology-driven biosensors shape diverse domains (Table 1) [22].

Analysis of Performance for Nanomaterial Enabled Wearable IoT Devices

This analysis delves into the remarkable advancements witnessed in the realm of sensors, with a particular focus on their applications within the biomedical and environmental sectors. These innovative technologies have ushered in a new era characterized by unparalleled sensitivity and novel approaches to detecting analytes and events, fostering groundbreaking possibilities for scientific and practical endeavors.

In the field of biomedicine, sensors have been crucial in the revolutionizing the process of illness detection and diagnosis, as well as the process of drug discovery and the development of point-of-care devices. Notably, electrochemical biosensors have emerged as significant instruments in the diagnostic process for disorders such as diabetes and cardiovascular diseases [23]. This is accomplished by the detection of biomolecules such as glucose, lactate, and cholesterol. The combination of microfluidics and sensors has been a fundamental driving force behind advances in drug development and antibiotic resistance research. This has made it possible to conduct efficient screenings of prospective drug candidates and to characterize the biological activities of these candidates. Data insights have been further enlightened, the possible applications of these insights have been widened, and our knowledge of complex phenomena has been increased as a result of the synergy of sensors, artificial intelligence, and machine learning (Figure 2).

Simultaneously, in the environmental domain, sensors have become invaluable as sets in monitoring air and water quality, pollution levels, and food safety. Their capability to rapidly and effectively identify pollutants in real time enables prompt interventions to minimize environmental degradation and gives insights into industrial operations. In addition, their capacity to do so provides a window into industrial activities. The relatively recent development of biosensors, which make use of biological components for the purpose of pollution detection, has unlocked the possibility for high-sensitivity and high-selectivity sensing, which in turn has strengthened efforts to monitor the environment. Although the applications of sensors in biomedicine and the environment may seem to be completely unrelated, they really share essential technologies

Table 1: Comparative analysis of literature review with key area identifications.

Area identified	Advances	Key finding
Micro and nanotechnology enabled sensors for biomedical and environmental challenges	Integration of nanotechnology, improved sensing performance, versatile applications	Covers nanotechnology definitions, mental characteristics and terminologies, transduction platforms, characterization techniques, and explanations of how change in properties can form the basis for sensing.
Nanomaterial enabled sensors for environmental contaminant detection	Facile, low-cost technology, field deployable sensors, pollution monitoring	Coverage of nano-enabled sensors is sparse. Nanomaterials are promising building blocks for wearable sensors due to their large surface area and outstanding material properties.
Nanotechnology enabled sensors and wireless sensing networks	Potential in mobile sensing, Enhanced security measures public safety applications	Nanomaterial enabled wearable sensors can be used for continuous health monitoring, daily and sports activity tracking, and multifunctional electronic skin.
Nano-polymer enabled sensors for biomedical applications	Exploration of nano-polymer classes, diverse sensing mechanisms	Micro- and nano-technology enabled sensors to have made remarkable advancements in the fields of biomedicine and the environment, enabling the sensitive and selective detection and quantification of diverse analytes.
Biosensors: diagnosis and monitoring	Comprehensive biosensor overview, various transduction methods, multidisciplinary applications	Numerous challenges still persist in the development of these sensors, such as enhancing basic sensing techniques, expanding detection capabilities, increasing sensitivity and selectivity, and optimizing sample preparation and material selection.
Nanotechnology enabled chemical sensors	Insight into chemical sensor systems, integration of nanoscience	Nanotechnology can be used to enhance the functionality of sensors, such as CNTs and nanoparticles.
Nanostructured gas sensors for environmental monitoring	Nanotechnology's impact on gas sensors, potential for commercial use	These sensors can be used in mobile sensing and wireless sensor networks for national security and public safety.
Nanowire based sensors for biological and medical applications	Exploration of nanowire sensors, ultra-sensitivity and ease of fabrication	Technical challenges associated with the development of such systems and networks must be addressed.
Nanotechnology enabled wearable sensors for IoT	Advantages of nano-enabled wearables, future potential and challenges	Sensing that is facilitated by nanotechnology is a burgeoning topic of multidisciplinary research in the new science that has dynamic multipurpose detecting capabilities.
Nanowire sensors for achieving better sensing performance	Focus on nanowire sensor advancements, integration potential	In recent years, there has been a proliferation of nanomaterial-based sensing techniques for the reliable and speedy detection and quantification of a variety of processes and chemicals. These sensing strategies are based on nanomaterials.
Nanomaterial enabled detection strategies for pathogen monitoring	Insights into nano-enabled biosensors, environmental surveillance	This article provides a summary of the sensing mechanisms through the use of schematic illustrations. It also discusses attempts to integrate the performance of various categories of nanomaterials in the design of sensors, knowledge gaps, regulatory aspects, future research directions, and the challenges of implementing such techniques in standalone devices.

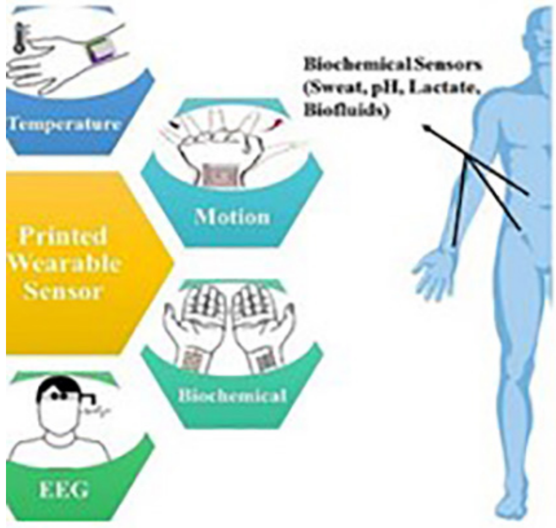

Figure 2: Nanomaterials-patterned sensor for wearable health [18].

that are necessary for their functionality. These technologies include transducer components, signal processing, data transfer, data analytics, and power management. Because of this interconnectedness, the sharing of developments and solutions across the fields is made easier, which in turn drives the overall collective progress of sensor technology research and application (Table 2).

Despite these transformative strides, several challenges demand attention. Increasing the ability of sensors to detect a wider variety of analytes with higher levels of sensitivity and selectivity continues to be an important area of research and development. The emergence of multiplexed sensors, capable of simultaneously detecting multiple analytes, stands as a notable advancement for high-throughput measurements. The integration of sensors with wireless communication technologies to enable the IoT has made substantial headway, while the challenge of power management has ushered in research opportunities in energy harvesting.

Furthermore, the pursuit of sensor reliability and consistency outside controlled laboratory environments necessitates the development of automated fabrication techniques. It is necessary to establish standards and regulations in order to guarantee the safety and effectiveness of these technologies, which will in turn encourage responsible innovation. In essence, the dynamic landscape of sensor technology presents a realm of possibilities yet to be fully explored, as well as a continuum of challenges demanding collaborative efforts and innovative solutions. The emergence of nano technology has ushered in a transformative era for biosensors, propelling the field to unprecedented heights [38]. By incorporating nanomaterials and nanostructures, biosensors have witnessed remarkable advancements in critical parameters such as limit of detection, accuracy, and reliability. This infusion of nanotechnology has paved the way for biosensors capable of single-molecule detection, amplified trans-duction outputs, and swift analyte identification. The deployment of such innovative biosensors has effectively surmounted previous bottlenecks, fostering practical implementations across various domains.

One of the pivotal achievements in biosensing owes its credit to nanotechnology, as it enables the realization of remarkable sensitivity that can detect individual molecules. This capability has profound implications in disease diagnosis, environmental monitoring, and food safety, where even trace amounts of analytes can provide vital insights. The amplified transduction outputs achieved through nanomaterial incorporation have magnified the response signal of biosensors, enhancing their accuracy and precision. This facet is particularly advantageous in medical diagnostics, where minute variations in analyte concentrations can carry critical diagnostic significance. Furthermore, the integration of nanotechnology has unlocked the potential for rapid analyte detection, addressing the urgent need for swift results in fields like clinical diagnosis and public health. The amalgamation of nanomaterials with biosensors has led to the development of point-of-care devices that empower rapid on-site analysis,

Table 2: Nanostructures utilized in IoT base wearable device.

Ref.	Nanostructures	Limit of detection	Analyte	Transduction mechanism
[24]	AuNPs	0.1 µg/L	Tumor markers	Electrochemical
[25]	AuNPs	1.52×10^{-10} mol/L	DNA hybridization	Electrochemical
[26]	AuNPs	0.18 µM	Glucose	Electrochemical
[27]	AuNPs	4.01×10^{-7} M	Horseradish peroxidase	Electrochemical
[28]	AuNPs	25 ng/ml	Antibody/Antigen interaction	Optical
[29]	AuNPs	1 pM	Enzymatic ligation reactions	Optical
[30]	AuNPs	0.234 ppb	Organophosphorus pesticides	Optical
[31]	AuNPs	10 pM	DNA hybridization	Optical
[32]	AuNPs	3.2×10^{-11} M	Gene sensing	Piezoelectric
[33]	AuNPs	10 µg/ml	DNA sensing	Piezoelectric
[34]	AuNPs	2.6×10^{-9} mol/L	DNA mutation detection	Piezoelectric
[35]	AuNPs	15.3 ng/ml	α-fetoprotein	Piezoelectric
[36]	AuNPs	10.9 µg/ml	Rabbit/goat anti-human IgG	Piezoelectric
[37]	CNTs	1.0×10^{-6} mol/L	Fructose	Electrochemical

bypassing the time-consuming laboratory processes. This is exemplified in the context of infectious diseases, where rapid detection and containment are paramount to prevent outbreaks [39].

However, despite these remarkable advancements, nanotechnology-enabled biosensors are not devoid of challenges and limitations. The release of nanoparticles into the environment is a significant concern, potentially leading to ecological and health-related consequences. Moreover, the quantum effects that contribute to heightened sensitivity can also introduce randomized noise and background signals. This can result in cross-sensitivity, nonlinear responses, and no repeatability upon exposure to certain analytes. Addressing these challenges is crucial to ensure the accuracy and reliability of biosensor measurements. Additionally, while nanomaterials like graphene hold immense promise for biosensing applications, challenges remain in their large-scale fabrication. Overcoming this obstacle is vital for making nanotechnology-enabled biosensors widely accessible and cost-effective. Further research and innovation are essential to unlock the full potential of these materials. In the broader context, this review article serves as a comprehensive exploration of biosensors realized through nanotechnology-enabled thin films and miniaturized structures. It delves into various nanomaterials, including thin films, AuNPs, CNTs, graphene, and quantum dots, elucidating their roles and applications in biosensing. Numerous examples from the literature underscore the diverse applications of these biosensors across medical diagnostics, environmental monitoring, and beyond.

Significantly, the review delves into the influence of nanotechnology-enhanced biosensors within the realm of cancer research. The exceptional sensitivity of these biosensors has profound implications for early cancer detection and monitoring, offering hope for improved patient outcomes. Looking ahead, the review offers a glimpse into the future of biosensors within the context of low-power sensors for the IoT [40]. The potential commercial prospects of nanotechnology enabled biosensors are highlighted, emphasizing their role in revolutionizing data collection and analysis. Moreover, the integration of machine-learning techniques into biosensing platforms holds immense promise in enhancing the accuracy, specificity, and interpretability of biosensor data.

Conclusion

Nanotechnology has propelled biosensors to new heights, challenges remain to be addressed. Wide-ranging applications have become possible due to the combination of improved sensitivity, enhanced transduction outputs, and quick detection capabilities. To fully utilize the capabilities of nanotechnology-enabled biosensors, it is essential to ensure environmental safety, reduce noise and background signals, and find solutions to fabrication issues. As research continues to evolve, these biosensors hold the potential to revolutionize healthcare, environmental monitoring, and technological advancements. The integration of nanotechnology has unlocked the potential for rapid analyte detection, addressing the urgent need for swift results in fields like clinical diagnosis and public health. The amalgamation of nanomaterials with biosensors has led to the development of point-of-care devices that empower rapid on-site analysis, bypassing the time-consuming laboratory processes. This is exemplified in the context of infectious diseases, where rapid detection and containment are paramount to prevent outbreaks.

Acknowledgements

The corresponding author would like to thank all the co-authors for their contribution while preparing the final manuscript.

Conflict of Interest

None.

References

1. Chen H, Bai L, Li T, Zhao C, Zhang J, et al. 2018. Wearable and robust triboelectric nanogenerator based on crumpled gold films. *Nano Energy* 46: 73-80. https://doi.org/10.1016/j.nanoen.2018.01.032
2. Jiang M, Lu Y, Zhu Z, Jia W. 2021. Advances in smart sensing and medical electronics by self-powered sensors based on triboelectric nanogenerators. *Micromachines* 12: 698. https://doi.org/10.3390/mi12060698
3. Kim BJ, Evans JW, Wright PK. 2018. Pulsed discharge of printed secondary Zn-MnO_2 batteries for IoT and wearable devices. *J Phys Conf Series* 1052(1): 012012. https://doi.org/10.1088/1742-6596/1052/1/012012
4. Tentzeris MM, Eid A, Lin TH, Hester JG, Cui Y, et al. 2021. Inkjet-/3D-/4D-printed Nanotechnology-Enabled Radar, Sensing, and RFID Modules for Internet of Things, "Smart Skin," and "Zero Power" Medical Applications. In Rahmat-Samii Y, Topsakal E (eds) Antenna and Sensor Technologies in Modern Medical Applications. Wiley-IEEE Press, pp 399-434.
5. Li X, Jiang C, Ying Y, Ping J. 2020. Biotriboelectric nanogenerators: materials, structures, and applications. *Adv Energy Mater* 10(44): 2002001. https://doi.org/10.1002/aenm.202002001
6. Hussain CM, Di Sia P. 2022. Handbook of Smart Materials, Technologies, and Devices: Applications of Industry 4.0. Springer Nature.
7. Colombo RN. 2022. Biosensors in point-of-care: molecular analysis, strategies and perspectives to health care. *Adv Bioelectrochem* 3: 169-198. https://doi.org/10.1007/978-3-030-97921-8_7
8. Agarwal S, Bhardwaj G, Saraswat E, Singh N, Aggarwal R, et al. 2022. Insurtech fostering automated insurance process using deep learning approach. In 2nd International Conference on Innovative Practices in Technology and Management, Uttar Pradesh, India.
9. Bodur G. 2020. Internet of Things (IoT) in healthcare: are we ready for the future? *Arch Health Sci Res* 7(1): 75-81. https://doi.org/10.5152/ArcHealthSciRes.2020.550716
10. Sun H, Yin M, Wei W, Li J, Wang H, et al. 2018. MEMS based energy harvesting for the internet of things: a survey. *Microsyst Technol* 24: 2853-2869. https://doi.org/10.1007/s00542-018-3763-z
11. Wang H, Han M, Song Y, Zhang H. 2021. Design, manufacturing and applications of wearable triboelectric nanogenerators. *Nano Energy* 81: 105627. https://doi.org/10.1016/j.nanoen.2020.105627
12. Zhao Z, Dai Y, Dou SX, Liang J. 2021. Flexible nanogenerators for wearable electronic applications based on piezoelectric materials. *Mater Today Energy* 20: 100690. https://doi.org/10.1016/j.mtener.2021.100690
13. Bito J, Bahr R, Hester J, Kimionis J, Nauroze A. 2017. Inkjet-/3D-/4D-printed autonomous wearable RF modules for biomonitoring, positioning and sensing applications. In Micro and Nanotechnology Sensors, Systems, and Applications IX, Anaheim, CA, USA.

14. Yang L, Ma Z, Tian Y, Meng B, Peng Z. 2021. Progress on self-powered wearable and implantable systems driven by nanogenerators. *Micromachines* 12(6): 666. https://doi.org/10.3390/mi12060666
15. Park J, Kim D, Kim YT. 2021. Triboelectric nanogenerator based E-skin for wearable energy harvesting and pressure sensing. In IEEE 21st International Conference on Nanotechnology, Montreal, QC, Canada.
16. Kim HJ, Yim EC, Kim JH, Kim SJ, Park JY, et al. 2017. Bacterial nanocellulose triboelectric nanogenerator. *Nano Energy* 33: 130-137. https://doi.org/10.1016/j.nanoen.2017.01.035
17. Jin L, Xiao X, Deng W, Nashalian A, He D, et al. 2020. Manipulating relative permittivity for high-performance wearable triboelectric nanogenerators. *Nano Lett* 20(9): 6404-6411. https://doi.org/10.1021/acs.nanolett.0c01987
18. Schreier G. 2014. The internet of things for personalized health. *Stud Health Technol Inform* 200: 22-31. https://doi.org/10.3233/978-1-61499-393-3-22
19. Tabrizi HO, Jayaweera HM, Muhtaroğlu A. 2018. A fully integrated autonomous power management system with high power capacity and novel MPPT for thermoelectric energy harvesters in IoT/wearable applications. *J Phy Conf Series* 1052(1): 012127. https://doi.org/10.1088/1742-6596/1052/1/012127
20. Blobel B. 2020. Track My Health: An IoT approach for data acquisition and activity recognition. In Proceedings of the 17th International Conference on Wearable Micro and Nano Technologies for Personalized Health, Prague, Czech Republic.
21. Asuncion LVR, De Mesa JXP, Juan PKH, Sayson NT, Cruz ARD. 2018. Thigh motion-based gait analysis for human identification using inertial measurement units (IMUs). In IEEE 10th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management, Baguio City, Philippines.
22. Karthicraja VM, Prasad VK, Kruthika U, Sivakumar R. 2018. Smart wearable systems for personal care with internet of things. In Fourth International Conference on Biosignals, Images and Instrumentation, Chennai, Tamil Nadu, India.
23. Papoutsis A, Botilias G, Karvelis P, Stylios C. 2020. A machine learning approach for human activity recognition. *Stud Health Technol Inform* 273: 155-160. https://doi.org/10.3233/SHTI200631
24. Dharmasena RD, Silva SR. 2019. Towards optimized triboelectric nanogenerators. *Nano Energy* 62: 530-549. https://doi.org/10.1016/j.nanoen.2019.05.057
25. Bhagade P, Kanawade S, Nikose M. 2016. Emerging Internet of Things in Revolutionizing Healthcare. In Satapathy S, Bhateja V, Joshi A (eds) Proceedings of the International Conference on Data Engineering and Communication Technology. Advances in Intelligent Systems and Computing. Springer, Singapore, pp 683-690.
26. Rojas JP. 2019. Organic-inorganic heterostructures for stretchable electronics. In Micro and Nanotechnology Sensors, Systems, and Applications XI. Baltimore, MD, USA.
27. Lhotska L, Doležal J, Adolf J, Potůček J, Křížek M, et al. 2018. Personalized monitoring and assistive systems: Case study of efficient home solutions. *Stud Health Technol Inform* 249: 19-28. https://doi.org/10.3233/978-1-61499-868-6-19
28. Gorup LF, Sequinel T, Akucevicius GW, Pinto AH, Biasotto G, et al. 2021. Nanostructured Gas Sensors in Smart Manufacturing. In Thomas S, Nguyen TA, Ahmadi M, Farmani A, Yasin G (eds) Nanosensors for Smart Manufacturing. Elsevier, pp 445-485.
29. Lee JP, Lee JW, Yoon BK, Hwang HJ, Jung S, et al. 2019. Boosting the energy conversion efficiency of a combined triboelectric nanogenerator-capacitor. *Nano Energy* 56: 571-580. https://doi.org/10.1016/j.nanoen.2018.11.076
30. Shen J, Li B, Yang Y, Yang Z, Liu X, et al. 2022. Application, challenge and perspective of triboelectric nanogenerator as micro-nano energy and self-powered biosystem. *Biosens Bioelectron* 216: 114595. https://doi.org/10.1016/j.bios.2022.114595
31. Türkeli S, Elmas F, Atay HT, Kurt KK, Sonmez RY. 2017. A hybrid algorithm for fall detection. *Stud Health Technol Inform* 237: 163-168. https://doi.org/10.3233/978-1-61499-761-0-163
32. Koay JS, Gan WC, Soh AE, Cheong JY, Aw KC, et al. 2020. An overlapped electron-cloud model for the contact electrification in piezo-assisted triboelectric nanogenerators via control of piezoelectric polarization. *J Mater Chem A* 8(48): 25857-25866. https://doi.org/10.1039/D0TA09506K
33. Arul C, Omkumar S. 2019. A hybrid energy efficient nano architecture using memristors chaos systems for secure communication. *Int J Eng Adv Technol* 8(6): 378-383. https://doi.org/10.35940/ijeat.E7730.088619
34. Guo X, Liu L, Zhang Z, Gao S, He T, et al. 2021. Technology evolution from micro-scale energy harvesters to nanogenerators. *J Micromech Microeng* 31(9): 093002. https://doi.org/10.1088/1361-6439/ac168e
35. Raj EFI. 2022. Data-driven modern health care systems with the internet of medical things combined with big data and machine learning. *AI Enabled IoT Smart Health Care Syst* 123-145.
36. Wang D, Zhang D, Yang Y, Mi Q, Zhang J, et al. 2021. Multifunctional latex/polytetrafluoroethylene-based triboelectric nanogenerator for self-powered organ-like MXene/metal–organic framework-derived CuO nanohybrid ammonia sensor. *ACS Nano* 15(2): 2911-2919. https://doi.org/10.1021/acsnano.0c09015
37. Lama J, Yau A, Chen G, Sivakumar A, Zhao X, et al. 2021. Textile triboelectric nanogenerators for self-powered biomonitoring. *J Mater Chem A* 9(35): 19149-19178. https://doi.org/10.1039/D1TA02518J
38. Maharjan P, Toyabur RM, Park JY. 2018. A human locomotion inspired hybrid nanogenerator for wrist-wearable electronic device and sensor applications. *Nano Energy* 46: 383-395. https://doi.org/10.1016/j.nanoen.2018.02.033
39. Rojas JP, Rehman MU, Albettar MA, Conchouso D, Arevalo A, et al. 2018. Folding and stretching a thermoelectric generator. In Micro-and Nanotechnology Sensors, Systems, and Applications X, Orlando, FL, USA.
40. Türkeli S, Kurt KK, Catamak A, Sonmez RY, Atay HT. 2016. Creating an IOT that notifies concerned people for the falls of geriatric patients. *Stud health Technol Inform* 224: 105-107. https://doi.org/10.3233/978-1-61499-653-8-105