Original Article

A scoping review of potential biomaterials as optimal platforms for triboelectric nanogenerators

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Abstract

The increasing human reliance on electricity, driven by rapid technological advancement, continues to depend largely on non-renewable fossil fuels, raising critical concerns about energy sustainability and environmental degradation. This study aims to explore the potential of biomaterials as alternative platforms for enhancing the performance of Triboelectric Nanogenerators (TENGs), using a scoping review approach. A systematic literature review was conducted utilizing the Scopus, Crossref, and Google Scholar databases, guided by the PRISMA Extension for Scoping Reviews (PRISMA-ScR) framework. Relevant studies were analyzed based on publication trends, types of biomaterials employed, synthesis methods, operational mechanisms, and key electrical output parameters. The findings indicate that biomaterials such as cellulose, chitosan, and natural proteins exhibit promising triboelectric properties, contributing to improvements in energy conversion efficiency, biocompatibility, and operational stability of TENGs. Further research is recommended to optimize material structures and surface modifications to enhance charge transfer mechanisms. Additionally, the incorporation of carbon-based materials such as graphene and MXene with biomaterials has demonstrated significant potential to amplify device performance. This review also underscores the wide-ranging applications of biomaterial-based TENGs in wearable electronics, biomedical sensing, and eco-friendly energy systems. Overall, this study provides a comprehensive overview and valuable insights into the strategic role of biomaterials in advancing next-generation green energy technologies.

Keywords: Triboelectric nanogenerator, biomaterial potential, sustainable energy, energy conversion, green energy

Introduction

Electricity is a very important energy for humans in this modern era. Every group, both children and adults, depends on electricity. Its use can be said to be in every aspect of human life, from electronics, transportation, to communication. Making this energy a basic need for people in everyday life [1]. This dependence is a problem, because the sources used so far come from non-renewable materials such as fossil fuels such as oil, coal, and natural gas which are consumed almost 85% in every aspect. In addition, its very large use causes various negative effects where environmental damage in the form of greenhouse gas emissions and energy security are two major problems that must be faced [2]. Therefore, a solution is needed to the dependence on the use of fossil energy by utilizing renewable energy sources.

The global demand for electricity continues to rise in parallel with technological advancements. Despite efforts to adopt renewable energy sources such as solar, wind, and

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hydropower, these technologies face significant limitations. For example, photovoltaic solar power systems (PLTS) entail high installation costs and are dependent on inconsistent environmental conditions [4]. Wind power plants (PLTB) require vast areas of land and suffer from fluctuating wind availability [5], while hydropower plants (PLTA) demonstrate limited conversion efficiency during low-frequency wave conditions and involve high maintenance costs [6]. Despite the global expansion of renewable energy adoption, several key challenges persist that hinder their universal applicability. According to the International Renewable Energy Agency (IRENA), solar and wind energy, though rapidly growing, still face intermittency issues and infrastructural limitations that restrict their deployment in remote or resource-limited regions [6]. Solar photovoltaics show a significant drop in performance during cloudy or rainy conditions, while wind turbines often require minimum wind thresholds and extensive installation areas [1,2,5]. These limitations create a technological gap in harvesting ambient and low-frequency mechanical energy—an area that is largely overlooked by current renewable systems. Triboelectric Nanogenerators (TENGs), with their ability to operate under low-energy, dynamic, and irregular input conditions, offer a strategic solution to complement and fill this gap.

In contrast, mechanical energy—abundantly present in the environment through sources such as vibrations, human motion, and airflow—remains underutilized. TENGs represent an emerging solution capable of harvesting low-frequency mechanical energy by leveraging the principles of contact electrification and electrostatic induction [7]. These devices can convert ambient mechanical energy from sources like raindrops, footfalls, and machine vibrations into electricity [8], while also functioning as self-powered sensors for motion detection and other applications, including ocean blue energy and distributed power for Internet of Things (IoT) systems. TENGs offer distinct advantages over conventional energy harvesters due to their lightweight, low-cost materials, and high sensitivity to small-scale energy inputs, making them a promising alternative for sustainable energy generation [9]. In recent years, there has been a significant increase in scholarly attention toward TENGs, yet mapping this research domain remains challenging through conventional literature reviews. This complexity underscores the value of bibliometric approaches, which provide structured insights into publication trends, research gaps, and collaborative networks. Bibliometric tools have been successfully applied in related fields, analyzing over 1,000 publications on solar energy [11], wind energy [12], and other renewable technologies [13].

Building upon these efforts, the present study employs a bibliometric review to examine over 1,000 articles published between 2010 and 2024 on the development and application of TENGs for energy generation. This includes citation analysis, author collaboration patterns, and keyword mapping to identify dominant and emerging research clusters. By systematically investigating these dimensions, the study aims to highlight the evolution of TENG research, its current limitations, and its future potential. The findings are expected to contribute to a clearer understanding of the technological trajectory of TENGs and their role in advancing sustainable energy solutions.

Methods

The literature search was conducted using the Scopus, Crossref, and Google Scholar databases, facilitated by the Publish or Perish (PoP) version 8 Pro software, to retrieve peer-reviewed articles published between 2010 and 2024. The review process adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines to ensure methodological transparency and comprehensiveness [14].

Literature screening

Data search was conducted using the PoP application in the Scopus, Crossref, and Google Scholar databases using the The search strategy used a combination of keywords relevant to the topic, including: "Triboelectric Nanogenerator" AND ("Biomaterial" OR "Graphene" OR "$CaCO_3$" OR "HA" OR "Calcium Phosphate" OR "Al_2O_3" OR "Carbon" OR "Bioelectronic" OR "Cellulose" OR "Chitosan" OR "Biopolymer"). This Boolean formulation was used to expand the search and capture a wide range of related articles. The initial search yielded 533 documents, consisting of 86 from Scopus, 232 from Google Scholar, and 204 from Crossref. These results included a variety of document types such as journal articles, conference papers, books, and theses. All retrieved documents were exported for further processing. From all the keywords, a database of 533 was obtained with scopus details of 86, google scholar of 232, and crossref of 204 covering various topics such as triboelectric, nanogenerator, and biomaterial. This number includes non-patents, books, and reviews using the PoP system. After obtaining articles using the PoP application, the next step is to validate the article as a whole according to the desired objectives, the inclusion and exclusion criteria are applied to select relevant articles.

Selection and exclusion criteria

The article criteria were then selected based on the number of duplications, title, abstract, having a pdf, appropriate topic, appropriate keywords, data must have electrical testing, and not a review or must be an original article. In addition, the selected articles must also meet the specified time range, which is published between 2010 and 2024, and in English. Exclusion of articles was based on the relevance and quality of the research, so that only articles that significantly contribute to the understanding and development of biomaterial-based triboelectric nanogenerators were included in this analysis.

Screening procedures

The initial screening process was carried out using the help of rayyan.ai to obtain the number of articles without duplication, which was 33. Furthermore, on the page, an initial screening was carried out to determine the title and abstract in accordance with the research criteria, which were then selected as 271 articles. The initial dataset, retrieved from multiple databases, underwent a deduplication process—both automated and manual—resulting in 33 unique entries. Titles and abstracts of these records were then independently reviewed by two researchers to assess their alignment with the review objectives. Discrepancies in article selection were discussed until consensus was reached, thereby increasing inter-rater reliability and minimizing selection bias. Subsequently, a second-level screening was performed to verify the availability of full-text PDFs, the inclusion of key terms relevant to TENGs and biomaterials, and the article's methodological adequacy. This process narrowed the selection to 80 articles. In the final phase, each article was thoroughly assessed to ensure it met the following criteria: (1) it reported on original experimental work (not reviews), (2) it included quantitative electrical performance data, and (3) it described material characteristics such as morphology, particle size, and structural mechanisms involved in energy harvesting. Only articles fulfilling all criteria were retained.

Ultimately, 19 articles were selected for inclusion. These studies represent the most relevant and methodologically sound contributions to the field. The time frame of 2010 to 2024 was selected to capture the development and evolution of TENG technologies in the last decade and a half, coinciding with the emergence of TENG-related publications in indexed journals. The selection strategy, screening phases, and article flow are summarized visually in **Figure 1** (PRISMA diagram), providing a transparent overview of the review process.

Data analysis and research clusters

Initial analysis was conducted by creating publication trends related to biomaterial-based TENGs analyzed using various instruments. Furthermore, the research was initially clustered based on year, country (https://app.datawrapper.de/), journal name, publisher, keywords, and number of citations. This aims to find out which journals and publishers consistently accept biomaterial-based TENGs and the number of citations obtained. The second clustering was then grouped based on the purpose of the research, the biomaterial used, the synthesis or deposition method required, the mechanism of biomaterial performance, and the results obtained. These results aim to increase insight into the direction of research in the potential use of biomaterials as TENGs. The third clustering then grouped the research based on the testing of the biomaterials used including Morphology, Particle size, Dielectric constant, Electrical conductivity, Resistance, Power density, testing and voltage against time. This aims to increase insight into which biomaterials have the highest electrical properties and have morphological suitability.

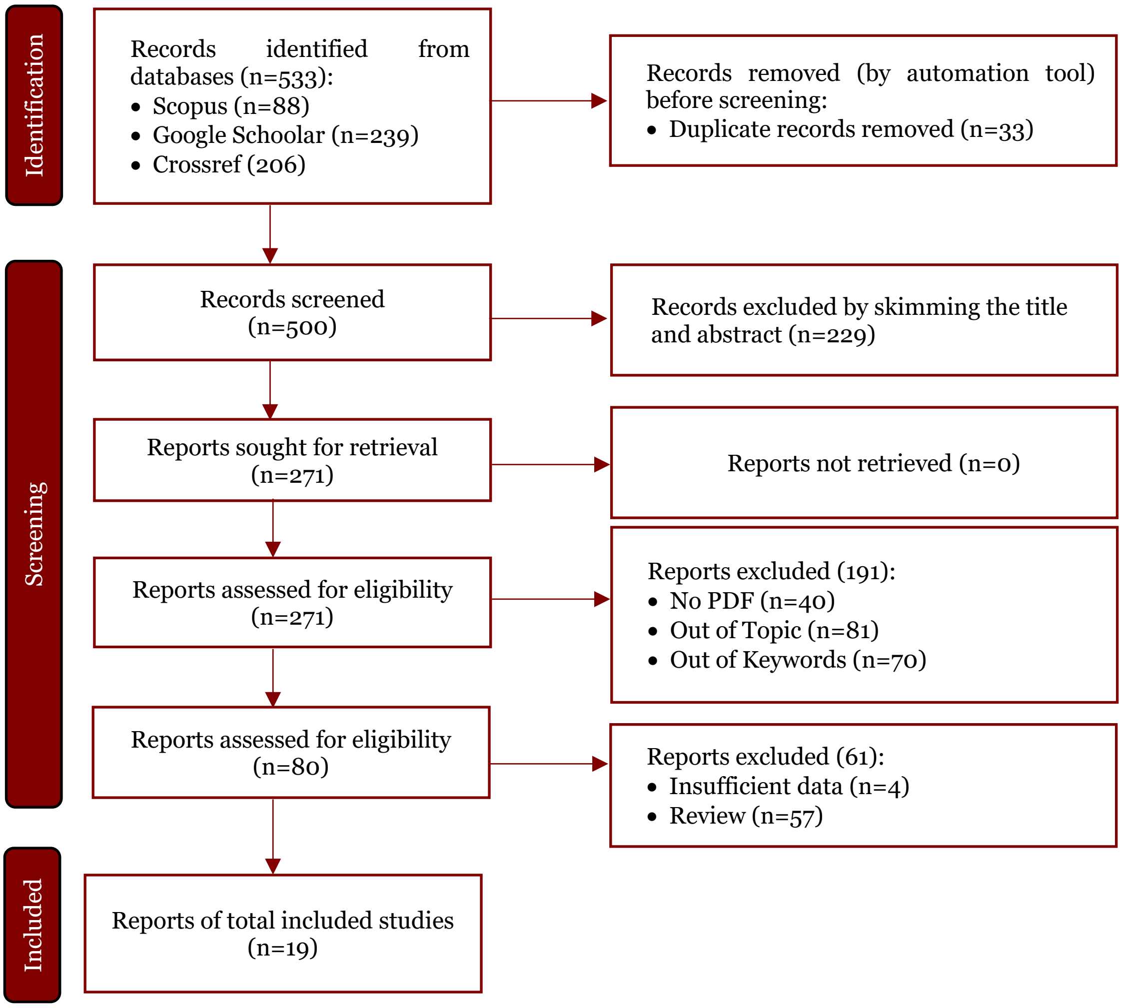

Figure 1. Flow diagram for the screening and selection from various databases.

Results

Study based on classification of article identity characteristics

Research on TENGs and related energy technologies has shown substantial growth in the last decade, culminating in a surge of publications by 2024 (**Table 1**). Notably, the field is dominated by contributions from Asian countries—particularly China, Korea, Thailand, and India. South Korea leads with significant outputs in high-impact journals such as *Nano Energy*, *Journal of Materials Science & Technology*, and *Advanced Energy and Sustainability Research*. China closely follows, with prolific contributions to journals including *Carbohydrate Polymers*, *Nano Energy*, and *Journal of Materials Science: Materials in Electronics*. This geographic concentration suggests a strategic regional focus on microenergy systems and materials innovation. The dominance of China and South Korea can be linked to several institutional and industrial drivers. Both countries have invested heavily in nanotechnology and sustainable energy R&D over the past decade, supported by robust government funding and policy frameworks prioritizing green innovation. Furthermore, the rise of consumer electronics and wearable device industries in these nations has created a demand-pull effect—driving the search for efficient, small-scale energy harvesters such as TENGs. In addition, China's extensive research ecosystem, which includes top-tier institutions and state-sponsored labs, facilitates the rapid translation of materials science advances into scalable energy technologies.

The global distribution of biomaterial-based TENG research is illustrated in **Figure 2**. China and South Korea are the most active countries, each contributing six studies in the last decade. Thailand and India also demonstrate strong engagement, reflecting growing regional interest in sustainable and affordable energy solutions. Meanwhile, countries such as Germany, Saudi Arabia, Turkey, the United States, Iran, and the United Kingdom, though contributing fewer studies, represent a growing international recognition of the potential of TENGs. The entry of these diverse economies into the field may signal increasing global collaboration and the diffusion of biomaterial-based TENG innovation across different socio-economic contexts. The growing attention to biomaterial-based TENGs is largely motivated by the dual imperative of developing low-cost, eco-friendly energy solutions and meeting the energy demands of emerging technologies such as wearables and the Internet of Things (IoT). Biomaterials offer significant advantages in terms of biocompatibility, sustainability, and adaptability—qualities that are critical for integration into flexible, portable energy systems. Consequently, countries with active biotech and materials science sectors are naturally drawn to this research niche.

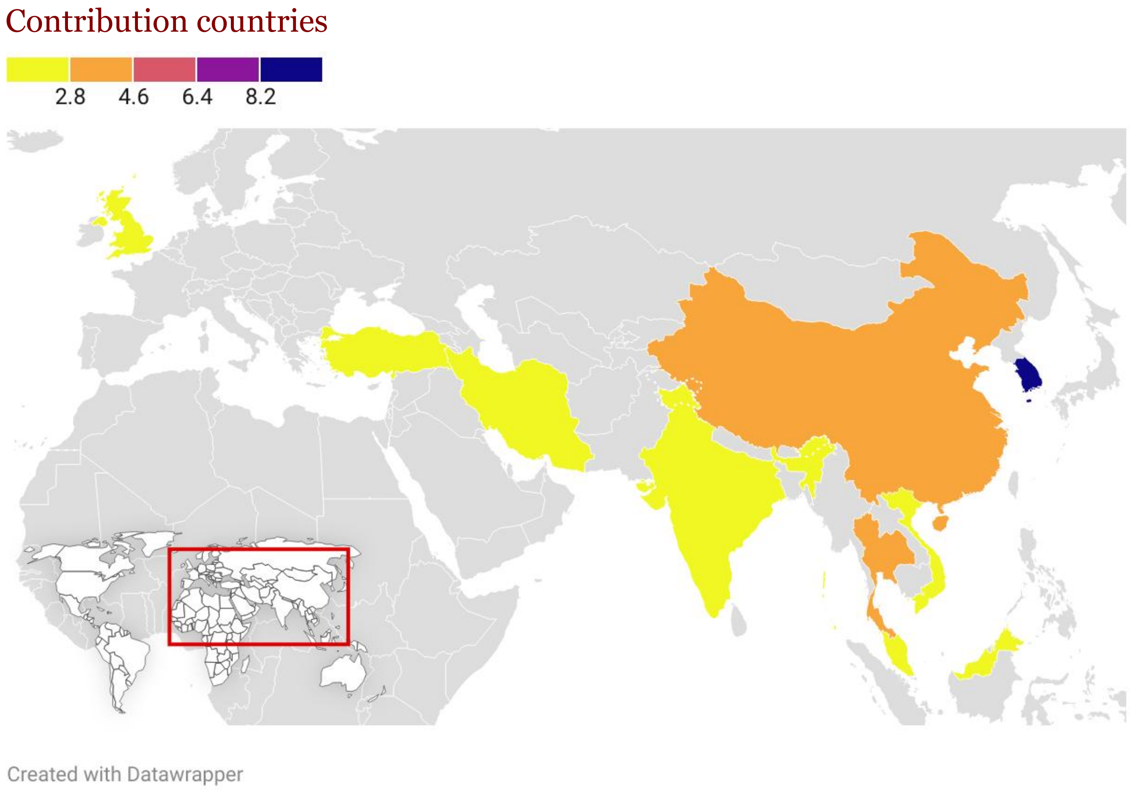

Figure 2. Publication trends of biomaterials-based triboelectric nanogenerators by country.

The journals publishing TENG-related studies predominantly specialize in materials science, energy conversion, and sustainable technologies. Leading outlets include Nano Energy, Carbohydrate Polymers, Materials Research Bulletin, and Smart Materials and Structures, often published by major scientific publishers such as Elsevier, Springer, and the Royal Society of Chemistry (RSC). This publishing pattern underscores the field's interdisciplinary nature, straddling materials engineering, nanotechnology, and applied energy systems. In terms of publication years, most studies were published between 2020 and 2024, with earlier publications (2020–2021) exhibiting higher citation counts—likely due to their longer presence in the scholarly ecosystem. However, recent publications (2023–2024), although less cited due to recency, reflect the current frontier of research, indicating emerging themes and novel material applications that are expected to shape the next phase of TENG development.

Research related to TENG continues to grow with a major focus on material innovation and its application in various modern technologies. From the list of published journals, Elsevier dominates as the main publisher in this field, reflecting that their journals are the main reference for researchers working on the development of energy harvesting, nanogenerators, and advanced materials. In addition to Elsevier, several other publishers such as the Royal Society of Chemistry (RSC), Wiley Online Library, Multidisciplinary Digital Publishing Institute (MDPI), Taylor & Francis, Institute of Physics Publishing (IOP) Publishing, De Gruyter, and Springer also contribute to TENG-related publications. The main focus of TENG research is largely related to the development of new materials that aim to improve energy conversion efficiency and expand the application of this technology.

Table 1. Article description by year, country, journal name, publisher, keywords, and citations

Year	Country	Journal name	Publisher	Keywords	Citation	Ref
2024	Thailand and Vietnam	Journal of Colloid and Interface Science	Elsevier	Human hair, Photoinduced charge, Carbon nanostructure, Energy harvesting, Triboelectric nanogenerator	1	[14]
2024	Thailand, Korea, United Kingdom	Materials Research Bulletin	Elsevier	Piezoelectric composite, Piezo-tribo-electric, Nanogenerator, Energy harvesting, BCZT	7	[15]
2022	China	Carbohydrate Polymers	Elsevier	Cellulose nanofiber, Copper calcium titanate, Triboelectric nanogenerator, Dielectric, Energy harvesting	23	[16]
2021	Korea	Ceramics International	Elsevier	Aurivillius Oxides, Lead-free, Impedance Dielectric, Piezoelectric nanogenerator	28	[17]
2024	Korea	Journal of Materials Science & Technology	Elsevier	CCTO particles, CCTO/PDMS FCF, CCTO FCF-TENG, Mechanical energy harvesting, Self-powered sensing	11	[18]
2020	Korea	Nano Energy	Elsevier	Triboelectric nanogenerator, Self-powered, Artificial intelligence, Smart electronics, Flexible electronics	91	[19]
2021	Thailand	Nano Energy	Elsevier	Chitosan, Chitosan/protein composites, Triboelectric nanogenerator, Biodegradable polymers	78	[20]
2020	India	International Journal of Green Energy	Taylor & Francis Group	Energy harvesting; nano, energy, triboelectric nanogenerator, biomaterials, egg	37	[21]
2023	Malaysia	RSC Advances	Royal Society of Chemistry	Hybrid piezo/triboelectric nanogenerator (H/P-TENG), Polymer ceramic composite films, Polydimethylsiloxane (PDMS) BZT–BCT piezoelectric ceramic, Corona poling	13	[22]
2023	Korea	Micromachines	MDPI	triboelectric nanogenerators, calcium carbonate, triboelectric series, CO2 absorption, eco-friendly technology, slap match	13	[23]
2023	Korea	Advanced Energy and Sustainability Research	Wiley. Online Liberary	Augmented reality and virtual reality (AR/VR), Hybrid Nanogenerators, Nanogenerators, Signal processing and analyzing units, Synergistic effects	11	[24]
2022	Turkey	Smart Materials and Structures	IOP Publishing	PVDF nanofiber, Electrospinning, Energy harvesting, β crystal phase, Design of experiment	13	[25]
2021	China	Nano Energy	Elsevier	Piezoelectric nanogenerator, Ag nanowires/PDMS electrode, BaTiO3-based piezoelectric ceramic, Wearable sensors	134	[26]
2020	China	Nanotechnology Reviews	De Guyter	Aluminum oxide, Chemical liquid deposition, Dielectric thin film, Triboelectric nanogenerator	16	[27]
2022	Korea	Nano Energy	Elsevier	Hierarchical wrinkle, Plasma-polymer-fluorocarbon, Triboelectric nanogenerators, Raindrops energy harvester, Triboelectric skin	11	[28]
2024	China	Journal of Materials Science: Materials in Electronics	Springer	Triboelectric nanogenerator, NaNbO3–$CaSnO_3$–$BaTiO_3$ (NN–CS–BT), Sintering process, Dielectric property, Polydimethylsiloxane (PDMS)	2	[29]
2024	Korea	Advanced Composites and Hybrid Materials	Springer Nature	Computer-assisted smart neurotherapy, Intrinsic hybrid nanogenerators, TENG, PENG	3	[24]
2020	Korea	Journal of Materials Chemistry A	RSC	piezoelectric, triboelectric, nanogenerator, self-powered sensor, body activity counter	43	[17]
2022	Iran	Nano Energy	Elsevier	Flexible triboelectric nanogenerator, Si polymer/$BaTiO_3$, AgNWs electrode, Transparent on/off switch, Tactile sensor	22	[30]

Some of the materials that are often used include polymers and biopolymers such as cellulose nanofibers, chitosan/protein composites, and polydimethylsiloxane (PDMS) which offer high flexibility and environmental compatibility. In addition, oxide and ceramic-based materials, such as $BaTiO_3$, CCTO (Calcium Copper Titanate), Aurivillius oxides, and Aluminum oxide, are used to improve the dielectric and piezoelectric properties in hybrid piezo-triboelectric nanogenerator devices. Meanwhile, conductive materials such as silver nanowires (AgNWs) and carbon nanostructures play an important role in improving the conductivity of electrodes, which ultimately improves the efficiency of TENGs. With the development of technology, TENGs have begun to be integrated with various modern systems such as artificial intelligence (AI) and smart electronics. Several publications have shown that TENGs can be used in flexible sensors, wearable devices, and smart electronics based on self-powered systems. One of the studies with the highest number of citations discusses Piezoelectric nanogenerators with Ag nanowires/PDMS electrodes and $BaTiO_3$-based piezoelectric ceramics for wearable sensors, which shows great interest in the application of TENGs in medical devices and Internet of Things (IoT)-based technologies. In addition, research is also beginning to move towards hybridizing TENGs with piezoelectric nanogenerators (PENGs) to improve energy efficiency, as seen in several publications discussing Hybrid piezo/triboelectric nanogenerators (H/P-TENGs).

Interestingly, several recent studies have begun to explore the application of TENGs in augmented reality (AR) and virtual reality (VR), as well as their use in computer-assisted smart neurotherapy, indicating the great potential of TENGs in healthcare and rehabilitation. Although these studies are still relatively new, this trend shows that TENGs have broad prospects in various industries. The high number of citations in publications focusing on flexible sensors and wearable technologies indicates that these topics are receiving great attention in the scientific community. Meanwhile, studies discussing the use of biopolymers and environmentally friendly materials also have a significant number of citations, indicating that the sustainability and environmental impact of TENGs are important considerations in their development.

TENGs integrated biomaterial platform

From various studies, biomaterials used in TENGs can be categorized into several main groups, such as natural polymers, oxide-based materials, carbon-based materials, and hybrid materials. Carbon-based materials such as Activated Carbon (AC), Reduced Graphene Oxide (rGO), and Cellulose Nanofibril (CNF) have shown improved TENG performance by utilizing their high conductivity properties and large pore structures to increase charge storage capacity. In addition, oxide-based materials such as Barium Calcium Zirconate Titanate (BCZT), Calcium Copper Titanate (CCTO), and Aluminum Oxide (Al_2O_3) are often used due to their high dielectric and piezoelectric properties, which enable synergy between triboelectric and piezoelectric mechanisms in hybrid TENGs. On the other hand, natural polymers such as Chitosan, Egg Shell Membrane (ESM), and Cellulose Paper are increasingly being used due to their biodegradability and abundance in nature. Integration of these materials with synthetic polymers such as PDMS and Polyvinyl Alcohol (PVA) results in flexible composites suitable for wearable electronics and self-powered sensors. Recent studies have also shown that these biomaterials can be combined with artificial intelligence (AI) and IoT-based technologies, such as in the development of self-powered transparent touchpads and Computer-assisted Smart Neurotherapy (CASNuT). In addition, innovations in the design and structure of biomaterials for TENGs have also resulted in new concepts such as Hierarchical Wrinkled Surface TENG (HWA-TENG) and Hybrid Piezo/Triboelectric Nanogenerator (H/P-TENG) that utilize layered structures and polymer-ceramic composites to improve energy conversion efficiency. For example, the use of $BaTiO_3$, $CaCO_3$, Graphene Oxide, and Ag Nanowires (AgNWs) have been shown to improve the surface charge density and electrical performance of biomaterial-based TENGs.

Biomaterial performance based on synthesis method and implications for TENGs

The performance of biomaterials in TENG (**Table 2**) is greatly influenced by the synthesis method used. Various synthesis methods such as carbonization, ball-milling, drop casting, sintering, spin coating, and chemical liquid deposition play a role in determining the structure, electrical properties, and working mechanism of biomaterials. The carbonization and ball-milling methods applied to Activated Carbon (AC), Reduced Graphene Oxide (rGO), and Cellulose Nanofibril (CNF) produce significant changes in surface morphology and element distribution, especially in increasing the polar γ-PVDF phase to increase dielectric polarization. Meanwhile, the sintering method used in the synthesis of Barium Calcium Zirconate Titanate (BCZT) and Multiwalled Carbon Nanotubes (MWCNT) contributes to producing high piezoelectric charge with additional flexibility from PDMS.

In the Tempo-oxidized Cellulose Nanofiber (TOCN)-based system using the TEMPO oxidation system, charge transfer occurs due to the charge difference between TOCN (positive) and CCTO (negative), which produces an electric field and electric current when the charge flows through the electrodes. In the case of $CaBi_4Ti_4O_{15}$ (CBTO), the solid-state method is applied to improve the dielectric, piezoelectric, and magnetic properties, with the dielectric constant decreasing with increasing frequency. This phenomenon occurs due to the dominance of interfacial polarization at low frequencies which changes to electronic polarization at high frequencies. Drop casting and coating methods are also widely used in the synthesis of biomaterials for TENGs. For example, in the combination of PDMS and $CaCO_3$, this method allows increasing the sensitivity of triboelectric sensors through variations in their crystal structures. In addition, applications on BCST and PDMS show that piezoelectric and triboelectric effects can be combined to improve energy harvesting efficiency, with the nanohybrid generator capable of producing a DC voltage of 326 V.

The use of the spin coating method in the synthesis of polydimethylsiloxane (PDMS) and polyvinyl alcohol (PVA) allows optimization of the triboelectric and piezoelectric effects, which increase the electrical output when the material undergoes mechanical deformation. In materials such as BCZT-BH/PDMS, the multi-stack configuration (MS-HG) with spin coating can produce a voltage of up to 300 V and a power density of 157 mW/m². Meanwhile, the chemical liquid deposition method applied to Al_2O_3 functions as a dielectric layer with a high breakdown field strength, as well as an electron barrier that enhances charge separation. In CNTs synthesized by sputtering-plasma, the hierarchical wrinkled surface increases the surface area and the ability to attract negative charges, which contributes to the charge transfer efficiency in the triboelectric system.

PVDF-TENG with AC-HH containing rGO nanosheets can increase the triboelectric charge density and form a polar γ-PVDF structure, as indicated in **Table 2**. In addition, this material exhibits photo-responsive properties with the highest power reaching 0.92 W/m², which is six times greater than ordinary PVDF, so it has potential in power generation, motion detection, and light response. Meanwhile, the BCZT/MCNTs/PDMS-based P-TENG with a composition of 50 wt% BCZT produces a voltage output of 39.7 V with a current reaching 1.9 μA. Its peak power is 157.7 μW with a power density of 9.85 μW/cm², and shows stability up to 6900 cycles and is able to charge capacitors. The TOCN/CCTO-20 composite film as a TENG produced an output voltage of 152 V and a short-circuit current of 33.8 μA, with a power density of 483 mW/m². The performance of this film is improved by 3.37 to 4.07 times compared to the pure TOCN-based TENG, although the aggregation of CCTO particles can affect the overall output.

The CBTO material in the piezoelectric generator (A-PENG) is capable of producing a maximum voltage of 3.56 V at a resonance frequency of 4500 kHz. This material has high flexibility, elasticity, and good sensitivity to mechanical excitation, so it has the potential to be used in flexible electronics, filter circuits, and high-performance sensors. The use of CCTO material in the FCF-TENG with a composition of 6 wt% CCTO shows an output voltage of about 250 V and a current of about 6.5 μA, with a charge density reaching 70 μC/m² and a power of 3.15 W/m². This material has been proven to be stable under extreme environmental conditions and is effective as a stand-alone sensor and mechanical energy harvester.

The TENG-based touchpad is able to accurately detect touch and swipe positions, with a deep learning algorithm that can recognize digit patterns with 93.6% accuracy. This technology has the potential to be applied in smart calculators as well as artificial intelligence (AI) and Internet of Things (IoT) applications. The chitosan (CS)-based TENG with silk fiber (SF) produces an output voltage (VOC) of 77 V and a current (ISC) of 13 μA, with a maximum power reaching 202 μW, which is six times higher than pure CS. The silk fiber structure in this material increases the charge transfer efficiency, and has good biodegradability, still producing output after 9 weeks of decomposition. The ESM exhibits electropositive properties and is able to generate a positive charge when in contact with PTFE. This material has the potential as a green energy source that can power small devices such as LEDs and watches. The H/P-TENG with BZT–BCT in PDMS produced an open-circuit voltage (Voc) of 127 V, a short-circuit current density (Jsc) of 66.6 mA/m^2, and a short-circuit charge density (Qsc) of 117.5 mC/m^2. The peak power was 7.5 W/m^2, an increase of 190% compared to pure PDMS, with forward polarization providing the best performance enhancement. The $CaCO_3$-based triboelectric sensor was shown to be effective in detecting impacts, increasing sensitivity, and enhancing the mechanical durability of the sensor. This material also contributed to carbon sequestration. The SVM-based machine learning algorithm applied to the sensor achieved an accuracy of 95.8%.

Morphological characteristics and particle size of biomaterials on electrical performance of TENG

From the table presented, it can be analyzed that the morphology of biomaterials has a significant influence on the resulting electrical and mechanical properties. Materials with agglomerated granule and film structures dominate, with some variations in the form of fibers and membranes. The porous structure of some materials, as shown in references [14] and [16], allows for an increase in the surface contact area that contributes to triboelectric efficiency. Meanwhile, materials with a fiber structure, such as in references [20] and [21], offer high flexibility that makes them potential candidates for flexible electronics and smart sensor applications. The particle sizes in the table show quite large variations, ranging from nanometer to micrometer scales. Materials with small particles, such as the fiber-film in reference [25] which has a size of 250–400 nm and the film in reference [24] with a size of 800 nm, tend to have higher conductivity due to the increase in surface area and more intense interactions between particles. In contrast, materials with larger particle sizes, such as the fiber-agglomerated granules in reference [30] that range from 6.1 to 526 μm, show more variable performance depending on the particle distribution and density.

In terms of dielectric constant, there is significant variation between the materials studied. Materials with high dielectric constant values, such as those recorded in reference [29] with a range of 297 to 1490, show better charge storage capacity, thus having greater potential in triboelectric applications. In contrast, some materials with lower dielectric constants, such as those in reference [14] that only range from 0.7 to 0.9, have limitations in charge storage applications but are still relevant for certain uses that require higher insulation. Electrical conductivity also shows striking differences, where some materials have quite high conductivity values, such as those in reference [17] that reach ~35 mS/m and reference [18] that range from 0 to 45 mS/m. These materials with higher conductivity have the potential to be used in low-power electronic and sensor devices. Meanwhile, materials with very low conductivity, such as in reference [25] which only has a conductivity value of 10e–21 μS/cm, are more suitable for use as insulators in dielectric applications. In terms of resistance, the large difference in values indicates the variety of material characteristics.

Lower resistance, such as that found in reference [19] with a value of 50 Ω, indicates good conductive properties, which are important in electronic applications that require optimal current transfer. Conversely, materials with high resistance, such as in reference [24] which reaches 100 MΩ, are more suitable for charge storage applications or as dielectric materials in electronic devices. The power density produced by each material also varies, ranging from 6.05×10^{-4} μW/m^2 to 11 W/m^2. Materials with the highest power densities, as shown in references [28] and [30] with values of 11 W/m^2 and 10.10 W/m^2 respectively, have great potential in triboelectric and piezoelectric energy harvesting.

In contrast, materials with lower power densities, such as in reference [26] with a value of only 6.05×10^{-4} μW/m^2, may have limitations in energy applications but still play a role in low-power sensor devices. In addition, the resulting voltage range also varies widely, ranging from 0 to 1200 V. The material with the highest voltage range is found in reference [30], which reaches 1200 V, showing its potential in high-power applications and energy harvesting. In contrast, some materials with lower voltage ranges still have uses in simpler electronic applications, such as pressure sensors or microelectronic devices.

Table 2. Article description based on objective, biomaterial, synthesis method, performance mechanism, and results obtained

Author (ref)	Purpose	Biomaterial	Synthesis method	Performance mechanism	The results obtained
Prasanwong *et al.,* [14]	This research introduces a novel and remarkable property of carbon nanostructures derived from human biowaste to enhance TENG performance, which is essential for the development of innovative energy-harvesting technology	AC, rGO, and CNF	Carbonization, Ball-Milling, and Drop casting	AC-HH improves PVDF-TENG by modifying surface structure and boosting γ-phase content, enhancing dielectric polarization and charge output.	Adding AC-HH/rGO to PVDF boosts tribo-charge density, induces a polar γ-phase, and adds photo-responsiveness, yielding 0.92 W/m^2 (6× pure PVDF) for energy, motion, and light sensing.
Buatip *et al.,* [15]	This work has developed a novel P-TENG that is capable of converting mechanical energy into electrical energy when operating in compressive mode.	BCZT, MWCNT	Sintering Pellet	BCZT produces piezoelectric charge, MCNTs increase conductivity, and PDMS provides flexibility.	The BCZT/MCNTs/PDMS P-TENG (50 wt% BCZT) delivers 39.7 V, 1.9 µA, and 157.7 µW (9.85 µW/cm^2) at 1 Hz, stable up to 6900 cycles and capable of charging capacitors.
Song *et al.,* [16]	The purpose of this study is to develop a cellulose-based composite aerogel film combining TOCN and CCTO nanoparticles, and to evaluate its performance in enhancing the TENG output, such as voltage, current, and power density, as well as to study the effects of external factors on its performance.	TOCN	TEMPO oxidation system	Contact between positive TOCN and negative CCTO enables charge transfer; separation creates an electric field that drives current through the electrode.	The TOCN/CCTO-20 TENG achieved 152 V, 33.8 µA, and 483 mW/m^2—over 3× higher than pure TOCN. CCTO enhanced performance, though particle aggregation may reduce efficiency.
Hajra *et al.,* [17]	The aim of this study is to develop and optimize an environmentally friendly (lead-free) piezoelectric nanogenerator based on CBTO composite, which is an Aurivillius oxide, and PDMS as a flexible polymer matrix.	CBTO	Solid-State	CBTO has dielectric, piezoelectric, and magnetic properties. Its dielectric response shifts from interfacial to electronic polarization with frequency, and it shows antiferromagnetic behavior with 0.11 µC/cm^2 remanent polarization.	CBTO-based A-PENG generates 3.56 V at 4500 kHz, with PDMS providing flexibility and sensitivity—suitable for flexible electronics and high-performance sensors.
Manchi *et al.,* [18]	The aim of this research is to develop a stable and high-performance CCTO FCF-TENG for mechanical energy harvesting and stand-alone sensor applications.	Cellulose paper	Solid-State	CCTO FCF-TENG operates via contact-separation between PDMS and cellulose paper, with CCTO boosting charge density for higher output.	The 6 wt% CCTO FCF-TENG delivers ~250 V, ~6.5 µA, 70 µC/m^2, and 3.15 W/m^2, stable in harsh conditions—ideal as a self-powered sensor and harvester for portable devices.
Yun *et al.,* [19]	Developed a self-powered transparent touchpad based on TENG array to detect touch and swipe in real-time, integrated deep learning algorithm for pattern recognition, and demonstrated its potential as an intelligent interface in AI and IoT applications.	Film ITO	Coating	CCTO FCF-TENG generates electricity via contact-separation between PDMS and cellulose paper, with CCTO enhancing charge density for improved output.	The TENG-based touchpad detects touch/swipe precisely and recognizes digits with 93.6% accuracy, offering smart calculator and AIoT interface potential.
Charoonsuk *et al.,* [20]	The aim of this study is to develop and explore the performance of biopolymer-based TENGs, specifically using chitosan, by combining protein-based compounds as fillers.	Chitosan	Top-Down	In CS/SF-based TENG, contact-separation triggers charge transfer, while the silk fiber network increases surface area to boost output.	The CS/SF-based TENG achieved 77 V, 13 µA, and 202 µW—6× higher than pure CS—due to enhanced polarity. It remained functional after 9 weeks of biodegradation.

Author (ref)	Purpose	Biomaterial	Synthesis method	Performance mechanism	The results obtained
Kaur *et al.*, [21]	The aim of this research is to develop and propose the use of ESM combined with organic and inorganic materials as an energy source to drive small electronic devices.	Egg Shell Membrane, dan Selulosa	Top-Down	ESM-based TENG, ESM gains a positive charge when contacted with PTFE; separation creates a potential difference that drives current flow.	Eggshell membranes (ESMs), as electropositive materials, generate charge with PTFE contact—sufficient to power small devices like LEDs and watches, making them a green TENG source.
Gopal *et al.*, [22]	The aim of this research is to design and develop a Hybrid H/P-TENG using a polymer-ceramic composite film made of PDMS and BZT–BCT piezoelectric ceramic.	PDMS dan PVA	Spin Coating and Poling	H/P-TENG performance combines triboelectric charge transfer between PVA and PDMS/BZT–BCT layers with added output from piezoelectric deformation.	Adding 15 wt% BZT–BCT to PDMS boosted H/P-TENG output to 127 V, 66.6 mA/m^2, and 7.5 W/m^2—190% higher than pure PDMS—with forward polarization yielding optimal results.
Kim *et al.*, [23]	The aim of this research is to develop a sustainable impact sensor by utilizing a triboelectric nanogenerator coated with a $CaCO_3$ layer produced through a CO_2 absorption method.	$CaCO_3$	Drop Casting and Coating	$CaCO_3$-based sensors generate charge through triboelectric contact and CO_2 absorption, with crystal structure affecting sensitivity. Impact signals are classified with 95.8% accuracy using SVM.	The $CaCO_3$-coated triboelectric sensor offers high-impact sensitivity, durability, and eco-friendliness via carbon sequestration, achieving 95.8% classification accuracy with SVM for impact detection.
Prasanna *et al.*, [24]	The aim of this study was to develop and characterize multi-crystalline BCST materials by physicochemical and ferroelectric analyses, and to prepare hybrid composite films using PDMS and BCST that synergistically combine piezoelectric and triboelectric effects.	BCST dan PDMS	Drop Casting and Coating	The BCST/PDMS hybrid combines piezoelectric and triboelectric effects to enhance energy harvesting, with double rectification producing 326 V DC for powering electronics.	The BCST/PDMS hybrid TENG combines piezoelectric and triboelectric effects, generating 326 V via double rectification—enough to power electronics and track finger motion for AR/VR use.
Oflaz & Özaytekin, [25]	The aim of this study was to develop composite PVDF nanofibers with enhanced β phase using graphene, boron nitrite, and quartz additives through electrospinning process.	Graphene and Quartz	Hammer	Enhanced β-phase in PVDF nanofibers—boosted by SiO_2, BN, and graphene—improves piezoelectricity. Under stress, the fibers generate more charge, with OPT-PVDF outperforming pure PVDF.	Electrospun PVDF nanofibers with SiO_2, BN, and graphene additives achieved 99% β phase and 8.68 V output—nearly 2× pure PVDF—optimized via Taguchi design with uniform structure and crystallinity.
Su *et al.*, [26]	The aim of this research is to develop an environmentally friendly flexible PENG based on BTO, by improving the electrical performance through doping, structural modification, and flexible electrodes, and utilizing this device for biomechanical energy harvesting and tactile sensing.	PDMS dan AgNWs	Solid-State	In PENG, pressure on BTS-BCT fillers generates voltage via piezoelectricity, while Ag NWs/PDMS electrodes collect the charge—enabling biomechanical energy harvesting on the body.	The BTS-BCT-based PENG with 3D porous structure and Ag NWs/PDMS electrodes generates 39 V, 2.9 µA, and 24.2 µW—sufficient for LED lighting via biomechanical energy harvesting.
D. Li *et al.*, [27]	Researching the fabrication of Al_2O_3 thin films using the CLD method and its potential as a dielectric layer and electron barrier to improve TENG performance.	Al_2O_3	chemical liquid deposition	The performance mechanism of Al_2O_3 biomaterial in TENG involves its role as a dielectric layer with a breakdown field strength of 1.74 MV/cm, as well as an electron barrier to enhance charge separation.	The Al_2O_3 CLD layer (1.74 MV/cm) boosts TENG output to 200 V and 9 µA—2.6× and 3× higher—offering a low-cost, eco-friendly method for semiconductor applications.

Author (ref)	Purpose	Biomaterial	Synthesis method	Performance mechanism	The results obtained
Cho *et al.,* [28]	The purpose of this study is to develop and evaluate the performance of HWA-TENG as a triboelectric material that can be used in small, compact, and conformal TENG devices.	CNT	Sputtering-Plasma	In HWA-TENG, contact between materials with different electron affinities (e.g., PPFC and SEBS/PTFE) causes charge transfer; PPFC's wrinkled surface boosts negative charge attraction.	The HWA-TENG with PPFC on SEBS achieved 200 V and 30 μA—20× higher than without HWA—due to a 3.5% surface area increase, enabling diverse uses from LEDs to triboelectric skin.
(B. Li *et al.,* [29]	The purpose of this study was to synthesize NN–CS–BT material to improve the performance of triboelectric nanogenerator, analyze its dielectric properties and ceramic structure, and evaluate its effect as a filler in PDMS film on voltage output.	$CaCO_3$ and PDMS	Sintering	NN–CS–BT enhances dielectric properties, enabling greater charge generation during contact, resulting in higher voltage output than pure PDMS in TENGs.	NN–CS–BT fillers in PDMS yielded 239 V output, showing superior triboelectric performance due to improved dielectric properties and dense ceramic structure.
Prasanna *et al.,* [24]	The aim of this research is to develop CASNuT for psychiatric and neurological rehabilitation, as well as the treatment of schizophrenia.	PDMS, BCST	Solid-State, film, pellet	When the glove is worn and subjected to mechanical stress, piezoelectric materials such as BCST generate an electrical charge in response to the deformation.	Smart gloves with PB-IHNGs generate high output by combining piezoelectric and triboelectric effects. Integrated CASNuT tech enhances sensing and supports intelligent medical assistance.
Hajra *et al.,* [17]	This study aims to improve the biometric energy harvesting performance by combining TENG and PNG technologies using BCZTBH particles in PDMS to enhance the TENG output and develop an efficient hybrid generator.	BCZT-BH/PDMS	Spin Coating	BCZTBH in PDMS acts as both triboelectric and piezoelectric layer, generating voltage on contact and pressure. MS-HG design boosts output to 300 V and 157 mW/m².	Adding BCZTBH particles boosts TENG output to 300 V and 157 mW/m². The multi-stack hybrid design (MS-HG) proves effective for wireless communication and activity monitoring.
Zamanpour *et al.,* [30]	This research aims to develop touch sensors and wearable electronics based on TENGs using elastic and transparent silicon polymer layers composited with various materials to improve the triboelectric properties and electrical power generated.	$BaTiO_3$, $CaCO_3$, Graphene Oxide, AgNWs, AL_2O_3	Vertical Contact-Separation Tapping	Composites enhance charge capacity and conductivity, generating electricity from mechanical motion, which is harvested for power use.	The Si/$BaTiO_3$ TENG achieved 660 V, 72 μA, and 10.10 W/m²—up to 94% better than pure Si. With AgNW electrodes, it reached 27 W/m² at 79% transparency and 8 mg/cm² weight.

AC-HH: Activated Carbon from Human Hair; rGO: Reduced Graphene Oxide; CNF: Cellulose Nanofibril; PVDF: Polyvinylidene Fluoride; BCZT: Barium Calcium Zirconate Titanate; MWCNT: Multiwalled Carbon Nanotubes; PDMS: Polydimethylsiloxane; TOCN: Tempo-Oxidized Cellulose Nanofiber; CCTO: Calcium Copper Titanate Oxide; FCF: Filter-Coated Film; ITO: Indium Tin Oxide; CS: Chitosan; SF: Silk Fibroin; ESM: Eggshell Membrane; PVA: Polyvinyl Alcohol; BZT–BCT: Barium Zirconate Titanate–Barium Calcium Titanate; SVM: Support Vector Machine; BCST: Barium Calcium Strontium Titanate; OPT-PVDF: Optimized Polyvinylidene Fluoride; BN: Boron Nitride; BTO: Barium Titanate; AgNWs: Silver Nanowires; CLD: Chemical Liquid Deposition; HWA: Hierarchical Wrinkled Architecture; PPFC: Perfluoropolyether Composite; SEBS: Styrene-Ethylene-Butylene-Styrene; NN–CS–BT: NaNbO3–CaSnO3–BaTiO3; CASNuT: Computer-Assisted Smart Neurotherapy; PB-IHNG: Piezoelectric–Triboelectric Hybrid Nanogenerator; BCZTBH: Barium Calcium Zirconate Titanate–Barium Hexaferrite; SiO_2: Silicon Dioxide.

Discussion

Research on biomaterial-based TENGs has progressed significantly in the last decade, driven by the urgent need for sustainable and decentralized energy sources compatible with emerging technologies such as wearable electronics and the Internet of Things (IoT). This review differs from prior surveys by focusing specifically on the integration of biodegradable and renewable biomaterials as functional components in TENGs, a niche that has received limited attention in existing literature. While previous reviews tend to center on inorganic nanogenerators or hybrid composites [18,21], the novelty of this study lies in its comprehensive synthesis of current biomaterial-based approaches and the evaluation of their scalability, sustainability trade-offs, and system-level applicability.

Among the biomaterials reviewed, chitosan, cellulose nanofiber, and egg shell membrane (ESM) have emerged as the most frequently used due to their favorable triboelectric properties, mechanical flexibility, and widespread availability [20,21,31-32]. Chitosan, derived from crustacean exoskeletons, offers excellent film-forming ability and is biodegradable, making it suitable for eco-friendly applications. Cellulose nanofiber, on the other hand, provides high surface area and mechanical strength, while ESM is notable for its inherent porosity and flexibility. However, these materials exhibit moderate electrical conductivity, limiting their standalone application in high-performance TENGs. To address this, composite integration with conductive synthetic polymers and carbon-based materials has become a widely adopted strategy. Notably, PDMS and PVA have been used to enhance mechanical durability and surface contact area, while GO and CNTs are integrated to boost charge mobility and output current [4]. For instance, chitosan–GO composites have demonstrated up to a 300% increase in open-circuit voltage compared to pure chitosan-based devices [11]. However, while carbon-based additives offer performance improvements, their inclusion may dilute the biodegradability of the final composite, introducing a sustainability-performance trade-off that needs to be carefully balanced.

Performance of TENGs is highly dependent not only on the base material but also on the synthesis and processing techniques. Methods such as carbonization, ball-milling, sintering, and spin coating have been employed to modify surface morphology, increase effective contact area, and enhance dielectric properties of biomaterials [1,3,11]. Sintering applied to BCZT enhances piezoelectric output by improving crystal orientation and polarization domains. Conversely, spin coating has proven effective in thin-film deposition of PDMS and PVA, improving their uniformity and triboelectric interaction. Chemical liquid deposition, particularly when applied to Al_2O_3 and other ceramic-based biomaterial composites, enhances breakdown field strength and allows more efficient charge separation and storage. This is essential for applications involving irregular mechanical input such as body motion or wind-induced vibration. Nevertheless, these methods often involve high energy inputs, complex equipment, and toxic solvents, raising questions about their life cycle environmental impacts and industrial scalability.

Biomaterial-based TENGs are envisioned to be central components of wearable devices, flexible sensors, biomedical implants, and autonomous monitoring systems. In recent studies, they have been explored in computer-assisted smart neurotherapy (CASNuT), self-powered pulse monitoring, and respiration sensors [33,34]. These applications exploit the intrinsic biocompatibility and softness of biomaterials, which makes them well suited for contact with human tissue or for integration into textiles. Additionally, the integration with IoT and AI systems opens possibilities for real-time sensing and energy harvesting in distributed environments.

Table 3. Characteristics and performance of biomaterials based on physical and electrical properties

Ref	Morphology	Particle size	Dielectric constant	Electrical conductivity	Resistance	Density power	V/s
[14]	Porous, homogeneous and evenly distributed material	10 µm	0.7–0.9	NA	0.1–50 MΩ	0.92 W/m^2	0–30
[15]	Homogeneous and evenly distributed	1–4 µm	NA	0.4 mS/m	18–2629 MΩ	9.85 µW/cm^2	0–35
[16]	Porous, agglomerated	2–5 µm	3.37–8.19	NA	1 MΩ–100 MΩ	130–483 mW/m^2	0–130
[17]	Agglomerated granules	5–10 µm	0–230	~35 mS/m	1 MΩ–100 MΩ	0–1.1 mW/m^2	0–22
[18]	Agglomerated granules	4–7 µm	4-13	0–45 mS/m	10^2 to 10^9 Ω	~3.15 W/m^2	7–230
[19]	Rough surface	5–15 µm	NA	NA	50 Ω	~242 µW/m^2	0–20
[20]	Fiber-wires	25.5–12.6 µm	NA	NA	5 MΩ	3.7×10^4 µW/m^2	10–80
[21]	Fiber-membrane	5.89 nm	NA	NA	2.3 MΩ	0.25 W/m^2	0–1.8
[22]	Film and granules	1±2.5 µm	2.1–8	NA	1–500 MΩ	2.6–7.5 W/m^2	59.8–127.1
[23]	Film and granules	5.65–37.8 µm	NA	NA	40 MΩ	37.97–51.46 mW/m^2	0–1
[24]	Film	800 nm	NA	NA	70 MΩ	233 mW/m^2	0–200
[25]	Film-fiber	250–400 nm	3.815–6.124	10e–21 µS/cm	NA	NR	0–8.68
[26]	Agglomerated granule film	~1 µm	NA	NA	70 MΩ	6.05×10^{-4} µW/m^2	0–38
[27]	Film	15 µm	8–10	NA	NA	NR	0–213
[28]	Film	26.5–43.5 nm	NA	NA	10 MΩ	11 W/m^2	0–200
[29]	Film-grain boundaries	2 µm	297–1490	NA	NA	NR	159–239
[24]	Film-grain boundaries	1–2 µm	3.1–5.3	NA	100 MΩ	368.66 µW/m^2	0–326
[17]	Agglomerated granules	229–320 nm	650–2250	NA	100 MΩ	160 mW/m^2	0–300
[30]	Agglomerated granules-fiber	6.1–526 µm	2.8–1200	NA	10 MΩ	10.10 W/m^2	218–1200

For instance, a biodegradable TENG embedded in agricultural soil could both monitor humidity and harvest mechanical vibrations from raindrops—creating a zero-energy-cost sensing node in smart farming applications. However, these applications will require reliable energy storage, hybrid power integration, and smart power management—areas that remain underexplored in current biomaterial-TENGs literature. Despite numerous experimental advances, a critical examination of the methodological robustness across studies reveals substantial limitations. Many papers report high voltage and current outputs under highly controlled laboratory conditions, such as fixed ambient temperature, stable pressure, and artificial mechanical input. These idealized settings often fail to reflect environmental fluctuations, such as humidity or repeated strain, that TENGs would encounter in real-life deployment [34]. Furthermore, longevity tests are rare. Less than 15% of the reviewed articles evaluated TENGs performance beyond 10,000 cycles, and almost none examined degradation under ultraviolet exposure or biochemical interaction. Another issue lies in the diversity of fabrication protocols, which undermines reproducibility. Variations in polymer molecular weights, drying temperatures, and spin-coating speeds result in widely divergent device properties, even when using the same base materials. Few studies use standardized protocols or benchmark their findings against well-established triboelectric pairs (e.g., PTFE–nylon), making it difficult to compare results across the literature. This inconsistency presents a major obstacle for meta-analysis or industrial replication, highlighting the need for community-driven standardization.

While the performance enhancements achieved by various biomaterial-based TENGs are impressive, cost-effectiveness and scalability of the associated synthesis techniques remain major concerns for real-world implementation, particularly in industrial and commercial contexts. Many of the reviewed studies employ advanced or multi-step synthesis methods—such as spin coating, sintering, plasma sputtering, and chemical liquid deposition (CLD)—which, although effective in laboratory environments, often present significant challenges in terms of equipment cost, energy consumption, process reproducibility, and waste generation when scaled up [14,15,27,28]. For instance, the study using AC-HH containing rGO nanosheets derived from human hair via carbonization, ball-milling, and drop casting (Ref. [14]) achieved a sixfold increase in power output compared to conventional PVDF. While this result is promising, the carbonization and ball-milling processes require controlled high-temperature environments and specialized equipment, which may not be feasible in low-resource settings. Additionally, the use of drop casting, while simple, is not scalable for mass production due to poor control over film uniformity and reproducibility.

Similarly, the fabrication of the BCZT/MCNTs/PDMS-based P-TENG (Ref. [15]) involved sintering of piezo-ceramic materials, a method known for its high energy demands and requirement for precise temperature control, often exceeding 1200°C. This process limits scalability and raises questions of environmental sustainability, especially when conducted on a commercial scale. Despite achieving a stable performance over 6900 cycles, the economic barrier of producing ceramic-based TENGs with sintered structures remains high. On the other hand, spin coating, used in the development of PDMS/PVA/BZT–BCT composite-based TENGs [22] and BCZT-BH/PDMS-based hybrids [17], allows for thin, uniform layers with controlled thickness and high surface area, which are beneficial for triboelectric performance. However, spin coating is typically limited to small-area deposition and often requires wasteful use of solvent-based materials, posing hazards to operator health and the environment, unless solvent recovery systems are implemented. Moreover, as device areas increase, the uniformity of spin-coated layers becomes difficult to maintain, leading to quality control issues.

CLD, as demonstrated in the Al_2O_3 dielectric layer study [27], offers an attractive alternative with moderate scalability potential. The CLD process produced a uniform Al_2O_3 layer with a breakdown field strength of 1.74 MV/cm and significantly improved TENG output. The method is reported to be relatively low-cost and environmentally friendly compared to physical vapor deposition (PVD) or atomic layer deposition (ALD). However, the availability of precursor chemicals, the control over colloidal stability, and residue removal in large-scale systems are still challenges that require further optimization. Sputtering-plasma techniques, such as those employed in the HWA-TENG fabrication (Ref. [28]), produce high-performance nanostructures with exceptional control over surface morphology and electron affinity. The hierarchically wrinkled surface produced via plasma-enhanced techniques achieved an output of 200 V and 30 μA, roughly 20 times greater than non-structured analogues. While this level of performance is valuable for AI- and IoT-integrated devices, the cost and complexity of plasma systems make them unsuitable for bulk production unless streamlined via roll-to-roll sputtering systems, which remain cost-prohibitive for most research labs and early-stage manufacturers.

In contrast, top-down processing techniques like mechanical grinding and bio-extraction, used in the fabrication of chitosan/silk-based TENGs [20] and eggshell membrane devices (Ref. [21]), offer a more accessible pathway. These methods leverage readily available biomaterials and avoid the use of extreme conditions or toxic solvents, making them more aligned with principles of green chemistry. However, their triboelectric outputs tend to be modest, and achieving consistency in performance remains a challenge due to natural variability in raw materials. From an industrial viewpoint, the trade-off between performance, environmental safety, and scalability must be assessed rigorously. Materials like CBTO, BCZT, and CCTO, although showing strong piezoelectric and triboelectric performance [15,16,17], require ceramic sintering processes that are difficult to miniaturize and mass-produce without significant energy input. This limits their attractiveness for low-cost consumer products. Composite approaches that incorporate PDMS, PVA, or AgNWs [26,30] offer a compelling compromise between flexibility, electrical performance, and processability. PDMS and PVA are widely available and compatible with techniques like screen printing and blade coating, which are more scalable and industry-friendly. However, the use of noble metals like AgNWs raises cost concerns and may not be economically sustainable unless used sparingly or replaced with cheaper alternatives such as carbon-based electrodes.

A key advantage of using biomaterials in TENGs lies in their renewability and biodegradability. However, this green narrative often overlooks the environmental trade-offs associated with upstream processing and downstream disposal. While chitosan and cellulose are biodegradable, their extraction and purification often involve harsh chemicals such as NaOH and acetic acid, which may pose toxicity and waste management issues [17,18]. Similarly, the carbonization of biomass, although renewable, is energy-intensive and can emit carbonaceous pollutants if not optimized. Moreover, some biopolymers used in TENGs, such as starch, alginate, or gelatin, are derived from food crops, raising concerns over resource competition with food systems—especially in developing regions [4,5]. A life cycle assessment (LCA) framework is urgently needed to quantify the net environmental benefit of biomaterial-based TENGs, considering all stages from raw material sourcing, synthesis, usage, to disposal or recycling. Without such analyses, the ecological credentials of these technologies remain unverified and may not align with global sustainability targets such as those outlined in the UN Sustainable Development Goals (SDGs).

In light of the discussion above, several strategic gaps and future directions are evident. First, there is a lack of system-level integration studies that examine how biomaterial-based TENGs can operate within hybrid power architectures, including supercapacitors and solar cells. Second, scaling-up fabrication methods remains largely unexplored. Pilot-scale manufacturing, cost analysis, and reliability testing under diverse environmental scenarios are necessary to move beyond lab-scale feasibility. Third, regional collaboration between leading countries—such as South Korea, China, and India—should be encouraged to standardize material libraries, share best practices, and avoid research duplication. Furthermore, exploration of untapped biomaterial sources, such as fungal mycelium, bacterial cellulose, or insect-derived silk fibroin, may unlock new design possibilities with unique surface properties and mechanical behavior. Similarly, digital twins and AI-driven materials discovery platforms could accelerate optimization by simulating material performance across diverse conditions before physical synthesis.

Future perspectives

The future of biomaterials as a core platform in Triboelectric Nanogenerators (TENGs) holds significant potential, yet requires a structured roadmap to guide research and implementation over the next five to ten years. In the short term (1–3 years), research should focus on optimizing the structure and surface characteristics of biomaterials through techniques such as nanoengineering, chemical modification, and biomimetic processing. These approaches are essential to enhance triboelectric charge transfer efficiency and ensure reproducibility under controlled conditions. Parallel to this, the development of hybrid composites that integrate biomaterials with advanced materials like graphene and MXene should be prioritized to improve electrical output and mechanical resilience. In the medium term (3–6 years), the emphasis should shift to enhancing the environmental stability and mechanical durability of biomaterial-based TENGs. This includes advancing coating and encapsulation techniques, exploring biodegradable protective layers, and reinforcing the structural integrity of TENG devices for real-world use. Biomedical applications, such as self-powered health sensors and implantable devices, are particularly promising due to the intrinsic biocompatibility of biomaterials. In the long term (6–10 years), attention should focus on integrating these TENGs into Internet of Things (IoT) ecosystems and smart environments. By leveraging artificial intelligence and real-time analytics, adaptive and self-optimizing TENG systems could support large-scale deployment in sectors such as healthcare, environmental monitoring, and energy-autonomous infrastructure. This future trajectory highlights the importance of interdisciplinary collaboration across materials science, bioengineering, and digital systems to fully realize the potential of biomaterial-based TENGs.

Despite these promising prospects, several critical limitations are apparent across the current body of research. Many studies are conducted under idealized laboratory conditions, with little consideration for environmental variables such as humidity, temperature fluctuations, or mechanical fatigue, all of which significantly affect the real-world performance of TENGs. Additionally, there is a notable lack of long-term durability data. Most articles do not assess the effects of aging, degradation, or repetitive mechanical stress on biomaterials, which poses concerns for their longevity, especially in biomedical or outdoor applications. Another major issue is the lack of reproducibility due to inconsistent fabrication methods, testing protocols, and performance metrics. This absence of standardization hinders cross-study comparisons and limits the development of universal benchmarks. Furthermore, scalability remains a challenge. While some materials perform well at the lab scale, there is minimal discussion about cost-effective mass production, manufacturability, or integration with existing systems. Addressing these methodological and technical constraints is crucial to ensuring that future research transitions from theoretical exploration to applied, commercially viable solutions.

Conclusion

This study has systematically reviewed the potential of biomaterials as an optimal platform for TENGs. From the results of the literature analysis, it can be concluded that biomaterials offer significant advantages in improving the performance of TENGs, especially in terms of sustainability, biocompatibility, and energy conversion efficiency. Several types of biomaterials, such as cellulose, chitosan, and natural proteins, have been shown to have promising triboelectric properties with the ability to increase the power output and stability of TENGs systems. In addition, the integration of biomaterials in TENGs shows great potential in applications in wearable devices, health sensors, and green energy systems. However, there are challenges in optimizing the structure of biomaterials to improve the effectiveness of charge transfer and long-term stability. Therefore, further research is needed to develop surface modifications, biomaterial composites, and more efficient fabrication methods to improve the performance of biomaterial-based TENGs.

Ethics approval

Not required.

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Competing interests

Authors have no known conflict of interest in relation to the publication of this work.

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Underlying data

Data underlying this study can be requested from the corresponding authors upon reasonable requests.

Declaration of artificial intelligence use

We declare that Grammarly was used to assist with language correction, and AI-GPT (ChatGPT by OpenAI) was employed to refine the phrasing and enhance the formality of the manuscript. The use of these tools was limited to language improvement only and did not influence the interpretation of results or the originality of the content.

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