

Wearable Nano sensors for Continuous Health Monitoring Application

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DOI: <https://doi.org/10.54392/nnxt2533>

Received: 10-06-2025; Revised: 02-09-2025; Accepted: 12-09-2025; Published: 23-09-2025

Abstract: The common trends in healthcare are that it is a paradigm shift in healthcare movement towards a continuous and personalized health management as opposed to episodic and hospital-centric care. This iserosive change spurred by the emergence of wearable nano sensors that can combine superior nanotechnology with bioelectronics in order to facilitate a real-time understanding of human health like never before. This review article offers a complete overview of principles, materials, fabrication, and applications of wearable nano sensors. It presents the cornerstone advantages of nanomaterials, including ultra-high sensitivity, miniaturization, and biocompatibility, which allow the tracking a broad spectrum of physiological and biochemical biomarkers. The report examines in detail novel fabrication methods, such as electrospinning and inkjet printing, and describes the pressing problem of power requirements with novel energy harvesting methods. It also looks further into the clinical utility of such devices in the treatment of chronic illnesses and the cutting-edge applications they are becoming in advanced systems such as BMIs and prosthetics. Lastly, an appraisal of the technical, biological and ethical issues, e.g., foreign body reaction, nano toxicity, data privacy and equity is provided. The conclusion of the analysis is that an ethical approach to implementing this technology into comprehensive clinical use can depend on a unified strategy that incorporates resilient materials science, low-power electronics, sophisticated data analytics, and an active ethical perspective.

Keywords: Biocompatibility, Nano, Sensor, Health.

1. Introduction: The New Paradigm of Personalized Healthcare

1.1 The Shift to Continuous, Personalized Health Monitoring

The classic paradigm of healthcare, which is based on the occasional doctor visits and electrophysiological tests which are only performed at a specific period of time is in itself not sustainable enough to provide insight into the physiological alterations that have occurred before or even during the course of a disease. A major societal aspiration is then to go beyond this paradigm and create precision health management platforms that can continuously survey an individual's health in real-time, instantaneously providing information to be used to make decisions and intervene. These systems, which can gather an enormous amount and variety of health-related data anytime, anywhere, have the potential to

transform healthcare into a predictive and preventative model, particularly to address aging populations and the development/management of chronic diseases such as diabetes, cardiovascular diseases, and neurodegenerative diseases [1].

The fundament in this revolution is a nano sensor. These devices could be defined as the ones using nanomaterials and are characterized by high sensitivity and specificity. The extraordinary sensitivity of nano sensors that is associated with the intrinsic properties of nanomaterial namely: the ultrafine size of nanomaterial, the high surface-to-volume ratio, and the varied physical properties of nanomaterials enable them to exhibit the extraordinary signal response to the weak physical and biochemical stimuli. The ability to measure these slight fluctuations in the existence of biomarkers is essential in early diagnosing of disease that would otherwise go undiagnosed by conventional



techniques. Nano sensors can also be modified with molecular recognition probes that specifically measure their target analyte providing additional confidence and accuracy to the data acquired [2]. Their convenient packaging as wearable nano sensors, allows them easy integration into personal and unobtrusive health monitoring, which makes it an essential prevention/prognosis tool.

The trend of personalized continuous health monitoring is a paradigm shift in healthcare philosophy. With nano sensor-enabled wearables and the potential to utilise machine learning to perform meaningful analysis, the quality and input of personal data provide individuals with opportunities to take ownership of their health and wellbeing as shown in the figure 1. This alters the dynamic of clinicians into preventive consultants who engage in the longitudinal data to predict symptoms and prevent health conditions [3].



Figure 1. Over view of Wearable Nano sensor Application

1.2 Scope of the Review

This review paper gives a systematic overview of the underlying concepts, important nanomaterials, novel manufacturing processes, and multifaceted applications of nano sensors in wearable devices. This starts by giving an outline of the advantages that nano sensors have over conventional wearable technology in

terms of convenience. Then, it gives an in-depth overview of nanomaterials that are in current use in this aspect detailing their special characteristics and trade-offs. The report also looks at the engineering hurdles and fixes of large scale manufacturing and device longevity, such as low-power electronics and power harvesting. The article includes a special chapter on the clinical and specialty uses of this technology, including application in chronic disease management and in optimization of sports functional performance. The review concludes with a discussion of the forefront of nano-bioelectronics [4], namely its use in brain-machine interfaces (BMIs), followed by a critical discussion of the numerous biological, technical and ethical concerns that must be overcome in applying this technology to a wide range of humans.

2. Foundational Principles and Key Nanomaterials

2.1. The Advantages of Nano sensors over Conventional Wearables

The raison d'être future of nanotechnology in wearable technology Nano sensors have the potential to address the problem of wearable device size and sensitivity that faces conventional sensors, presenting an opportunity to create a category of devices that are able to collect data with all the fidelity and at all times. Nanomaterials applied in these devices have many performance advantages, mainly due to the extreme high surface-to-volume ratio. This effect has strengthened a more effective communication of the biological analytes making it able to detect a small concentration of biomarkers in bodily fluids such as sweat, blood and saliva. Such sensitivity is essential in detecting the subtle physiological perturbations that can be an indicator to the existence of a medical condition.

Moreover, the miniaturization involved in the use of nanomaterials as well as flexibilities will continue to propel a giant leap in design of wearable devices. The dimensions of sensors can be a micro- or a nanometre, making them smooth and easy to integrate into clothing, patches or other everyday materials to enjoy lightweight and the extended use with maximum comfort. The comparative elasticity of these materials will enable them to fit the contours of the human body to increase the precision of the connection and transmission of the sign [5]. These features coupled with the excellent electrical, physical, and chemical properties of nanostructured material make them a

very important tool to develop a new generation of wearable sensors.

2.2. A Compendium of Key Nanomaterials for Wearable Bioelectronics

The nanomaterials choice is not a simple trade debut but a dilemma optimization problem and involves weighting both the original material properties and limitations, and possible trade-offs. Practical uses of wearable sensing in the future may depend on synergistic, multi-material systems to achieve an optimal performance, safety, and functionality combination with the strengths of different nanomaterials.

Carbon based Nanomaterials: Graphite & Carbon Nanotubes (CNTs)

The new wearable bioelectronics materials, graphene, as a two-dimensional allotrope of carbon, is a truly revolutionary material because of its properties with respect to electronics, mechanical, and optical properties. Graphene has been described as potential biosensors in its ability to be very lightweight; sensitive as well, extendable, and integrate easily within the body of the human being. ApoE controls its extraordinary conductivity and electrochemical stability to unlock the ability to recognize a large variety of possible biomarkers [6]. Significantly, the surface chemistry of graphene can be easily modified to fit with various biorecognition components hence allowing the protection of special analytes.

Carbon nanotubes (CNTs) that may be envisioned as rolled-up sheets of graphene are also very promising in the area of neural interfaces and bioelectronics. These one-dimensional nanostructures have both superior electrical conductivity, high mechanical properties as well as high surface- to - volume ratio, which is a key factor in decreasing the electrode impedance and signal to noise ratios [7]. CNTs have been reported to be highly biocompatible and they offer a framework/ scaffold to which nerve cells adhere, owing to their special structure that raises surface roughness and functional surface area. Pristine CNTs are, however, hydrophobic in nature thus prone to aggregation and may cause toxic effects in biological systems likely warranting the need to functionalize them with molecules and polymers to enhance their solubility and biocompatibility in the biological setting.

Metallic and Semiconductor Nanomaterials: Gold, Silver and Quantum Dots

Gold (AuNPs) and silver (AgNPs) nanoparticle metallic nanoparticles are extensively researched to serve in wearable sensors because they possess a superior thermal and electrical conductivity, low cost (AgNPs), and large surface area, which is referred to as the surface-to-volume ratio. Gold nanoparticles in particular are preferred due to their high chemical and mechanical properties and minimal amounts of toxicity along with optimal biocompatibility [8], which make them valuable across a wide spectrum of applications including optical nano sensors and targeted drug delivery systems.

Nonetheless, there is another challenge in the case of some metallic nanoparticles in direct contact with neuronal tissue, namely gold and silver. Although AuNPs have been widely referred to as exceptionally biocompatible, other studies have demonstrated that AuNPs disrupt the development of human embryonic neural precursor cells and, when administered in the CNS, can induce hyper-excitability in neurons and exacerbate seizures [9]. In a comparable fashion, it has been demonstrated that the AgNPs can augment apoptosis and DNA damage in stem cell and the fact that they can cross the blood brain barrier. This indicates that even otherwise biocompatible materials may have complicated and potentially damaging effects on the nanoscale, in effect proving that such large-scale applications are in dire need of further research into nano toxicity.

Quantum dots (QDs) are a type of semiconductor nanocrystal with specific benefits because their optical properties can be tailored to a specific need by carefully controlling their shape and size during their manufacture. The resulting optical sensors also have great sensitivity to variations in biomolecular interactions [10], which is due to this special quantum confinement effect. Because of that, they can be included into wearable sensors and allow detection of a wide variety of biomarkers and other physiological parameters.

3. Advanced Fabrication and System Integration

3.1 Scalable Manufacturing Techniques

Bringing wearable nano sensors to market will require low-cost and scalable manufacturing methods as lab-scale prototypes simply cannot produce cost-effective wearable nano sensors. The top-down or bottom-up methods allow the exact assembly of a complex geometry at the nanoscale.

Table 1. Key nanomaterials with advantages, properties, and applications in biosensor technologies

Nanomaterial	Primary Advantages	Key Properties	Primary Applications
Graphene	High conductivity, flexibility, biocompatibility, high surface-to-volume ratio	Electrical: High conductivity, excellent electron mobility; Mechanical: High strength, flexibility; Chemical: Easily functionalized, chemically stable; Optical: Transparent	General biosensors, wearable sensors for real-time monitoring of various analytes, neural interfaces
Carbon Nanotubes (CNTs)	High conductivity, mechanical strength, large surface area-to-volume ratio, scratch resistance	Electrical: Low impedance, high charge injection capacity; Mechanical: High strength, flexibility	Biosensors, neural implants (improving electrical properties and cell adhesion), smart textiles
Gold Nanoparticles (AuNPs)	High biocompatibility, chemical stability, high electrical conductivity, low toxicity	Electrical: High conductivity; Physical: High surface area, plasmon resonance; Chemical: Stable	Optical nanosensors, biosensors, drug delivery systems, theranostics
Silver Nanoparticles (AgNPs)	High electrical/thermal conductivity, low cost, stability, excellent selectivity	Electrical: Best electrical conductor among all metals; Physical: High thermal conductivity	Biosensors, antimicrobial coatings, wound disinfection
Quantum Dots (QDs)	Tunable optical properties, high sensitivity	Optical: Tunable emission frequency, narrow emission spectrum; Electrical: Semiconductor properties	Wearable displays, biological sensing platforms, photoresistors, phototransistors

More conventional techniques such as photolithography are in use, but new strategies seem more appropriate to the flexible and complex designs needed in wearables [11].

Electrospinning: This involves electrohydrodynamic and is used to make continuous nanoscale fibers of polymers. The simplicity, scalability, and capability to generate porous fibrous membranes with a high surface area-to-volume ratio makes it especially attractive to wearable sensing. The mechanical properties of electro spun materials such as flexibility and elasticity are exceptional and therefore enable the conformability of the materials to the skin to suit sensing stability of the materials [12]. This has been applied to the production of materials that are capable of collecting an electric charge when the wearer is in motion, providing a step towards self powering sensors.

Inkjet Printing: Fast, highly flexible and scalable method of production, inkjet printer

incorporates a drop-on-demand printing process, both reducing waste and enabling high-resolution patterning of flexible substrates. Scientists have succeeded in creating so-called nanoparticle inks, which will allow printing arrays of different sensors on the same flexible carrier [13]. Such methodology has been effectively applied to produce wearable sweat sensors, which were fabricated using molecule-selective core-shell nanoparticles to simultaneously monitor multiple biomarkers, including vitamins, hormones, metabolites and drugs in real time.

3.2. Low-Power Electronics and Energy Harvesting

The demand to achieve health monitoring continuously and in real time poses a critical challenge; namely the need to secure a continuous and stable power supply that is also adequate. Although these miniaturized nano sensors consume low power and the area of the actual sensors are small, the whole system, which covers signal-processing equipment [14], data

storage and wireless communication, is power-consuming. The battery, with all its limitations, including weight, short lifespan, and the danger of chemical leakage is a big challenge to present longevity and user comfort. To surmount all these restrictions, scientists are leaning towards the use of energy harvesting, which involves the extraction and conversion of free environmental energy such as sound, heat to electricity. Such a solution, that enables self-powered, battery-less devices, is an essential step to improving both the lifetime and applicability of devices. The use of nanostructured materials is on the front burner of the move as it is possible to achieve a high degree of improvement in converting energy [15]. As an example, piezoelectric/triboelectric materials employ mechanical force and friction to produce electric charge, and can capture energy during human motion, incorporating the sensor as an active element of the power solution, rather than a passive recipient. This has been a step towards bioelectronic engineering of fully integrated systems in which the functionality of the device and the energy source are inseparable on the material level.

4. Clinical and Specialized Applications

4.1. Monitoring of Physiological and Biochemical Biomarkers

Nano sensors in a wearable format are promising to non-invasively measure many types of biomarkers in a variety of biofluids, including sweat, tears, and interstitial fluid (ISF) as an alternative to invasive blood measurements. This is disrupting the process of gathering health data and in the process making it possible to continuously monitor essential physiological and biochemical parameters [16]. Wearable devices have become able to analyze an extensive set of indicators, including metabolites such as glucose and lactate, electrolytes such as It includes among others, sodium (Na^+) and potassium (K^+) ions as well as hormones such as cortisol. The degree to which it is multi-parameter sensing gives a much more informed and preventive perspective of an individual health and the information gained will prove to be of irreplaceable value to health management and detection of disease processes.

4.2. Disease Diagnostics and Chronic Condition Management

The proactive management of chronic diseases and disorders is being vastly enhanced with the

continuous and high-fidelity data transferred by wearable Nano sensors. Also in cardiovascular disorders, the devices are providing real-time warnings of arrhythmia e.g. atrial fibrillation. In the management of diabetes, continuous glucose monitors (CGMs) cut a lifeline thread by monitoring the trends of glucose levels and precluding the development of dangerous glucose conditions. In neurological diseases such as Parkinson's disease and epileptic seizures, wearable devices have the capacity to track motorized movement and gait patterns, which may be looped to forecast an epileptic attack and help with prompt drug interventions [22]. A union that holds a great deal of potential is the minimally invasive self-screening of Alzheimer disease. The strategy was a new wearable nanosensor that employed a microneedle-based interstitial fluid (ISF) sampling device and an ultrasensitive graphene field-effect transistor (GFET) chip capable of detecting key Alzheimer biomarkers (A B-42, A B-40 and P-tau 217). The technology provides a noticeable alternative to invasive and cumbersome existing diagnostic modalities and opens the possibility of earlier diagnosis and patient-specific treatment.

4.3. Specialized Applications in Sports, Fitness, and Environmental Sensing

Outside the clinical sphere, wearable sensors are helping improve performance in athletic activities and rate the link between individual health and environmental conditions. In sports training, such devices (typically in combination with a deep neural network (DNN) model) continuously record real-time physiological and biomechanical data, such as heart rate variability, motion acceleration, oxygen saturation (SpO_2), and muscle fatigue.

Through the analysis of this data, the AI-driven system can offer personal insights and predictive metrics and ultimately better performance and training schedules. Moreover, these devices are transforming environmental observation through a rich flow of data about environmental exposures such as air quality, sound, and UV. When these two metrics come together (personal health and environmental data), one will be able to directly observe the relationship between their environment and the results of their health [23], leading them to make better lifestyle decisions, including changing their routes in order to avoid pollutants. The aggregated data of such wearables can also be useful in terms of urban planning and overall better functioning of the health policy.

**Table 2** Categories of parameters monitored by biosensors and their clinical relevance.

Category	Specific Parameters Monitored	Examples of Clinical Relevance	Source
Physiological	Heart rate, heart rate variability, blood pressure, respiratory rate, body temperature, motion, sleep patterns	Early detection of arrhythmias and cardiovascular trends; stress response; gait analysis for neurodegenerative disorders	[17]
Metabolic	Glucose, lactic acid, creatine, creatinine, ketone	Real-time management of diabetes; assessment of fatigue and energy use in athletes; monitoring of kidney function	[18]
Hormonal	Cortisol, estrogen, testosterone	Monitoring of mental stress and well-being; endocrine disorder management	[19]
Other Biochemical	Electrolytes (Na ⁺ , K ⁺), pH, vitamins, drugs	Assessing hydration status and muscle function; monitoring medication levels for dose personalization in patients	[20]
Environmental	Air quality, noise levels, UV radiation	Correlating environmental exposures with individual health outcomes; informing lifestyle choices to minimize exposure to pollutants	[21]

5. The Frontier: From Wearables to Brain-Machine Interfaces

5.1. The Convergence of Nano-Bioelectronics and Neural Interfaces

The final manifestation of nano-bioelectronics is realized in brain-machine interfaces (BMIs) that establish a direct interface between an electrical activity in the brain and the outside machinery. The intersection of nanotechnology, artificial intelligence (AI) and neuroscience has opened the path to a new generation of intelligent nanoengineered BMIs that can learn and respond to changing functional needs in-vivo [24]. This convergence is an important step toward erasing the boundary between the non-living, electronic world, and the living, biological world and the ultimate blending of nanoelectronics devices with the information processing systems of the brain.

5.2. Nanomaterial-Enabled Neural Recording and Stimulation

Nanomaterials in neural interfaces promise to be a huge step forward in terms of improving sensitivity (as compared to conventional electrodes) and biocompatibility.

Reduction in the size of electronic transducer devices to the nanoscale enables the higher spatial and temporal resolution and is essential to map and comprehend the brain activity [25]. The materials such as silicon nanowires, graphene are being exploited to capture high-resolution electrophysiological data and to manufacture high-integrity devices that can be integrated into three-dimensional cell networks.

In addition to documentation, nanomaterials offer the potential of providing a new wave of non- or minimally invasive neural electrical stimulation methods by acting as mediators of converting wirelessly-transmitted external stimuli into a localized secondary stimulus. The main signal, which instigates the primary stimuli, like light, magnetic fields or ultrasound can pass through tissue without direct electrical contact, and then the nanomaterial converts this energy to a local electric field, causing heat to stimulate or modulate the neural activity. These methods potentially provide a high spatial resolution and cell-type specificity which is a prerequisite to further the basic neuroscience research as also well as the drug intervention.

**Table 3.** Transduction mechanisms in nanomaterial-based biosensors.

Transduction Mechanism	Primary Stimulus	Secondary Stimulus	Key Nanomaterial	Source
Opto-electric	Light	Electric field	Quantum dots	[26]
Opto-thermal	Light	Heat	Gold nanomaterials	[27]
Magneto-electric	Magnetic field	Electric field	Magneto-electric nanoparticles	[28]
Magneto-thermal	Magnetic field	Heat	Superparamagnetic nanoparticles	[29]
Acousto-electric	Ultrasound	Electric field	Piezoelectric nanomaterials	[30]

5.3. Advancements in Advanced Prosthetics

Nanomaterials are transforming the area of coronet advanced prosthetics in increasing its functionality, comfort, and life-span. Nano materials especially those based on carbon, stand out in leading this endeavour since they are stable, have high transmission mechanisms and are cheap. These are being integrated into superior nerve sensors capable of being applied to the surface of skin or used internally in nerve signalling. Nanocomposites are also under development to enable highly advanced e-skin with multimodal sensing capacities including high order neuro tactility [31]. The aim is to design devices that emulate nature and the behaviour of limbs reacting to the true desires of the user.

The development of materials which heal themselves, namely, hydrogels, is also overcoming the problem of device longevity and bio integration. Nano-bioelectronics have the end goal of developing a bio-integrative platform that is seamless and actively responds to the disease and facilitates the health at the interface with the device.

Conventional neural implants, which consist of inert material, such as silicon or platinum often led to a continuous host inflammatory reaction, better known as the foreign body reaction (FBR). This immune reaction generates a fibrous scar which covers around the implant making it totally ineffective to resist severe rise in electrode impedance and a dramatic decrease in recording performance with time [32]. To address this inherent shortcoming, researchers are attempting to design so-called biohybrid and living electrodes that combine biomaterial coatings and living cells to encourage the healthy survival of host neurons, and to lessen the inflammation reaction. This practice is a radical overhaul in the philosophy of design going

beyond at the minimum harm, and actively fostering a long-term physiological relationship on the cellular level.

6. Critical Challenges and Future Outlook

Although wearable nano sensors hold tremendous potential, there are several important issues to be resolved before they can safely, equitably and as widely as possible be implemented. These obstacles cut across biological, technical and ethical worlds.

6.1. Biological Challenges

The Foreign Body Reaction (FBR): The FBR is the major biological complication when it comes to any implantable device. The mechanical disparity between a hard implant and a soft nervous tissue initiating a continuous inflammatory reaction event, which results in its encapsulation and a substantial loss of the device efficiency.

Biocompatibility and Nanotoxicity: Though an increasing number of nanomaterials are supposed to be biocompatible, the structures of nanotoxicology are not developed yet. The potential long-term consequences of the majority of nanoparticles on the human body are not completely understood [33]. The research has made it known that some nanoparticles including silver and even gold have toxic effects on the neural cells, disrupting their growth in addition to their enhancement of neuron excitability in pathological conditions. This highlights the importance of a more solid, long-term study to entail more information regarding the negative aspects of nanomaterials,

especially their capability to penetrate the blood-brain barrier.

6.2. Technical Hurdles

Signal Integrity and Data Processing: High density arrays on wearable sensors may generate an immense amount of data that need a streamlined processing and compression of the signals on the side of generation in order to retrieve valuable information. The advances in artificial intelligence and machine learning are essential to developing smart interface that would be able to process this amount of information and change its functioning depending on the demands.

Power and Life Time: The short life of the batteries and the related risks to battery leaking, including toxic substances is, still, a major challenge to wearables and implants. Although energy harvesting could be a potential solution, the requirement of a continuous, steady power source to energy harvesting harnessing systems to perform over long-term applications remains a complicated engineering problem.

6.3. Ethical and Societal Concerns

The ongoing process during and after which granular personal data are being collected by wearable sensors poses a series of ethical and societal issues to reflect on.

Data Privacy and Security: Wearable devices acquire very sensitive, and highly personal health-related data, which poses a security risk to their data unless they are well-protected. Known vulnerabilities, such as poor encryption and insecure protocols and communications systems, place at risk unauthorized access, and infiltrated data. This makes it objectionable that data can be used to carry out activities like surveillance, profiling or even discriminatory procedures by insurance providers or employers.

Informed Consent and Data Ownership: A logical issue is that it is not possible to give meaningful informed consent, since users might not have a comprehensive understanding of the amount and the type of the data being captured and shared with third parties. The passivity and enduring character of data gathering using devices that are not intended to interact with the users adds complexity to the domain of guaranteeing them autonomy and the ability to get control over their health data. The question of

ownership of data captured in commercial devices and the utilization of the data towards further purposes is generally not answered in the current legal frameworks.

Equity: The democratization of high-tech wearable devices has the potential to worsen existing health disparities by creating a high-tech "digital and technological divide". Access to these products and the capacity to read the information that they generate is paramount to ensure the benefits of the move do not end up limited to the affluent.

7. Literature Survey

The following table synthesizes key research findings from the provided literature on nano-bioelectronics and neural interfaces, highlighting the diversity of nanomaterials, applications, and advancements in the field.

8. Discussion

This review highlights the disruptive paradigm shift in healthcare interventions where episodes of treatment are hospital-based to actual multi-weeks of personalized health management through wearable nanodevices. Nanotechnology and bioelectronics convergence has allowed the creation of devices that possess an unprecedented degree of sensitivity, miniaturization, and biocompatibility to the extent greater usability of devices intended to monitor various physiological and biochemical biomarkers in real time has become possible [48]. These developments carry a huge promise in terms of the management of diseases, early detection, and the use of patient-specific approaches in terms of treatment approaches. Nanomaterials are still the foundation of such developments, as their particular electrical, mechanical and chemical characteristics allow sensing of very small biological signals. The electrospinning technique and inkjet printing reviewed are scalable and flexible fabrication processes, something that is paramount to the production of wearable devices [49]. However, power consumption and autonomy will continue to be a major obstacle; although energy harvesting innovations like biofuel cells and triboelectric nanogenerators have potential, they must still be optimised further before long-term practicality is established.

Wearable nanosensors thus have applicative implications beyond simple sensing, to including the burgeoning biomedical arenas of brain-machine interfaces (BMIs) and prostheses, ultimately leading

to the creation of customizable and assistive healthcare [50].

Table 4. Applications of nanomaterials in neural interfaces and neuro-bioelectronics.

Nanomaterials Used	Application/Focus	Key Findings	Source
Silicon Nanowires (SiNWs), Carbon Nanotubes (CNTs), Graphene	Nanoelectronics and living biological systems; 3D cell networks; electrophysiology	Emerging nano-bioelectronic tools yield higher spatial and temporal resolution than traditional methods. Kinked nanowires can improve cell/device junctions.	[34]
Graphene	Brain organoid stimulation; brain-machine interface; Alzheimer's disease modeling	Graphene-mediated optical stimulation (GraMOS) accelerates organoid maturation and enhances neuronal communication. GraMOS-enabled organoids successfully controlled a simple robot in real time.	[35]
Undisclosed (biohybrid materials)	Biohybrid neural interfaces; foreign body reaction (FBR) reduction	Conventional neural implants trigger FBR due to mechanical mismatch. Biohybrid approaches, including cell-laden biomaterial coatings, can improve biointegration and long-term performance.	[36]
Carbon Nanotubes (CNTs)	Neural implants; biomaterials; functionalization	Pristine CNTs can be toxic due to their hydrophobic nature. Functionalization via oxidation, polymer wrapping, or covalent bonding improves biocompatibility and solubility.	[37]
Carbon Nanotubes (CNTs)	Neural interfaces; multi-electrode arrays (MEAs)	CNT-modified gold MEAs have low impedance, high stability, and durability. Their high surface area and 3D structure support nerve cell adhesion, enhancing the bio-nano interface.	[38]
Gold (AuNPs), Silver (AgNPs) nanoparticles	Nanotoxicity; effects on human embryonic neural precursor cells (HNPCs)	Both AuNPs and AgNPs interfere with the growth profile of HNPCs. AgNPs, in particular, cause a significant increase in apoptosis, highlighting the need for more nanotoxicology research.	[39]
Gold Nanoparticles (AuNPs)	Neuronal excitability; seizure activity in the mouse brain	Intracellular AuNPs increase the excitability of neurons and can aggravate seizure activity, suggesting a need for careful consideration when using them as therapeutic delivery vehicles in the central nervous system.	[40]
Carbon-based nanomaterials, metallic nanomaterials, hydrogels	Nanomaterial-based prosthetic limbs; e-skin; nerve sensors	Carbon-based nanomaterials are widely studied for nerve sensors due to their stability and transmission properties. Nanocomposites with hydrogels and elastomers are used to create sensitive and flexible e-skin.	[41]
Graphene	Graphene properties for neural interfaces	Graphene has high mechanical strength, chemical stability, and excellent electrical conductivity. It can be used as a neuroprotective agent and a carrier for targeted drug delivery to treat neuronal diseases.	[42]

Various biomaterials and living cells	Biologically-inspired neural interfaces; foreign body response (FBR)	Next-generation interfaces use biologically-derived materials and living cells to promote host neuronal survival and reduce the FBR, improving chronic device-tissue integration.	[43]
Chiral plasmonic nanoparticles	Neural stimulation; hydrogel models for spinal cord injury	A hydrogel containing chiral plasmonic nanoparticles is being designed to act as optical switches to induce neural stimulation and aid axon growth, offering a non-invasive alternative to hard electrodes.	[44]
Graphene (GFET)	Alzheimer's disease (AD) screening; wearable nanosensor	An ultrasensitive wearable nanosensor using a graphene field-effect transistor (GFET) chip can detect AD biomarkers in interstitial fluid (ISF), offering a minimally invasive alternative to traditional diagnostic methods.	[45]
Graphene (GraMOS)	Brain-machine interfaces; neuro-biohybrid systems	Graphene, with its optoelectronic properties, can be used to convert light into gentle electrical cues, accelerating brain organoid maturation without genetic modification or direct currents.	[46]
Gold and Carbon Nanomaterials	Neural Interfaces; electrode coatings	Nanoparticle coatings on electrodes can significantly reduce impedance and improve the signal-to-noise ratio (SNR). Combining noble metals with carbon can enhance neuron growth and charge storage capacity.	[47]

Nevertheless, device stability, foreign body reaction and obtaining appropriate sensor functionality in a real-world dynamic environment are still technical issues that require cross-disciplinary collaborations. Of great concern are the biological and ethical issues that are brought forth by this technology. Concerns like the possible nanotoxicity, biocompatibility after long-term use, privacy of the information, and equal distribution of these new and provocative technologies demand further efforts [51]. Ensuring patient data is safe and inclusive must be applied in order to not worsen existing disparities in healthcare.

Given that a competent clinical realization of wearable nanosensors relies on balanced solutions that encompass resilience in material science, energy efficiency in electronics, competent data analytics, and effective ethical guidelines, it is essential to highlight that the future of wearable nanosensors and the potential application areas, including the life sciences and healthcare, could be painted by a bigger canvas that includes all the specified factors [52]. Further interdisciplinary collaboration will also be necessary to bring such potentially promising technology to a wide and practical application in healthcare that will result in better patient outcomes and health empowerment of the population.

9. Conclusion

Wearable nanosensors have the potential of marking a revolutionary step towards the goal of personalized and continuous health monitoring. The application of nanomaterials to the bioelectronic products has imparted the production of sensorics with unequaled proficiencies in limited wearable applications. Those fundamental strengths-high surface area-to-volume ration, in-place miniaturization, mechanical flexibility-are making it possible to non-invasively collect high-fidelity health data in real time. Nevertheless, the discipline is at a rupture point.

The process of laboratory innovations to commercially and clinically viable products is impaired by processes that are complicated and have multiple dependencies. On the biological side, their long-term biocompatibility, including the effects on potential nanotoxicity, should be determined, especially in the case of implants where the foreign body reaction remains the greatest obstacle to device lifetimes. Technologically, there will be a paradox of low-power nano sensors in the context of power-hungry systems, and that necessitates a directional shift concerning self-sustainable architectures, where energy harvesting is embedded at the material level.

Finally, and most importantly, the proliferation of wearable nano sensors will remain contingent upon limiting a complicated set of ethical and societal issues. The ongoing generation of sensitive personal data requires a well-developed data security and privacy mechanism integrated into the device but not an afterthought of regulatory mandate. Data ownership should not be as opaque as it now is and transforming the problem of gaining informed consent to data sharing should be addressed. If these concerns are not met, there may be a risk of a digital divide whereby those who will have access to this potentially life-changing technology are restricted to only a few, and thus contribute to the widening of health disparities.

Finally, the future of the wearable nano sensors and nano-bioelectronics is an impressive paradigm. Whether or not this technology will succeed boils down not only to the technical prowess of such an effort, but the extent to which the scientific and medical community is able to operate archetypally joining the many aspects of biological, technical, and ethical concerns in making this effort succeed. Developing a platform of trust, visibility, and fairness, wearable nano sensors can live up to the expectations of restructuring healthcare, shifting toward a health-sustain system as the prior one, which was based on the treatment of the diseases only.

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Conflict of interest

The Authors declares that there is no conflict of interest anywhere.

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Funding

The authors did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability

No datasets were generated or analyzed during the current study. All data supporting the findings of this study are included in the manuscript.