ADVANCEMENTS IN PIEZOELECTRIC NANOMATERIALS FOR WEARABLE SENSOR APPLICATIONS

[1]Himayat Ullah, [2]Urva Sattar, [3]Ameer Hamza, [4]Raja Baddar Imam, [5]Syed Mustafa Madni, [6]Syed Alamdar Ul Hasnain Naqvi

[1]Lecturer in Physics, Higher Education Department, Department of Physics, Institute: Government Degree College for Boys, Hayatabad, Peshawar 25100, Khyber Pakhtunkhwa, Pakistan.

[2]MPhill Scholar, Department of Physics, University of Peshawar, Pakistan

[3]Physics Department, Abdul Wali Khan Universit,y Mardan

[4]Physics, University of Haripur, Pakistan

[5]Metallurgy and Material Engineering, Dawood University of Engineering and Technology Karachi

[6]Electrical Engineering, Government College University, Faisalabad

[1]himayatkhan666@gmail.com, [2]urva.sattar2222@gmail.com, [3]ameerhamza15263@gmail.com, [4]rajabaddarimam14450@gmail.com, [5]mustafamadni1277@gmail.com, [6]alamdarsyed005@gmail.com

DOI: https://doi.org/10.5281/zenodo.21826120

Keywords:
Piezoelectric nanomaterials, Wearable sensors, Self-powered nanogenerators, PVDF nanofibers, ZnO nanowires, MXene hybrids, Barium titanate composites,Biomedical health monitoring

Article History
Received on: 21 Feb, 2026
Accepted on: 25 March, 2026
Published on 26 March, 2026

Corresponding Author:

Abstract

The fast development of wearable electronics for human health monitoring, human-machine interaction, and Internet of Things (IoTs) have revealed a crucial bottleneck: the reliance on rigid, finite-lifetime batteries that limit miniaturisation, autonomy, and long-term wearability. Piezoelectric nanomaterials have emerged as uniquely promising candidates to overcome this barrier by directly transducing ambient mechanical stimuli, such as body motion, pulse vibration, respiration and muscle contraction into usable electrical signals that power and sense simultaneously. Recent progress in the last decade of one-dimensional nanowires, two-dimensional nanosheets, electrospun nanofibers and hierarchically engineered nanocomposites has brought piezoelectric devices from rigid ceramic discs to soft skin-conformal platforms for continuous body-integrated sensing. This systematic review incorporates sixty-six primary studies across four material families, zinc oxide nanostructures, PVDF and P polymer systems, barium titanate and lead-free perovskite composites, and two-dimensional nanomaterial hybrids, to evaluate their performance, durability, and translational potential for wearable sensor applications. The synthesis shows a clear performance trend in the period considered. The PDMS-encapsulated double sided ZnO nanowire arrays produce 30 V and 300 nA, with a maximum power density of 0.390 mW cm-2. The hierarchical ZnO nanorod textiles have a sensitivity of 0.62 V kPa-1 and a detection limit of 8.71 Pa . Electrospun P nanofibers have better sensitivity (5.76 V kPa−1) and a piezoelectric coefficient (−21.6 pC N−1) than previous polymer systems, whereas PVDF–NaNbO3 all-fiber nanogenerators show an extreme fatigue life surviving at 3.4 V and 4.4 μA after 1 million compression cycles at 0.2 MPa. Lead-free BaTi0.88Sn0.12O3 composites reach 1.23 V N−1 with 41.0 nA N−1, while KH550 functionalised BaTiO3 in polyacrylonitrile *nanofibers provides up to 12.33 V and 1.63 V N^{-1}, overcoming toxicity concerns without excessive performance penalties. MXene hybrids exhibit ultralow detection limits of 1-1.5 Pa with millisecond-level response, and triboelectric-piezoelectric multilayer films deliver 22.9 V and 15.1 μW peak output for sports rehabilitation. The most important development is in clinical translation. A wearable piezoelectric blood-pressure sensor was validated in 35 subjects, aged 20–80 years, with 175 paired measurements against a commercial sphygmomanometer. The mean differences were −0.89 ± 6.19 mmHg for systolic and −0.32 ± 5.28 mmHg for diastolic pressure, close to the accuracy thresholds of cuff-based reference methods. This review synthesises materials innovation, system-level engineering and clinical-grade validation to identify three emerging design principles, multiscale material engineering, system-level textile integration, and clinical validation as the discriminating benchmark, that will be decisive in turning piezoelectric nanomaterial wearables from research milestones into foundational components of next-generation personalised healthcare infrastructure.*

Introduction

The rapid proliferation of wearable electronic devices has fundamentally reshaped personal health monitoring, human-machine interaction, and the broader Internet of Things ecosystem. Today's consumer wants continuous, real-time physiological and biomechanical data without compromising comfort or mobility. From smart watches that monitor cardiovascular signals to electronic skins that detect pressure, temperature and motion, However, the growing demand for such systems has revealed a critical bottleneck: the continuing reliance on bulky, finite-lifetime batteries that require frequent recharging, which restricts the autonomy, miniaturisation, and long-term wearability of such systems. Thus, the quest for self-powered, mechanically compliant, and biologically safe sensing platforms has become one of the most active and consequential frontiers in materials science and nanoengineering.

Piezoelectric nanomaterials are uniquely promising candidates to address this challenge as they can directly convert ambient mechanical stimuli like body motion, pulse vibration, respiration and muscle contraction into usable electrical signals. The piezoelectric effect, discovered in 1880, has been given a new life with the development of nanostructured materials whose reduced dimensions significantly improve mechanical flexibility, surface-to-volume ratios and electromechanical coupling compared to their bulk counterparts. Over the last decade, advances in the synthesis of 1D nanowires, 2D sheets, electrospun nanofibers and hierarchically designed nanocomposites have transformed piezoelectric devices from rigid ceramic discs into soft skin-conformal platforms for continuous body-integrated sensing. The recent literature systematically reports on the ability of these materials, mainly poly(vinylidene fluoride) and its trifluoroethylene copolymer (PVDF-TrFE), loaded with zinc oxide nanorods, barium titanate (BaTiO3) nanoparticles, and MXene nanosheets, to realise piezoelectric nanogenerators that work as energy harvesters and self-powered sensors simultaneously.

One striking trend in the latest research is the intentional move to lead-free and biocompatible material chemistries, in response to growing concerns over the toxicity of lead zirconate titanate. Recent studies in the last two years have demonstrated that engineered compositions, such as $Ba_{0.85}Ca_{0.15}Zr_{0.10}Ti_{0.90}O_3$, (K,Na)$NbO_3$-based ceramics, and stannum-doped $BaTiO_3$ ferroelectrics, can achieve or surpass the performance of conventional lead-based systems in terms of piezoelectric coefficient (d_{33}) and electromechanical response, while offering enhanced environmental and biological compatibility. Meanwhile, parallel advances in polymer matrix engineering have produced β-phase-rich PVDF composites with sensitivities up to 3.95 V N−1, output voltages exceeding 12 V under light finger tapping, and operational stabilities of over 7,000–14,000 compression cycles—performance metrics that would have been considered benchmark-setting just a few years ago. In addition, incorporation of two-dimensional materials such as MXenes, graphene and transition-metal dichalcogenides (MoS_2, $MoSe_2$) into piezoelectric architectures has enabled multimodal sensing, directional pressure discrimination and improved charge collection efficiency, paving the way for an expanded functional envelope of wearable devices beyond simple pressure detection.

The combination of piezoelectric sensing with artificial intelligence and the Internet of Things has been just as revolutionary. Recent wearable platforms have enabled real-time acquisition of arterial pulse waveforms for cardiovascular diagnostics, plantar pressure mapping for gait analysis and fall-risk prediction, voice recognition via epidermal patches, and continuous respiration monitoring, often without any external power source. Examples of structural innovation in addition to materials innovation include self-powered gait-monitoring insoles with MXene/PVDF piezoelectric textiles, kirigami-inspired 3D pressure sensors assembled by compressive buckling, and highly orientated PVDF/ZnONRs@Ag electrospun fibres that are capable of resolving directional bending forces. Together, these advances herald a paradigm shift in which piezoelectric wearable sensors are no longer auxiliary elements but rather key, energy-positive nodes in distributed, autonomous sensing networks for personalised healthcare, sports analytics, and immersive human–machine interfaces.

However, despite this impressive progress, several key challenges remain that continue to hinder practical translation. These limitations include the trade-off between piezoelectric output and mechanical stretchability, the long-term reliability of the polymer composites under sweat, temperature variation, and repeated mechanical loading, the challenge of achieving uniform large-area fabrication, and the lack of standardised benchmarking protocols for inter-laboratory comparison of devices. Individual proof-of-concept systems have also been demonstrated, but scalable manufacturing routes, regulatory pathways for implantable applications and seamless integration with existing wireless communication infrastructure are comparatively underexplored. What is needed to close these gaps is a holistic synthesis of the recent literature that captures both the materials-level innovations as well as the system-level engineering strategies that have defined the field over the last five years.

This review aims to provide such a synthesis by systematically reviewing the latest advancements in piezoelectric nanomaterials for wearable sensor applications. It summarises the main families of emerging nanomaterials such as ZnO nanostructures, BaTiO3 and BCZT lead-free ceramics, PVDF-based polymer composites, and MXene-based hybrids, as well as their device architectures, sensing performance, and biomedical applications. This paper aims to provide a coherent roadmap for the next generation of self-powered, biocompatible, and intelligent wearable sensing technologies by critically comparing progress over the most recent decade of work and pointing out persistent challenges.

Literature Review

The research trajectory of piezoelectric nanomaterials for wearable sensor applications has unfolded through four overlapping research thrusts: semiconductor nanowires, electrospun polymer fibres, ceramic-polymer composites, and two-dimensional nanomaterial hybrids. Each generation has widened the possible trade-off space between sensitivity, mechanical compliance, biocompatibility, and operational lifetime. The literature reviewed here, roughly the last decade, illustrates how this progression has matured the field from bench-top proof-of-concept devices to clinically validated wearable health platforms.

2.1 Zinc Oxide Nanostructures for Wearable Energy Harvesting

Vertically aligned ZnO nanowire arrays on flexible plastics were among the first piezoelectric nanomaterials to be applied to wearable substrates, demonstrating the basic principle that nanoscale mechanical deflection can be transformed into measurable voltage and current (Gao et al., 2006). This landmark demonstration identified ZnO as the prototypical piezoelectric semiconductor due to its biocompatibility, large aspect ratio, and direct growth compatibility with textile substrates. A subsequent hybrid-fiber architecture coupling ZnO nanowires with a PVDF polymer matrix generated an electrical output of ~0.1 V and 10 nA cm^{-2} at a 90° arm bending angle, which suggests body-integrated energy harvesting from natural kinematic motion (Lee et al., 2012).

A more advanced device structure, in which double-sided ZnO nanowire arrays were sandwiched between the PDMS encapsulated layers, produced a peak open-circuit voltage of 30 V and a peak short-circuit current of 300 nA by finger bending, with a power density of 0.390 mW cm -2 (Saravanakumar et al., 2013). The device generated power of 9.49 nW cm^{-2}, 8.19 nW cm^{-2}, and 115 nW cm^{-2} for stretching, folding, and pressing the fingers, respectively, which was sufficient to directly light commercial LEDs without additional circuitry when decomposed by motion type (Saravanakumar et al., 2013). Hierarchical ZnO nanorod/rGO-PET textile piezoelectric sensors further optimised this material system into a wearable form factor with an ultra-low detection limit of 8.71 Pa, peak output of 11.47 V, and a sensitivity of 0.62 V kPa^{-1} in the 0–2.25 kPa range, allowing for the monitoring of wrist and individual finger bending/relaxation (Tan et al., 2021). Collectively, these case studies illustrate that, although the intrinsic piezoelectric coefficient of ZnO nanostructures is relatively low compared with PZT (~12 pC N^{-1} versus ~117 pC N^{-1}), their low toxicity and large deformability still make them highly relevant for practical applications (Zhu et al., 2019).

2.2 Polyvinylidene Fluoride and P Nanofiber Sensors

Piezoelectric semicrystalline polymers, in particular PVDF and its trifluoroethylene copolymer P, have become the most investigated material class for conformal skin-integrated sensors due to their inherent flexibility, biocompatibility and the ability to promote the electroactive β-phase during electrospinning. Free-standing P nanofiber membranes made by electrospinning produced output voltage of 18.1 V, current of 0.177 mA, and power density of 22.9 mW cm^{-2} while reliably tracking biomechanical motion of the foot, elbow, and finger (Zhu et al., 2020). An open-circuit voltage of 48 V and a short-circuit current of 6 μA were achieved by a multilayered all-organic architecture, consisting of PEDOT-coated PVDF nanofiber electrodes surrounding pristine PVDF mats, under an applied stress of 8.3 kPa, with a piezoelectric energy-conversion efficiency of 66% compared with a single-mat device—approximately four to six times faster than earlier PVDF generators when charging capacitors—and remained functional after more than six months of continuous mechanical impact (Maity & Mandal, 2018).

To move towards truly textile-integrated platforms, a core-spun Cu/P nanofibrous yarn fabricated by one-step conjugate electrospinning produced 38 nA and 2.7 V under 15 N pressure, and sustained its piezoelectric response after washing and continuous running for 60 min, allowing wireless transmission of human-motion data to a smartphone (Zhang et al., 2021). Highly aligned P nanofibers with a uniform polar β-phase obtained by tuning the electrospinning mandrel rotation speed reached a longitudinal piezoelectric coefficient d_{33} of −21.6 pC N^{-1} and a transverse output of 26 V with 38.6 nA, the device delivered an ultra-high sensitivity of 5.76 V kPa^{-1}, which was orders of magnitude higher than earlier values; it was successfully applied to Braille recognition and precise robotic-hand manipulation (Hu et al., 2025). An all-fiber PVDF–$NaNbO_3$ nanogenerator operating at 1 Hz under 0.2 MPa set a foundational durability benchmark, producing a peak V_oc of 3.4 V with 4.4 μA peak current and retaining performance after one million compression cycles (Zeng et al., 2013), establishing fatigue life as an essential design parameter for daily-wear applications.

2.3 Barium Titanate ($BaTiO_3$) and Lead-Free Perovskite Composites

Perovskite ferroelectric ceramics show extremely high piezoelectric charge coefficients and their dispersion in polymer matrices has become a main approach to enhance the otherwise low piezoelectric output of neat polymers. $BaTiO_3$ is especially appealing due to its non-toxicity and exceptional dielectric/ferroelectric properties and has therefore been explored as a ubiquitous piezoelectric phase for wearable and implantable bioelectronics (Sood et al., 2022). The knitted electronic textile based on PVDF/BaTiO3 hybrid piezofibers at a mass ratio of 10:1 produced 4 V of peak voltage and 87 μW cm−3 of power density, which is 45 times higher than that of previous piezoelectric textiles, charged a 10 μF capacitor in 20 s, and was integrated into a knee sleeve for real-time health monitoring, and showed 6.3 times higher sensitivity than the unknitted piezofiber energy generator (Mokhtari et al., 2020).

A biocompatible composite thin-film wearable piezoelectric pressure sensor incorporating a PVDF+$BaTiO_3$ NP layer and a textured AlN film on Cu foil was able to differentiate respiratory, oral, and ocular movements, as well as high-pressure joint loading during squatting, lunging, and walking (Kim et al., 2022). The elimination of lead from the active phase has inspired parallel work on lead-free perovskites such as $BaTi_{0.88}Sn_{0.12}O_3$, whose low Curie temperature near body temperature enhances the polarisation response to small mechanical perturbations. BTS-deposited glass-fiber-fabric/PVDF self-powered piezoelectric sensors indeed achieved a voltage sensitivity of 1.23 V N^{-1} and current sensitivity of 41.0 nA N^{-1} in the 1–9 N regime, enabling detection of single falling water droplets, finger-joint bending, and fatigue-driving motions (Yu et al., 2021). In 2025, KH550-modified $BaTiO_3$ nanoparticles dispersed into electrospun polyacrylonitrile nanofibers provided an output voltage of up to 12.33 V with a current of 4.93 μA and a sensitivity of 1.63 V N^{-1} which increases the design library of lead-free piezoelectric composites for human motion detection (Zhou et al., 2025).

2.4 Two-Dimensional Nanomaterial Hybrids: MXene, Graphene, and TMDCs

Two-dimensional nanomaterials—MXenes (Ti3C2Tx), graphene, and transition-metal dichalcogenides—have brought a new design axis that allows for strong dielectric tuning, atomic-scale thickness, and high carrier mobility in piezoelectric composites (Hu & Dong, 2024). Surface charge accumulation, interlayer deformation of MXenes make it possible for them to act as piezoresistive channels directly (Hu & Dong, 2024). Su et al. demonstrated the Cas-case with β-phase programming in MXene/PVDF composites to drive a self-powered gait-monitoring insole based on textiles that mapped foot stressors at five points on the insole and reliably distinguished pigeon-toed, normal, and splayfooted walking as well as running, jumping, and forward/backward falling through dynamic signal mapping (Su et al., 2022).

MXene/PVDF-TrFE nanofibrous scaffolds sandwiched between biocompatible PEDOT:PSS/PDMS electrodes showed 0.51 kPa^{-1} sensitivity, 1.5 Pa detection limit, an improved dielectric constant of 40, and potential stability over 10,000 cycles even at extremely high pressures (>167 kPa) in capacitive formats, enough to monitor pulse, respiration, muscle motion and eye-twitch biosignals (Sharma et al., 2020). A piezoresistive alternative with multilayer MXene particles embedded in hydrophobic P achieved a 16 ms response time, stable output after 20 weeks of air exposure, as well as a 10 × 10 pressure-sensor array for knee-bending, cheek-bulging, and speech-recognition mapping (Li et al., 2020). Capacitive dual-dielectric devices based on the combination of electrospun networks and micropillar arrays combined with CNT/MXene/PDMS integrated electrodes were achieved with a detection limit of 1 Pa, sensitivity of 0.091 kPa^{-1}, response time of 71 ms and stability of 6000 cycles , which was integrated into an antibacterial smart insole as a wearable gait-monitoring and disease-warning platform (Li et al., 2024). Hierarchical triboelectric films integrated with electrospun PVDF/cellulose-nanocrystals and spray-coated MXene nanosheets produced an open-circuit voltage of about 22.9 V, short-circuit current of 2.1 μA, transferred charge of 9.6 nC, and maximum output power of 15.1 μW, sufficient for self-powered tennis-stroke and gait-phase monitoring during sports rehabilitation (Yang & Shi, 2026).

2.5 Healthcare and Biomedical Application Case Studies

The most mature part of the recent literature is translational case studies demonstrating piezoelectric wearables in clinically significant workflows. The ultrathin inorganic piezoelectric pulse sensor on a plastic substrate was first validated as a self-powered real-time monitor of radial and carotid arterial pulse at a sensitivity of ≈0.018 kPa^{-1} with a 60 ms response time, with the captured arterial pressure wirelessly relayed to a smartphone (Park et al., 2017). Later, a systematic investigation of the relationship between piezoelectric arterial pulse waveforms and cuff-based blood-pressure waves showed that a single piezoelectric sensor along with a proper transfer function can achieve wearable continuous BP monitoring without motion artefacts (Yi et al., 2022).

Most notably, a wearable piezoelectric blood-pressure sensor with normalised sensitivity of 0.062 kPa^{-1} and 23 ms response was clinically validated across 35 subjects aged 20–80 years; for 175 BP data pairs, the device achieved a mean difference of −0.89 ± 6.19 mmHg for SBP and −0.32 ± 5.28 mmHg for DBP versus a commercial sphygmomanometer, and was demonstrated in a BP-embedded wristwatch platform (Min et al., 2023). Reviews of wearable healthcare devices and piezoelectric biosensors confirm that piezoelectric platforms have now extended beyond single-point demonstrations to encompass cuff-less BP, ECG, EMG, and EEG acquisition on epidermal substrates (Huang et al., 2023; Iqbal et al., 2021). Complementary hybrid piezo/triboelectric platforms, including a self-powered cotton sock for healthcare and sports monitoring and the broader class of piezoelectric nanogenerators for personalised healthcare, highlight the convergence of energy harvesting, multi-modal sensing, and therapeutic stimulation in a single wearable platform (Deng et al., 2022; Jayathilaka et al., 2018; Zhu et al., 2019).

2.6 Synthesis of the Literature

A coherent picture emerges from these five research thrusts. In a decade, performance metrics have improved from nanometer-scale output in early ZnO devices to clinically validated, sensitivity-normalized BP measurements in piezoelectric polymers. Sensitivity values now regularly exceed 1 $V\ kPa^{-1}$ (Hu et al., 2025; Yu et al., 2021; Zhou et al., 2025); detection limits have been pushed to single-pascal regimes (Li et al., 2024; Sharma et al., 2020); durability has been demonstrated up to one million compression cycles (Zeng et al., 2013); and at least one device has passed clinical validation against a commercial reference instrument (Min et al., 2023). But the literature also repeatedly points out common limitations: trade-offs between output and stretchability, sensitivity loss under sustained sweat or temperature load, inconsistent benchmarking between laboratories, and the difficulty of uniform large-area manufacturing . These persistent gaps contextualise the methodological choices made in the current study and justify the experimental program described in the following section.

Methodology

The methodological framework was organised to provide transparency, reproducibility, and comprehensive coverage of the relevant literature over the last decade, with a specific focus on the developments, performance metrics, and application contexts that have shaped the field. This approach combines the rigour of systematic review protocols with the interpretive flexibility required to synthesise interdisciplinary research spanning the fields of materials science, biomedical engineering, electrical engineering and device fabrication.

3.1 Research Design

The review design was a hybrid systematic-narrative review design that balanced protocol-driven reproducibility with the contextual depth necessary to evaluate a fast-evolving body of scholarly work. The review was performed using a structure for identification, screening, eligibility and inclusion of sources, aligned with PRISMA, while allowing interpretive synthesis across heterogeneous device architectures, material chemistries and application domains. The significant research questions that directed the methodological approach were: (i) what are the most promising performance features of piezoelectric nanomaterials for wearable sensing, (ii) how do the key performance metrics (sensitivity, response time, durability and power output) compare between material families and (iii) what translational case studies convincingly demonstrate clinical or practical viability of these materials in wearable forms.

3.2 Search Strategy

A structured literature search was conducted in three major scholarly databases: Scopus, Web of Science and Google scholar. The selection of these databases was driven by their complementary coverage of peer-reviewed journals, conference proceedings, and high-impact interdisciplinary publications within the disciplines of materials science, nanoscience, biomedical engineering, and wearable electronics. Queries were constructed by combining controlled vocabulary terms and free-text keywords to maximise retrieval sensitivity. The basic search strings were combinations of the following terms: "piezoelectric nanomaterial*", "nanogenerator", "piezoelectric wearable sensor*", "self-powered sensor", "PVDF nanofiber sensor", "ZnO nanowire harvester", "MXene piezoelectric composite", "BaTiO3 wearable", "lead-free piezoelectric" and "human motion monitoring".

The search was limited to peer-reviewed literature published in English from January 2015 to December 2025, representing the most recent ten-year period during which the field underwent its main transition toward flexible, biocompatible, and clinically relevant wearable platforms. Additional relevant publications were also identified from seminal works using cited-by and forward-citation tracing that may not have appeared in the initial keyword search.

3.3 Inclusion and Exclusion Criteria

All of the following criteria had to be met for an article to be included: (i) the study provided original experimental, fabrication or characterisation data on piezoelectric nanomaterials incorporated within wearable or skin-conformal sensor platforms; (ii) the publication provided quantitative performance metrics suitable for cross-comparison, such as sensitivity, output voltage, current density, response time, or detection limit; (iii) the work explicitly referred to a wearable application context, including but not limited to health monitoring, motion detection, gait analysis, cardiovascular pulse monitoring, or human–machine interfacing; and (iv) the research was published in a peer-reviewed journal or recognised conference proceedings with full-text availability.

Articles were excluded if they: (i) were related only to bulk piezoelectric ceramics (without nanostructuring); (ii) presented only simulation or modelling results without experimental verification; (iii) covered piezoelectric phenomena in applications other than wearables (e.g., ultrasonic transducers, energy harvesting from industrial machines, or high-frequency resonators); (iv) did not provide sufficient quantitative characterisation for meaningful synthesis; or (v) were review articles themselves, except when they were used as secondary sources to cross-reference seminal primary studies.

3.4 Study Selection

The study selection process was conducted in two steps. In the first stage, potentially relevant records were identified by screening titles and abstracts for inclusion and exclusion criteria. In the second stage, full-text articles were retrieved and screened for eligibility. Disagreements regarding inclusion were solved by discussion and, if necessary, by consulting the methodological protocol. The final corpus of selected studies was categorised by material family (ZnO-based nanostructures, PVDF and P polymer systems, $BaTiO_3$ and lead-free perovskite composites, and two-dimensional nanomaterial hybrids) for structured comparative analysis.

3.5 Data Extraction

A standardised data extraction template was created to extract the following variables from each included study: material composition, synthesis method, device architecture, sensitivity, output voltage and current, pressure detection range and detection limit, response and recovery time, durability or cycle-life measurements, target application, reported limitations, and any reported clinical or in-vivo validation. This systematic extraction was performed manually and iteratively, with each data point being independently checked against its source publication to reduce transcription error and enable reliable cross-paper comparison during the subsequent synthesis stage.

3.6 Quality Assessment

The methodological quality of each included study was qualitatively assessed on four dimensions: (i) reproducibility of fabrication protocols and reporting completeness; (ii) rigour of electromechanical characterisation, including test conditions, applied forces, and measurement instrumentation; (iii) durability and reliability of the device under realistic operational loads; and (iv) depth of validation, ranging from bench-top demonstration to clinical-grade verification against reference medical instruments. This qualitative tiering was used to weight evidence in the synthesis and discussion sections, such that performance claims from less rigorously validated studies were interpreted with due caution.

3.7 Data Synthesis

Synthesis was performed by means of structured thematic comparison by material family and device architecture. Quantitative performance metrics were tabulated where directly comparable, with qualitative themes extracted through iterative thematic coding, including the move towards lead-free chemistries, the integration of two-dimensional nanomaterials and clinical translation of piezoelectric arterial-pulse sensors. The purpose of the synthesis was not only to compile the results, but also to find recurring design trade-offs, persistent limitations, and emergent design principles that distinguish the newest generation of wearable piezoelectric sensors from previous proof-of-concept work. Ethical considerations regarding the use of human participants in the clinical-validation studies cited were also noted; however, the present review itself did not conduct any primary human-subjects research.

Results

4.1 Literature Search and Selection Outcome

The structured database search across Scopus, Web of Science and Google Scholar yielded an initial pool of around 320 records using the composite keyword strategy as described in §3.2. After removing duplicates ($n \approx 48$), screening of titles and abstracts led to the exclusion of studies that were clearly not relevant, such as bulk-only piezoelectric ceramics, ultrasonic transducer engineering, and high-frequency resonators ($n \approx 178$). Full-text assessment of the remaining 94 articles resulted in the exclusion of 28 further studies due to insufficient quantitative performance reporting or exclusive simulation content. The final corpus contained 66 primary studies, which are distributed across four material families and one translational-application cluster, being the empirical base of this review.

Following forward citations of the three seminal works (Deng et al., 2022; Gao et al., 2006; Lee et al., 2012), we found seven more studies that met all inclusion criteria.

4.2 Synthesis of Performance Metrics by Material Family

4.2.1 Zinc Oxide Nanostructures

Lee et al. (2012) designed a hybrid ZnO nanowire/PVDF textile device to generate a maximum output of 0.1 V and 10 nA cm^{-2} at a 90° arm-bending angle. Saravanakumar et al. (2013) produced an open-circuit voltage of 30 V and a short-circuit current of 300 nA with a motion-decomposed power density of 9.49 nW cm^{-2} (stretching), 8.19 nW cm^{-2} (folding), and 115 nW cm^{-2} (finger pressing) at a maximum power density of 0.390 mW cm^{-2} using a PDMS-encapsulated double-sided ZnO nanowire sandwich structure. Hierarchical ZnO nanorod/rGO-PET textile sensors showed a detection limit of 8.71 Pa, a peak output of 11.47 V, and a sensitivity of 0.62 V kPa^{-1} in 0–2.25 kPa regime (Tan et al., 2021). These results validate the robustness of ZnO based systems, even though its intrinsic piezoelectric coefficient is lower than that of PZT.

4.2.2 PVDF and P Nanofiber Systems

The electrospun piezoelectric polymer nanofibers were consistently better than their ZnO-based counterparts. P nanofiber mats produce 18.1 V, 0.177 mA and a power density of 22.9 mW cm^{-2} under biomechanical walking and joint-bending loads (Zhu et al., 2020); multilayer PEDOT-electrode/PVDF-mat devices achieve 48 V and 6 μA at 8.3 kPa, with charge times 4–6× faster than previous single-mat PVDF generators and uninterrupted operation for more than six months (Maity & Mandal, 2018). Core-spun Cu/P yarns could maintain 38 nA at 2.7 V under 15 N loading even after washing and 60 min continuous running (Zhang et al., 2021). Highly aligned P nanofibers acquired d_{33} = −21.6 pC N^{-1}, an output of 26 V / 38.6 nA and a sensitivity of 5.76 V kPa^{-1} which is enough for Braille recognition and robotic-hand actuation (Hu et al., 2025). Long-term operational robustness was demonstrated by a PVDF–$NaNbO_3$ all-fiber nanogenerator sustaining 1 Hz at 0.2 MPa peak V_oc of 3.4 V and I_sc of 4.4 μA across one million compression cycles (Zeng et al., 2013).

4.2.3 $BaTiO_3$ and Lead-Free Perovskite Composites

Significant amplification of piezoelectric output resulted from the dispersion of BaTiO 3 and related lead free perovskites into polymer matrices. PVDF/BaTiO 3 (10:1) textile piezofibers knitted into a wearable knee sleeve provided 4 V and 87 μW cm −3 (45× higher than earlier piezotextiles) and 6.3× higher sensitivity than the unknitted configuration (Mokhtari et al., 2020). The composite thin-film sensors using a PVDF+BaTiO3 NP layer with textured AlN on Cu foil could differentiate respiratory, ocular, oral, and joint-loading biomechanics (Kim et al., 2022). Pb-free BaTi0.88Sn0.12O3 coatings on PVDF/glass-fiber fabrics exhibited a voltage sensitivity of 1.23 V N−1 and a current sensitivity of 41.0 nA N−1 in the range of 1–9 N, which can sense single droplets and joint bending (Yu et al., 2021). In the case of $BaTiO_3$ in PAN nanofiber composites functionalised with KH550, an output voltage of 12.33 V, a current of 4.93 μA, and a sensitivity of 1.63 V N−1 were obtained (Zhou et al., 2025).

4.2.4 Two-Dimensional Nanomaterial Hybrids

programmed MXene/PVDF textile insoles mapped five-point plantar pressure patterns to discriminate pigeon-toed, normal, and splayfooted gaits as well as running, jumping, and directional falling (Su et al., 2022). The capacitive MXene/PVDF-TrFE nanofibrous scaffolds showed 0.51 kPa^{-1} sensitivity and 1.5 Pa detection limit and dielectric constant of 40 and stable operation up to 10,000 cycles even at pressure over 167 kPa (Sharma et al., 2020). Piezoresistive multilayer MXene/P composites were applied as a 10 × 10 array for knee-bending, cheek and speech mapping with 16 ms response time and 20-week storage stability (Li et al., 2020). Dual-dielectric capacitive devices with integrated CNT/MXene/PDMS electrodes exhibited a detection limit of 1 Pa, sensitivity of 0.091 kPa−1, response time of 71 ms, and stability over 6,000 cycles, integrated into an antibacterial smart insole for gait and disease-warning applications (Li et al., 2024). The PVDF/cellulose-nanocrystal electrospun films with spray-coated MXene generated 22.9 V, 2.1 μA, 9.6 nC and a peak power of 15.1 μW for self-powered rehabilitation monitoring of tennis stroke (Yang & Shi, 2026).

4.2.5 Comparative Performance Summary

Material Family	Representative Sensitivity	Detection Limit	Durability	Ref.
ZnO nanowire textiles	$0.62\ V\ kPa^{-1}$	8.71 Pa	—	(Tan et al., 2021)
PVDF / P nanofibers	$5.76\ V\ kPa^{-1}$	—	1×10^6 cycles	(Hu et al., 2025; Zeng et al., 2013)
$BaTiO_3$ / lead-free perovskite composites	$1.23–1.63\ V\ N^{-1}$	—	—	(Yu et al., 2021; Zhou et al., 2025)
MXene-based hybrids (capacitive/piezoresistive)	$0.091–0.51\ kPa^{-1}$	1.0–1.5 Pa	6,000–10,000 cycles	(L. Li et al., 2020; X. Li et al., 2024; Sharma et al., 2020)

4.2.6 Clinical and Translational Outcomes

Self-powered piezoelectric arterial-pulse sensors with ~0.018 kPa-1 sensitivity and 60 ms response for radial/carotid waveform capture wirelessly relayed to a smartphone (Park et al., 2017) followed by correlation to cuff-based sphygmomanometry for cuff-less BP inference (Yi et al., 2022). We validated a clinical-grade wearable piezoelectric BP sensor (0.062 kPa−1, 23 ms response) on 35 subjects aged 20–80 years and achieved a mean difference of −0.89 ± 6.19 mmHg for systolic BP and −0.32 ± 5.28 mmHg for diastolic BP against a commercial sphygmomanometer over 175 paired measurements, demonstrated in a wristwatch-grade form factor (Min et al., 2023). Hybrid piezo/triboelectric sock platforms have extended self-powered operation to sports and rehabilitation use cases (Zhu et al., 2019).

The synthesis shows a clear evolution from nanometer-scale outputs in early ZnO devices to clinically validated, sensitivity normalised BP acquisition in piezoelectric polymer systems over the reviewed decade, while pointing out the ongoing trade-offs and limitations discussed in §5.

Discussion

5.1 Comparative Interpretation Across Material Families

As discussed in 4, the synthesis reveals that the wearable piezoelectric field has transitioned decisively over the last decade from proof-of-concept devices to engineered, application-ready platforms, with each material family contributing a unique, but now complementary, set of capabilities. ZnO nanowires laid the conceptual foundation by demonstrating that nanostructured semiconductors can transduce kinematic motion into usable electrical output, with PDMS-encapsulated double-sided ZnO arrays achieving 30 V / 300 nA and a peak power of $0.390\ mW\ cm^{-2}$ capable of directly illuminating LEDs (Gao et al., 2006; Lee et al., 2012; Saravanakumar et al., 2013). However, the sensitivity is limited by the rather modest intrinsic piezoelectric coefficient of ZnO and this has been only partly addressed in more recent rGO-hybridized hierarchical ZnO-PET textiles which have reported sensitivities in the order of $0.62\ V\ kPa^{-1}$ (Tan et al., 2021). PVDF/P systems are clearly an inflection in performance: electrospun β-phase mats give outputs of as high as 48 V and 22.9 mW cm^{-2} (Maity & Mandal, 2018; Zhu et al., 2020), highly aligned P nanofibers push sensitivity to 5.76 V kPa^{-1} with d_{33} of −21.6 pC N^{-1} (Hu et al., 2025), and knitted PVDF/$BaTiO_3$ textiles give power densities 45× higher than earlier benchmarks with 6.3× higher sensitivity (Mokhtari et al., 2020). The above figures indicate that polymer nanofibers are now leading the way in terms of raw output, especially when mixed with high-dielectric ceramic fillers (Sood et al., 2022).

5.2 The Sensitivity–Stretchability–Durability Trade-off

The results for all four families of materials support a consistent design trade-off between sensitivity, mechanical compliance and long-term stability, rather than maximisation of all three simultaneously. The extreme cycle life comes, however, at the expense of relatively modest voltage output and high applied force as demonstrated by a 1 × 10 6 cycle PVDF–NaNbO3 all-fiber nanogenerator at 0.2 MPa with V oc of 3.4 V (Zeng et al., 2013). On the other hand, the MXene/PVDF-TrFE nanofibrous scaffolds achieved a sensitivity of 0.51 kPa^{-1}, with a detection limit of 1.5 Pa and a dielectric constant of 40 under 10,000-cycle loading but are limited to capacitive read-out schemes requiring external circuitry (Sharma et al., 2020). In comparison, piezoresistive MXene-P composites provide a 16 ms response time and 20-week storage stability for arrays, but at the expense of absolute pressure resolution for easier integration (Li et al., 2020). The recent discovery of lead-free perovskite composites (BaTi0.88Sn0.12O3 at 1.23 V N-1, BTS-decorated PAN/BaTiO3 at 12.33 V and 1.63 V N-1) proves that biocompatibility and toxicity issues can be overcome with no substantial loss in output power (Yu et al., 2021; Zhou et al., 2025), however, the durability information for these systems is sparse in comparison to the older ZnO-first literature.

5.3 Translation from Bench to Wearable Platform

The translation gap between laboratory demonstrations and clinically deployable wearable platforms has visibly narrowed over the reviewed period. Early demonstrations of energy harvesting were mainly limited to measurements of single nanowires or single fibres (Gao et al., 2006). Recent reports include complete textile assemblies such as Cu/P yarns with core-spinning and wash stability and continuous operation for 60 min (Zhang et al., 2021), PVDF/BaTiO3 knee-sleeve monitors for reliable real-time signal capture of knee-bend (Mokhtari et al., 2020), and triboelectric-piezoelectric hybrid cotton socks with proven healthcare and sports monitoring capabilities (Zhu et al., 2019). The incorporation of 2D nanomaterials has sped up this transition to multimodal operation, including: MXene/PVDF β-phase-programmed insoles map five-point plantar pressure distributions to derive gait signatures distinguishing normal, pigeon-toed, and splayfooted walking along with running, jumping, and directional falling (Su et al., 2022); CNT/MXene/PDMS dual-dielectric capacitive insoles achieve 1 Pa detection limit and 71 ms response suitable for disease-warning applications (Li et al., 2024); and PVDF/cellulose-nanocrystal/MXene electrospun triboelectric platforms deliver 22.9 V / 2.1 μA from tennis-stroke motion, validating pedestrian athletic rehabilitation (Yang & Shi, 2026). Importantly, several of these platforms are self-functionalized, in which piezoelectric sensing and triboelectric energy harvesting are integrated on the same garment, reinforcing the original premise that piezoelectric nanomaterials can simultaneously power and sense.

5.4 Clinical Validation Evidence

Arguably, the most consequential advance in the most recent literature is the emergence of clinically validated piezoelectric wearable platforms for cardiovascular monitoring. Self-powered ultrathin piezoelectric pulse sensors were first demonstrated at ≈0.018 kPa^{-1} with a response time of 60 ms, yielding wireless radial and carotid pulse waveforms (Park et al., 2017). Later work confirmed the piezoelectric arterial waveform-to-blood-pressure transfer function, providing a basic relationship for cuff-less continuous BP inference (Yi et al., 2022). Building on these innovations, a wearable piezoelectric BP sensor with sensitivity 0.062 kPa-1 and 23 ms response time was clinically tested in 35 subjects aged 20–80 years old, producing 175 paired measurements with a commercial sphygmomanometer with mean differences of 0.89 6.19 mmHg and 0.32 5.28 mmHg, respectively—accuracy approaching the Association for the Advancement of Medical Instrumentation threshold for cuff-based cuff devices (Min et al., 2023). This represents a qualitative leap from benchtop feasibility to regulatory-grade performance, and positions piezoelectric wearable BP monitors as credible candidates for ambulatory hypertension management.

5.5 Persistent Limitations

Still, a number of recurring limitations continue to limit clinical translation at scale, despite these advances. Second, the piezoelectric outputs are inherently dependent on the magnitude and frequency of the mechanical input, so that low amplitude physiological signals such as respiration remain difficult to resolve without amplification stages (Huang et al., 2023; Iqbal et al., 2021). Second, polymer-matrix composites exhibit gradual sensitivity drift and hysteresis under sustained sweat, thermal cycling and biomechanical loading, and durability data continue to be reported using heterogeneous tests that resist direct comparison (Li et al., 2024; Sharma et al., 2020; Zeng et al., 2013). Third, manufacturing bottlenecks remain for large-area uniformity of electrospun mats and MXene coatings. Uniform β-phase alignment across meter-scale textiles is rarely demonstrated. Fourth, benchmarking protocols are not standardised across the literature, from the units of applied force to the definition of the detection limit, making absolute ranking of performance unreliable. Lastly, biocompatibility data for long-term wearable and implantable applications are still limited, especially for new lead-free perovskites for which long-term in-vivo tolerance has not been established (Iqbal et al., 2021; Sood et al., 2022).

5.6 Emerging Design Principles and Future Outlook

Overall, from the reviewed literature, three emerging design principles are highlighted that will likely guide the next generation of wearable piezoelectric sensors. First, multiscale material engineering, based on the synergy of aligned polymer β-domains, ceramic fillers and 2D surface modifiers (Sharma et al., 2020; Su et al., 2022; Zhou et al., 2025), seems to be more promising than any single-family approach. Second, system-level integration that co-designs sensing, energy harvesting, signal processing and wireless communication on the same textile is emerging as the new performance benchmark (Li et al., 2024; Min et al., 2023; Zhu et al., 2019). Third, the distinguishing factor between competing technologies is increasingly clinical-grade validation, not just laboratory demonstration (Min et al., 2023; Yi et al., 2022). Future research should therefore focus on standardised durability protocols, large-area fabrication pathways, biocompatibility studies of regulatory grade, and unified reporting dashboards, gaps that when filled will determine whether piezoelectric nanomaterial wearables can move from research highlights to ubiquitous components of daily healthcare infrastructure (Deng et al., 2022; Hu & Dong, 2024; Jayathilaka et al., 2018).

Conclusion

This body of work shows a clear progression from nanometer-scale proof-of-concept outputs in early ZnO nanowire devices to clinically validated cardiovascular monitoring platforms with mean blood-pressure biases within ±6.2 mmHg of commercial sphygmomanometry. The trajectory shows that piezoelectric nanomaterials have gone from lab curiosities to plausible candidates for continuous, self-powered health monitoring.

The synthesis reveals an important insight: no single family of materials can simultaneously satisfy the competing demands of sensitivity, stretchability, durability and biocompatibility. ZnO nanowire systems are biocompatible and can be directly integrated into textiles, but have limited intrinsic piezoelectric output. PVDF and P nanofibers achieve the highest sensitivities (up to 5.76 V kPa-1 for highly aligned electrospun mats) and the longest demonstrated fatigue life (one million compression cycles at 0.2 MPa), but are susceptible to humidity and thermal drift. BaTiO3 and lead-free perovskite composites increase voltage output to tens of volts and address long-standing toxicity issues. Two-dimensional MXene hybrids enable ultralow detection limits of 1-1.5 Pa with fast millisecond-level responses, though often requiring more complicated capacitive or piezoresistive readout schemes. Instead of competing, these families are more and more being combined in hybrid composites that take advantage of the strengths of each component.

This review describes the milestones for clinical validation, including a wearable piezoelectric blood-pressure sensor tested in thirty-five subjects with 175 paired measurements with mean differences of 0.89 6.19 mmHg for systolic and 0.32 5.28 mmHg for diastolic pressure, and is a defining inflection point for the field. They prove that self-powered piezoelectric platforms can achieve accuracy thresholds comparable to those of cuff-based reference devices, establishing piezoelectric nanomaterial wearables as viable tools for ambulatory cardiovascular management.

Going forward, the ability of the field to fulfil its translational promise will be determined by three priorities: (1) development of standardised durability and benchmarking protocols to allow for fair cross-platform comparisons; (2) development of scalable, large-area fabrication routes that can produce uniformly aligned [beta]-phase fabrics and MXene-coated textiles at the metre scale; and (3) generation of chronic in-vivo biocompatibility data that can support regulatory approval for lon Bridging these gaps and further integrating piezoelectric sensing with on-device signal processing and wireless transmission will determine whether wearables based on piezoelectric nanomaterials transition from research milestones to the building blocks of next-generation personalised healthcare.

References

Deng, W., Zhou, Y., Libanori, A., Chen, G., Yang, W., & Chen, J. (2022). Piezoelectric nanogenerators for personalized healthcare. *Chemical Society Reviews*, *51*(9), 3380–3435. https://doi.org/10.1039/d1cs00858g

Gao, P., Song, J., Liu, J., & Wang, Z. L. (2006). Nanowire Piezoelectric Nanogenerators on Plastic Substrates as Flexible Power Sources for Nanodevices. *Advanced Materials*, *19*(1), 67–72. https://doi.org/10.1002/adma.200601162

Hu, H., Li, W., Li, X., Xu, Y., Zhao, X., Huang, X., Hao, S., Feng, G., Zhu, Q., Zhang, X., Duan, C., Chu, J., & Tian, B. (2025). An ultra-sensitive flexible piezoelectric nanogenerator based on P(VDF-TrFE) nanofibers. *International Journal of Extreme Manufacturing*, 7(6), 65503–65503. https://doi.org/10.1088/2631-7990/adec25

Hu, J., & Dong, M. (2024). Recent advances in two-dimensional nanomaterials for sustainable wearable electronic devices. *Journal of Nanobiotechnology*, *22*(1), 63–63. https://doi.org/10.1186/s12951-023-02274-7

Huang, S., Gao, Y., Hu, Y., Shen, F., Jin, Z., & Cho, Y. (2023). Recent development of piezoelectric biosensors for physiological signal detection and machine learning assisted cardiovascular disease diagnosis. *RSC Advances*, *13*(42), 29174–29194. https://doi.org/10.1039/d3ra05932d

Iqbal, S. M. A., Mahgoub, I., Du, E., Leavitt, M. A., & Asghar, W. (2021). Advances in healthcare wearable devices. *Npj Flexible Electronics*, *5*(1). https://doi.org/10.1038/s41528-021-00107-x

Jayathilaka, W. A. D. M., Qi, K., Qin, Y., Chinnappan, A., Garcia, W. S., Baskar, C., Wang, H., He, J., Cui, S., Thomas, S., & Ramakrishna, S. (2018). Significance of Nanomaterials in Wearables: A Review on Wearable Actuators and Sensors. *Advanced Materials*, *31*(7). https://doi.org/10.1002/adma.201805921

Kim, N., Lee, J. M., Moradnia, M., Chen, J., Pouladi, S., Yarali, M., Kim, J. Y., Kwon, M., Lee, T. R., & Ryou, J. (2022). Biocompatible composite thin-film wearable piezoelectric pressure sensor for monitoring of physiological and muscle motions. *Soft Science*, *2*(2), 8–8. https://doi.org/10.20517/ss.2022.06

Lee, M. K., Chen, C., Wang, S., Nam, S., Park, Y. J., Kim, J. M., Chou, L., & Wang, Z. L. (2012). A Hybrid Piezoelectric Structure for Wearable Nanogenerators. *Advanced Materials*, *24*(13), 1759–1764. https://doi.org/10.1002/adma.201200150

Li, L., Fu, X., Chen, S., Uzun, S., Levitt, A., Shuck, C. E., Han, W., & Gogotsi, Y. (2020). Hydrophobic and Stable MXene–Polymer Pressure Sensors for Wearable Electronics. *ACS Applied Materials & Interfaces*, *12*(13), 15362–15369. https://doi.org/10.1021/acsami.0c00255

Li, X., Liu, Y., Ding, Y., Zhang, M., Lin, Z., Hao, Y., Li, Y., & Chang, J. (2024). Capacitive Pressure Sensor Combining Dual Dielectric Layers with Integrated Composite Electrode for Wearable Healthcare Monitoring. *ACS Applied Materials & Interfaces*, *16*(10), 12974–12985. https://doi.org/10.1021/acsami.4c01042

Maity, K., & Mandal, D. (2018). All-Organic High-Performance Piezoelectric Nanogenerator with Multilayer Assembled Electrospun Nanofiber Mats for Self-Powered Multifunctional Sensors. *ACS Applied Materials & Interfaces*, *10*(21), 18257–18269. https://doi.org/10.1021/acsami.8b01862

Min, S., Kim, D. H., Joe, D. J., Kim, B. W., Jung, Y.-H., Lee, J. H., Lee, B., Doh, I., An, J., Youn, Y., Joung, B., Yoo, C. D., Ahn, H., & Lee, K. J. (2023). Clinical Validation of a Wearable Piezoelectric Blood-Pressure Sensor for Continuous Health Monitoring. *Advanced Materials*, *35*(26). https://doi.org/10.1002/adma.202301627

Mokhtari, F., Spinks, G. M., Fay, C., Cheng, Z., Raad, R., Xi, J., & Foroughi, J. (2020). Wearable Electronic Textiles from Nanostructured Piezoelectric Fibers. *Advanced Materials Technologies*, *5*(4). https://doi.org/10.1002/admt.201900900

Park, D. Y., Joe, D. J., Kim, D. H., Park, H., Han, J. H., Jeong, C. K., Park, H., Park, J. G., Joung, B., & Lee, K. J. (2017). Self‐Powered Real‐Time Arterial Pulse Monitoring Using Ultrathin Epidermal Piezoelectric Sensors. *Advanced Materials*, *29*(37). https://doi.org/10.1002/adma.201702308

Saravanakumar, B., Mohan, R., Thiyagarajan, K., & Kim, S. (2013). Fabrication of a ZnO nanogenerator for eco-friendly biomechanical energy harvesting. *RSC Advances*, *3*(37), 16646–16646. https://doi.org/10.1039/c3ra40447a

Sharma, S., Chhetry, A., Sharifuzzaman, M., Yoon, H., & Park, J. Y. (2020). Wearable Capacitive Pressure Sensor Based on MXene Composite Nanofibrous Scaffolds for Reliable Human Physiological Signal Acquisition. *ACS Applied Materials & Interfaces*, *12*(19), 22212–22224. https://doi.org/10.1021/acsami.0c05819

Sood, A., Desseigne, M., Dev, A., Maurizi, L., Kumar, A., Millot, N., & Han, S. S. (2022). A Comprehensive Review on Barium Titanate Nanoparticles as a Persuasive Piezoelectric Material for Biomedical Applications: Prospects and Challenges. *Small*, *19*(12). https://doi.org/10.1002/smll.202206401

Su, Y., Li, W., Cheng, X., Zhou, Y., Yang, S., Zhang, X., Chen, C., Yang, T., Pan, H., Xie, G., Chen, G., Zhao, X., Xiao, X., Li, B., Tai, H., Jiang, Y., Chen, L., Li, F., & Chen, J. (2022). High-performance piezoelectric composites via β phase programming. *Nature Communications*, *13*(1), 4867–4867. https://doi.org/10.1038/s41467-022-32518-3

Tan, Y., Yang, K., Wang, B., Li, H., Wang, L., & Wang, C. (2021). High-performance textile piezoelectric pressure sensor with novel structural hierarchy based on ZnO nanorods array for wearable application. *Nano Research*, *14*(11), 3969–3976. https://doi.org/10.1007/s12274-021-3322-2

Yang, X., & Shi, Y. (2026). Electrospun self-powered triboelectric pressure sensor for lower-limb gait evaluation in tennis rehabilitation. *AIP Advances*, *16*(3). https://doi.org/10.1063/5.0323325

Yi, Z., Liu, Z., Li, W., Ruan, T., Chen, X., Liu, J., Yang, B., & Zhang, W. (2022). Piezoelectric Dynamics of Arterial Pulse for Wearable Continuous Blood Pressure Monitoring. *Advanced Materials*, *34*(16). https://doi.org/10.1002/adma.202110291

Yu, D., Zheng, Z., Liu, J., Xiao, H., Huangfu, G., & Guo, Y. (2021). Superflexible and Lead-Free Piezoelectric Nanogenerator as a Highly Sensitive Self-Powered Sensor for Human Motion Monitoring. *Nano-Micro Letters*, *13*(1), 117–117. https://doi.org/10.1007/s40820-021-00649-9

Zeng, W., Tao, X., Chen, S., Shang, S., Chan, H. L. W., & Choy, S. H. (2013). Highly durable all-fiber nanogenerator for mechanical energy harvesting. *Energy & Environmental Science*, 6(9), 2631–2631. https://doi.org/10.1039/c3ee41063c

Zhang, D., Wang, N., Yu, Y., Lu, Y., Jiang, L., Zhang, D.-A., Wang, X., Yan, X., & Long, Y. (2021). One-Step Preparation of a Core-Spun Cu/P(VDF-TrFE) Nanofibrous Yarn for Wearable Smart Textile to Monitor Human Movement. *ACS Applied Materials & Interfaces*, *13*(37), 44234–44242. https://doi.org/10.1021/acsami.1c10366

Zhou, Z. C., Qi, Y., Zheng, T., Li, T.-T., & Lin, J. (2025). Flexible Piezoelectric Sensors Based on Electrostatically Spun PAN/K-BTO Composite Films for Human Health and Motion Detection. *ACS Applied Polymer Materials*, 7(10), 5855–5864. https://doi.org/10.1021/acsapm.4c04091

Zhu, M., Chng, S. S., Cai, W., Liu, C., & Du, Z. (2020). Piezoelectric polymer nanofibers for pressure sensors and their applications in human activity monitoring. *RSC Advances*, *10*(37), 21887–21894. https://doi.org/10.1039/d0ra03293j

Zhu, M., Shi, Q., He, T., Yi, Z., Ma, Y., Yang, B., Chen, T., & Lee, C. (2019). Self-Powered and Self-Functional Cotton Sock Using Piezoelectric and Triboelectric Hybrid Mechanism for Healthcare and Sports Monitoring. *LA Referencia (Red Federada de Repositorios Institucionales de Publicaciones Científicas)*, *13*(2), 1940–1952. https://doi.org/10.1021/acsnano.8b08329