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A nanogenerator review of current trends, advancement and future directions

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Abstract

Nanogenerators are significant in the era of the emerging biodegradable energy harvesting systems, Internet of Things (IoT) application and wearable gadgets, where battery replacement and external power supply are challenging. The rise in energy demand coupled with concerns regarding environmental contamination caused by fossil fuel-based energy generation has spurred research and development of novel sustainable methods for energy harvesting. Nanogenerators increase the operational life of IoT devices by providing sustainable power source. Various nanogenerators like the piezoelectric nanogenerator, triboelectric nanogenerator, thermoelectric nanogenerator, pyroelectric nanogenerator and hybrid nanogenerator are used for sophisticated detection of systems in various fields that are small, inexpensive and environmentally benign. Generally, the choice of a nanogenerator depends on its intended application and the environment in which it will operate. Due to high output and different applications in different conditions and frequency ranges, triboelectric nanogenerators are extensively investigated. Piezoelectric nanogenerators have properties that are well-suited for wearable electronics and environmental sensing. Various studies have reported nanogenerators with high open-circuit voltages of 18 kV, 10 kV, 753 V and 578 V. and short-circuit currents of 348, 320 and 63.3 μ A. Nanogenerator also have high operational lifetimes of 3,960,000, 1,260,000, 860,000 and 90,000 cycles. This review presents a comprehensive analysis of the state-of-the-art in green energy technologies focusing on the cutting-edge advancements in nanogenerator principles, simulations, material selection and applications in the emerging field of nanoscale energy conversion.

Keywords Nanogenerator · Biodegradable · Energy harvesting · Simulation · Hybrid nanogenerator · Applications

Introduction

Massive miniature electronics including actuators, spectroscopy sensors, wearable devices, self-powered devices and wireless transmitters have been implemented in every part

of the environment because of the advancement of Internet of Things and the increasing demand for energy-efficient smart autonomous operating systems for real-time data collection [1–7]. Nanogenerators (NGs) are IoT-enabled devices that can be used in security, biochemical detection, remote controls, self-powered wearable electronics, environmental protection, health monitoring and wireless transmission [4, 8, 9]. IoT devices and smart grids are closely linked, IoT technologies are important for modernizing and optimizing functionality of different smart grids. Smart grid is a next-generation power system that enables information to be connected in intelligent, stable and efficient operation modes [10–12]. Electrical and voltage analysis is significant for enhancing power efficiency in smart grids. The conventional wired voltage monitoring systems are not always able to meet the adaptability demands of smart grids [9, 11–14]. Smart grids and self-powered devices are symbiotic as both technologies complement each other to create a more sustainable and efficient energy ecosystem.

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Self-powered devices or networks are the systems that can function naturally for data processing, transmission, sensing and detection in the absence of external supply. NGs are self-powered systems that can collect small-scale energies like thermal energy and mechanical energy from the surrounding atmosphere, which are later converted to electrical energy [15–18].

Electrical energy has been an integral part of everyday life and industrial production, a lot of experiments were conducted related to electricity [19]. One example is the well-known experiment conducted by Benjamin Franklin using electricity extracted from thunderstorms, which significantly increased awareness of electricity across the globe. Michael Faraday created a constant electric current after discovering the electromagnetic induction phenomena in 1831. The second industrial revolution was primarily fueled by the subsequent in-depth and comprehensive research of electricity, which also served as the basis for the third scientific and technological revolution [20]. The sun, water, geothermal heat, wind and biomass are instances of natural sources generating green energy. As a result of ecological restrictions, scarcity in fossil reserves and depletion of non-renewable resources, a lot of significant issues arise confronting modern society in the energy transition. Instead of relying on fossil fuels, these green energies are alternative sources of electrical energy [19, 21]. Traditional batteries have significant environmental drawbacks due to their large size, short lifespan and hazardous components. With major advantages of low production costs and low maintenance, NGs offer a way to harvest energy from natural as well as artificial sources [21]. Nanogenerators present a transformative approach to energy harvesting by utilizing the principles of nanoscale engineering. Nanogenerators have wide applications in humanoid robotics, large-scale blue energy, flexible power sources, wearable electronics, IoT based health monitoring, self-powered systems, and for scientific instruments and devices [22–27].

Recent developments in nanogenerator technology focused on enhancing energy conversion using multiphysics energy harvesting methods, surface nano-structuring and interfacial charge density engineering [28]. Surface enhancement improves mechanical deformation and effective contact area in triboelectric and piezoelectric nanogenerators which increase the charge transfer and output power density. Dielectric polarization and electrical conductivity are enhanced by using advanced functional materials including graphene, MXene and ferroelectric polymers [5, 29–31]. The energy harvesting from ambient energy sources are harvested by hybrid nanogenerators that integrate thermoelectric, piezoelectric and triboelectric effects. This helps to enhance overall efficiency and operational stability. In order to enable nanogenerators as a sustainable power source for

wearable electronics, IoT devices and autonomous sensor networks, the current research focuses on power management integration, the development of self-powered sensing systems and reliability under environmental conditions like wear, humidity and fatigue [32–40].

A brief development history of different nanogenerators

Historical development representing the first discovery of nanogenerator harvesting devices to more current developments are represented in Fig. 1. Three phases are considered to separate the evolutionary stages of NG research. (i) The initial phase (2006–2011) involves the investigation and introduction of the first NG, the piezoelectric nanogenerator. Zhong Lin Wang along with his coworkers introduced the idea of nanogenerators in 2006. They developed the first piezoelectric nanogenerator using a vertically aligned Zinc oxide (ZnO) nanowire arrays. This nanogenerator transform mechanical strain into electrical energy. This basic idea of energy harvesting has developed a new way for the future research on self-powered nano systems [16, 30, 31, 41–45]. (ii) The second phase is considered from the year (2012–2013), where thermoelectric nanogenerators, triboelectric nanogenerator and piezoelectric random number generator NGs are developed. The same research team introduced the triboelectric nanogenerator (TENG) in 2012. TENG works by combining electrostatic induction with contact electrification, greatly increasing electrical output and facilitating the effective collection of low-frequency mechanical energy [27, 32–36] (ii) The third stage (2014–2015) involves expanding and exploring the uses of nanogenerators [37–40, 46]. Between 2015 and 2025, the field of NGs had a revolutionary year in which basic discoveries developed into useful technologies that are influencing the direction of self-powered systems in the future [38, 47–50].

Piezoelectric, triboelectric, pyroelectric and thermoelectric NGs are now durable platforms for harvesting mechanical and thermal energies [5, 35, 46, 61–63]. After the invention of hybrid nanogenerators, a substantial advancement is made in nanogenerator development and as a result of enhancement in system integration, device designs and material engineering. In addition, large-scale environmental energy harvesting technologies like oceans blue energy has been developed. The recent studies conducted between 2020 and 2026 are focusing on flexible, wearable, self-powered and biodegradable sensor systems [17, 18, 33, 53, 64, 65].

The output power density, conversion efficiency and durability through methodical advancements in materials design, surface engineering and device architecture is highly improved [66]. When combined with flexible electronics, artificial intelligence and the IoT, NG have demonstrated

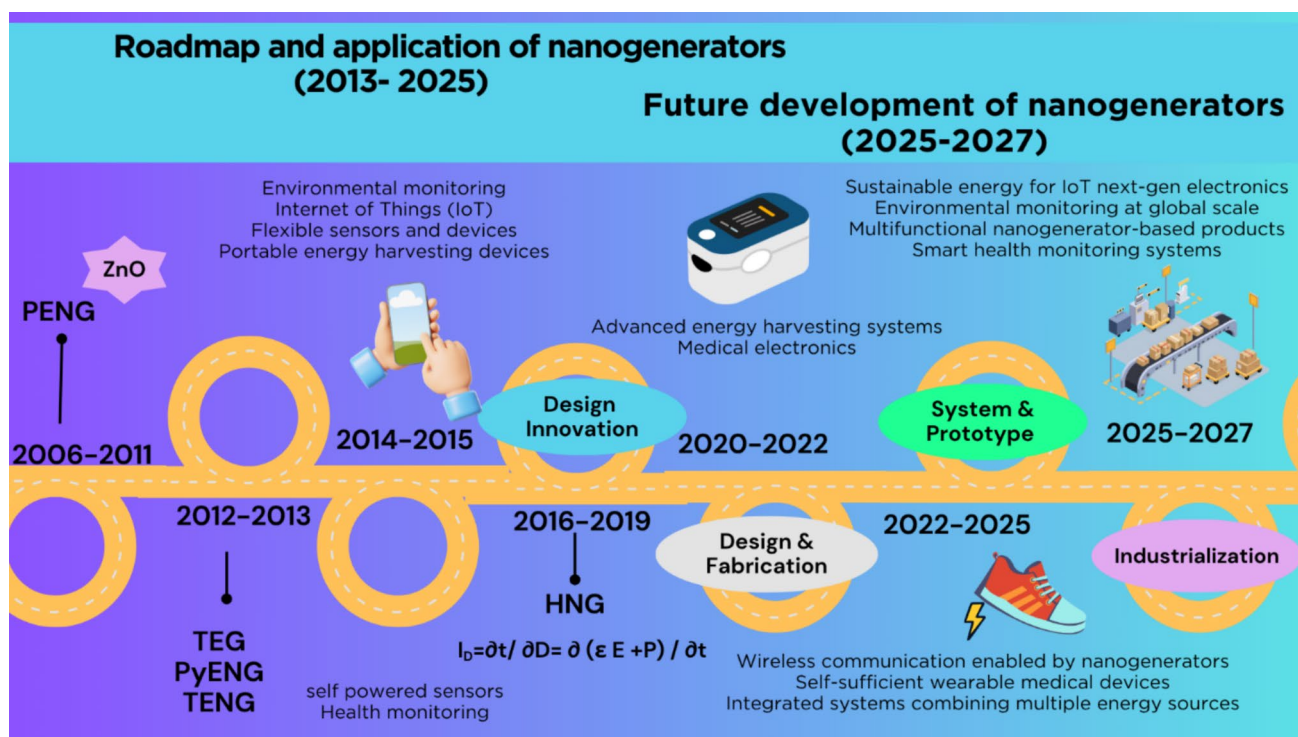


Fig. 1 Roadmap for nanogenerators [5, 9, 16, 29, 30, 41–46, 51–60]

their exceptional potential to offer sustainable, compact and maintenance-free energy solutions for environmental sensing, biomedical monitoring and human–machine interface [67–69]. The transition from lab-scale prototypes to scalable fabrication and system-level applications is a significant achievement that establishes NGs as essential technologies.

In this comprehensive review, the working principles, classifications, materials, applications, simulation, fabrication processes and future directions of NGs is discussed in detail. The piezoelectric, triboelectric, thermoelectric and pyroelectric NGs have enhanced energy harvesting by transforming ambient mechanical, thermal and vibrational energy into electricity at the nanoscale and allow electronics to function independently of traditional power sources. Nanogenerators have versatility of applications in different areas due to its efficiency to operate with different parameters. Material selection is very important in determining the performance of NG, both bio-based and synthetic materials give distinct benefits. Advanced manufacturing techniques will definitely enable large-scale production of devices. The computational approaches such as molecular dynamics and finite element analysis are performed through different simulation tools, which help to optimize device efficiency. To achieve the safe and practical application of NGs in sustainable energy, many challenges related to efficiency, large-scale fabrication and durability are needed to be taken in account.

Scope and organization of this review

This review paper bridges the gap in the existing literature by offering a consistent analysis and material-driven comparative methodology of different nanogenerator technologies. A very few research papers give a cohesive idea across several nanogenerator mechanisms. In this regard, the current review incorporates (i) The working principles of all the major nanogenerators like piezoelectric, triboelectric, thermoelectric, pyroelectric, hybrid nanogenerators and developing nanogenerators are compiled and compared in a single study. (ii) The study offers a focused analysis of innovative materials and their effect on energy conversion efficiency and nanogenerator performance. (iii) This review also gives an idea on multiphysics modeling and simulation techniques for the analysis and optimization of various nanogenerator systems. (iv) The review describes challenges, current trends and potential research areas for next-generation energy harvesting devices. Figure 2 gives a brief introduction towards the organization of review paper.

Different types of nanogenerators

The Piezoelectric nanogenerator (PENG), Pyroelectric nanogenerator (PyENG), Thermoelectric nanogenerator (TEG), and Triboelectric nanogenerator (TENG) along with Hybrid

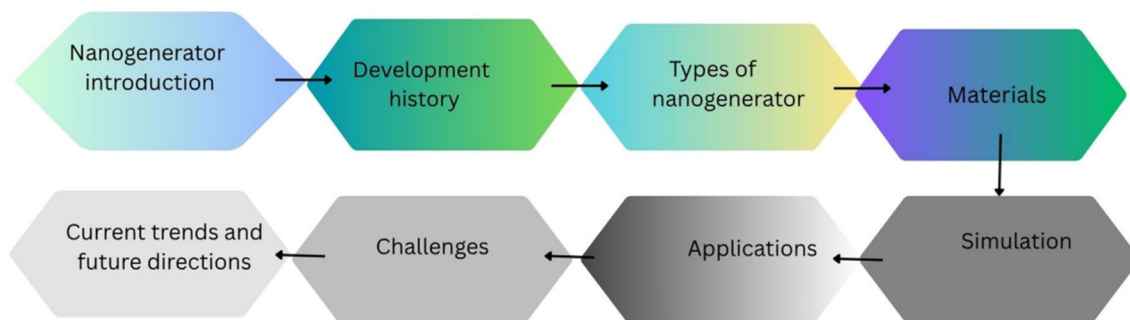


Fig. 2 A brief introduction to the organization of the review paper

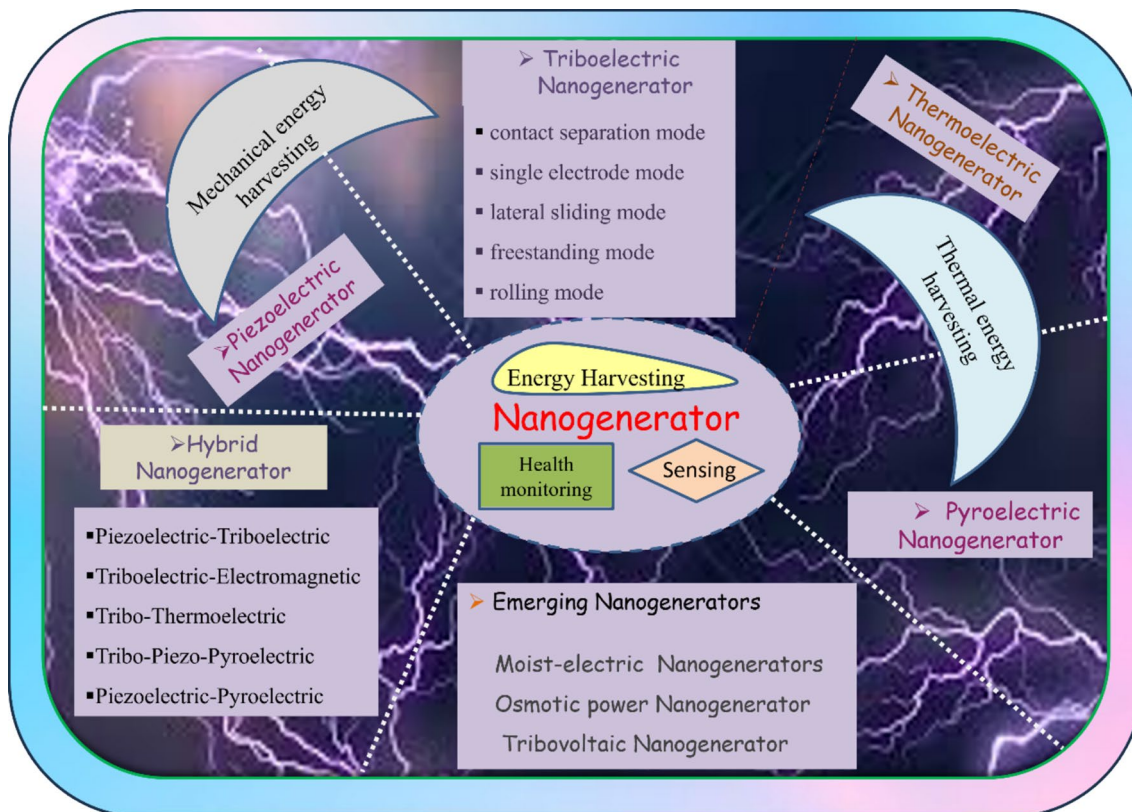


Fig. 3 Different types of nanogenerators

nanogenerator (HNG) like electromagnetic nanogenerators combined with triboelectric nanogenerators, represent the different types of nanogenerators (NGs) [70]. Figure 3 illustrates the classification of nanogenerators. TEG and PyENG nanogenerators harvest thermal energy, while piezoelectric and triboelectric nanogenerators harvest mechanical energy [36, 71]. Electromagnetic nanogenerators are devices where electromagnetic induction phenomena are applied to generate electrical energy [72]. Currently available electromagnetic nanogenerators obtain energy mostly from mechanical forces and friction, and most of these processes ignore magnetic fields and acoustic vibrations [72]. The interaction of certain materials with airborne water molecules like

moisture generates electricity in moist-electric nanogenerators [73, 74]. The osmotic pressure or the difference in ion concentration between two fluids is transformed into electrical energy in an osmotic power nanogenerator [74]. Energy harvesting efficiency is mainly influenced by output voltage, current, power density and impedance, which define the electrical performance of NGs.

New approach for energy harvesting from environmental factors like salinity gradients and humidity have recently started to gain interest and were used to in Osmotic power nanogenerator (OPNG), Moist-Electric nanogenerators (MENG) and Tribovoltaic nanogenerator (TVNG). This emerging MENG and OPNG ion transport in nanostructured

materials to transform moisture or salinity-gradient energy into electricity. Compared to other nanogenerators like piezoelectric and triboelectric nanogenerators, research in these areas is less, but new studies show their potential for sustainable energy harvesting from ambient environmental sources. TVNGs which generate electricity from mechanical friction using the tribovoltaic effect.

In order to maximize energy transfer, impedance matching must be optimized, even though overall power generation is improved by output current and voltage. The output voltage (V_o) is the electrical potential generated by the energy input. The short-circuit current (I_{sc}) occurs due to charges between electrodes. The output voltage and short-circuit current are the two important parameters of NGs that reveal the efficiency of NG [75–77]. The potential difference in the TENG, PENG, TEG and PyENG for energy conversion is given by its output voltage. A greater output voltage indicates that energy is transferred more effectively [37]. Nanogenerator applications for real-world uses are determined by their power density, which is influenced by structural design and material characteristics. Changes in the electrical parameters have an impact on the efficiency of the device. The external load conditions, surface charge density and material choice are efficiency of NG. are the important aspects for the performance optimization [38, 78].

MENGs, OPNGs and TVNGs are emerging technologies that have not achieved the same level of popularity as other nanogenerators, due to the limitations in source availability and practicality. MENG, OPNG and TVNG depends on moisture gradients, osmotic pressure or friction. Moisture dependent upon location and osmotic energy necessitates freshwater-saltwater interfaces, which are restricted to estuaries or artificial configurations. The other NGs includes, electromagnetic nanogenerators (EMGNGs) that make use of the concepts of electromagnetism. A shift in magnetic flux results the coil to experience an electrical current

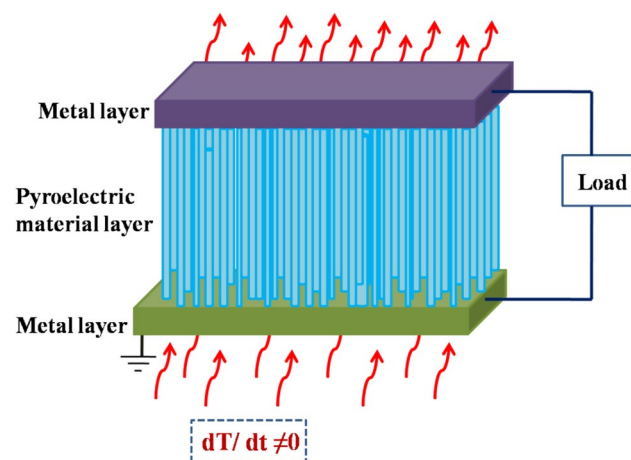


Fig. 4 Structural diagram of a PyENG for thermal Energy Harvesting [83]

which causes electricity to be produced when the magnet and coil are moving relative to one another [47]. EMGNGs are mainly used in smart building, wearable and portable devices and implantable medical devices [79]. Recently ferroelectric NGs were used as a viable substitute for kinetic energy harvesting [80, 81].

Pyroelectric nanogenerator

PyENGs convert time-dependent thermal fluctuations into electricity by the pyroelectric effect. Some materials exhibit this phenomenon of generating an electric potential due to polarization changes with temperature fluctuations. PyENGs efficiently harvest thermal energy from such variations, unlike TEGs, which cannot operate under these conditions of time dependent temperature variations [82].

Factors like thermal stability, pyroelectric coefficients and compatibility are taken into account with nanoscale production techniques, for effective energy conversion in PyENGs. Figure 4 represents the structure of a pyroelectric nanogenerator consisting of two metal electrode and a pyroelectric material layer. The PyENG consists of three key layers, a pyroelectric material layer and two metal layers. Thin conductive layers of Gold (Au), Silver (Ag) or any conductive metals are deposited encasing the pyroelectric material to collect the generated charges and establish the electrical contact [83]. A supporting substrate is used which are off flexible or rigid materials to provide mechanical stability and adaptability for various applications [50].

Consider a pyroelectric nanogenerator where an Ag film is used to construct the top electrode, an indium tin oxide (ITO) film acting as bottom electrode and a nanowire (NW) material is used as the pyroelectric layer. Nanowires are preferable because they have low mechanical constraints, maximize strain, dipole polarization and surface charge production. NW are ideal for sensitive PENGs, upon an increase in the device temperature a pyroelectric potential is generated across the NW-composite film, and as a result a negative electric potential is developed in the ITO electrode. This lifts the conduction band energy level as well as Fermi energy level of the ITO. This increase in energy level helps the electrons to move from the ITO electrode towards the Ag electrode. On the reverse hand, the cycle is completed when the electrons return to the top electrode as the temperature decreases. The nanowire material responds to time-dependent changes in temperature like periodic heating and cooling. This temperature fluctuation may arise from natural environmental changes like body heat or artificial thermal sources. When the material experiences a change in temperature, the asymmetry in its crystal structure leads to a redistribution of charges resulting in a transient electric

field and potential. The transient charges generated during the temperature fluctuation are collected by the electrodes.

Thermoelectric nanogenerator

TEGs are mostly based on the seebeck effect and sometimes on the peltier effect that transforms thermal energy from temperature gradients, into electrical energy. TEGs consist of multiple thermopiles to enhance output power, with each thermopile comprising thermocouples (TCs). A voltage change, V is induced by a temperature gradient due to the Seebeck effect and is given in Eq. (1). N is the number of thermocouples attached, A and B are the different materials used in the TEG and α denotes the Seebeck coefficients of different materials.

$$V = N \cdot (\alpha A - \alpha B) \cdot \Delta T \quad (1)$$

ΔT is the temperature difference across the thermocouple (TC) junctions i.e. $T_{\text{hot}} - T_{\text{cold}}$ [84]. In a vertically connected thermoelectric nanogenerator the thermocouples are aligned between the hot junction and cold junction directing the heat flow through thermoelement arms and substrates [84]. Resembling Peltier-based refrigeration modules, this design offers high integration density, a simplified structure and an enhanced output voltage, making it the most commercially adopted configuration [85].

Figure 5 shows the fundamental structure of a TEG. The basic components of the TEGs are thermoelectric materials and semiconductor materials [86]. The thermoelectric material is supported on a substrate, which can be made up of either rigid materials like ceramics and silicon wafers or flexible materials like polymer films [87]. Metallic or conductive layers are deployed on both ends of the thermoelectric material to collect and transport the charge carriers efficiently. Materials such as Au, Ag and Cu are typically employed to ensure minimal resistance and high

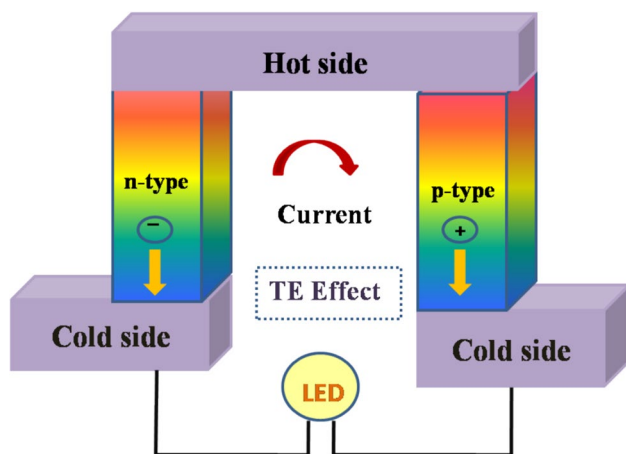


Fig. 5 TEG nanogenerator structure and its different constituents [86]

conductivity. These layers are important for maintaining device stability and operational longevity [88, 89]. A temperature gradient is achieved by maintaining one side of the material interacting with a higher temperature (heat source) and the other side with a lower temperature (heat sink or cooler environment) resulting in diffusion in charges. This diffusion generates an electrical potential. The charge carrier movement between devices is triggered by temperature differences, hence generating electricity by harvesting thermal energy [6].

Piezoelectric nanogenerator

In PENGs, mechanical energy from motion, pressure or vibrations are transformed to electricity [40]. Stress in the form of stretching, bending, compression or vibration produces an electric charge in piezoelectric materials. When stress is applied, the asymmetry in the crystal structure of the piezoelectric material causes a redistribution of charges creating an electric dipole moment. Here, the piezoelectric effect occurs due to dipole moments produced by piezoelectric materials. The two electrodes are subjected to the materials which are naturally, electrostatically balanced in terms of Fermi levels. At the contacts a piezoelectric potential is generated due to the strain applied to the material and a difference in the Fermi level arises. The contact mechanism between the two electrodes and the nanostructures are due to Schottky contact in one interface and ohmic contact in the other interface because of the difference in the work function between the nanomaterials and the electrodes. The ohmic contact allows effective charge collection and transmission to the external circuit, whereas the Schottky contact functions as a rectifying junction which, regulates the flow of carriers. By improving the separation and transfer of piezoelectric charges, NGs electrical output can be enhanced.

Electricity is produced by rebalancing the variations in Fermi levels, ultimately leading to a new balanced electrostatic condition. These electrodes can be thin metal films like Ag and Au or transparent conductive oxides like ITO. Silicon wafers or polymer sheets like Polyethylene Terephthalate (PET) are used as substrates. The piezopotential generated in the piezoelectric material is the working principle of a PENG [61]. The operation of a PENG is depicted in Fig. 6. The electric dipole moment, created inside a vertically aligned nanostructure (NS) of piezoelectric material, such as ZnO causes deformation when a parallel force is exerted in the tip surface.

Zinc oxide (ZnO) can produce electricity in response to external micromechanical forces like sounds or winds depending on its linked piezoelectric and semiconducting capabilities. This accumulation at the schottky diode causes

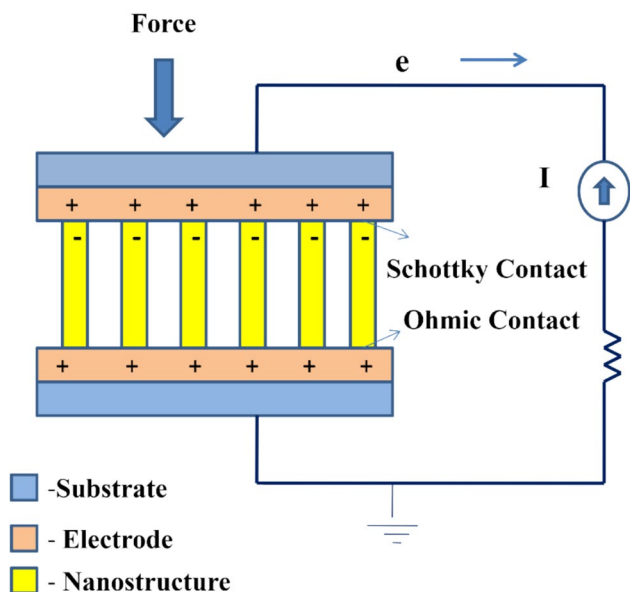


Fig. 6 Schematic representation of a PENG [46]

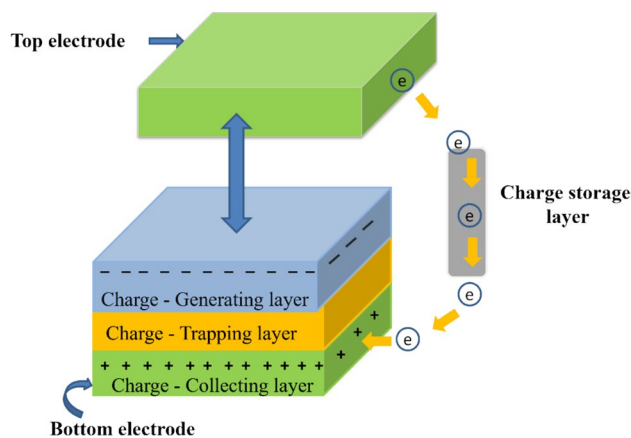


Fig. 7 Layered structure of a TENG and the charge transport mechanism [95]

electrons to flow through the ZnO nanowires generating electricity. Subsequently as the slider reverses the direction similar conditions repeat producing power [90, 91].

Triboelectric nanogenerator

The basic structure of a TENG is represented in Fig. 7. TENGs are a revolutionary energy technology that uses electrostatic induction and also the triboelectric effect to transform mechanical energy into electrical energy [1, 62, 92]. In contact electrification phenomena, the triboelectric effect occurs when some materials come into frictional contact with another substance and acquire an electrical charge. Electrostatic induction is the method of creating a charge on a material without making direct physical contact. This happens when a charged object redistributes charges on a

neutral material surface, generating a potential difference that creates electricity [20, 63, 64, 93, 94]. TENGs are highly successful at capturing energy from various mechanical sources, including vibrations, movements of nature, and motions, because they can produce electricity from slow and irregular motions [53, 65].

The structural elements of a TENG have a significant effect on its performance. External stimuli are used by the charge-generating layer to generate charges. The charge-trapping layer traps charges momentarily and stores or retains the created charge to improve efficiency and also helps the charge-collecting layer from rapidly dissipating. This Charge generating layer is same as the tribo-positive or tribo-negative layer listed in TENGs different modes of operation shown in Fig. 10 made from tribo-positive or tribo-negative material from tribo series of materials listed in Fig. 9. The charge trapping layer is same as dielectric 1 and dielectric 2 layer and charge collecting layer act as the electrode. The charge-storage layer is the layer that stores and gathers charges and moves the produced charge to an external circuit for sensing or energy harvesting applications. Each layer plays an important role in optimizing triboelectric power generation by contributing to charge generation, retention, collection and storage processes [20, 67, 95].

TENGs equivalent electrical circuit model and formal physical model are shown in Fig. 8. The formal physical model and the equivalent electrical circuit model are the two primary modeling techniques for a TENG. Maxwell's equations, which can be further represented using the Poisson equation and Gauss theorem or a simplified quasi-electrostatics model that captures charge distributions and field interactions, are used to describe the device in the physical model. Conversely, the electrical circuit model simplifies circuit-level comprehension by converting the physics into differential equations. The capacitive model, in which the open-circuit voltage (V_{oc}) is related to capacitance, load impedance and Norton's equivalent circuit, which describes short-circuit current (I_{sc}) using Norton's theorem with the impedance of the source. These models work in tandem to offer comparable insights, the circuit model allows for the realistic design, simulation and integration of TENGs into actual systems, while the physical model incorporates basic electrostatics.

Their interrelations are essential for the complete understanding and optimization of the device. The potential drop (ϕ_{AB}) equals the voltage in the load V and is given in Eq. (2).

$$V = N \cdot (\alpha_A - \alpha_B) \cdot \Delta T \tag{2}$$

TENG physics is governed by variations in potential (ϕ), Maxwell's displacement current (I_D), dielectric polarization (P), time (t), impedance (Z) and electric field (E). The

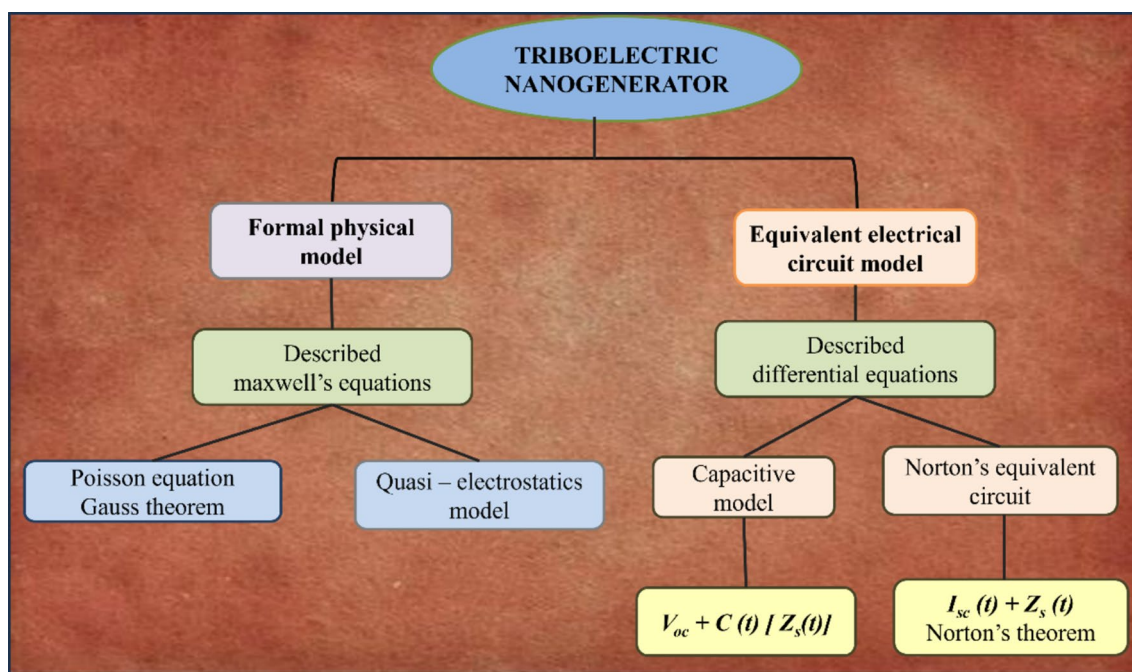


Fig. 8 TENG equivalent electrical circuit model and formal physical model [68]

circuit models define external outputs. These models are unified under Wang's expanded Maxwell's equations as

$$I_D = \partial t / \partial D = \partial (\epsilon E + P) / \partial t \quad (3)$$

where ϵ is the medium permittivity, D is the electric displacement field and P is the dielectric material polarization [20, 68, 94].

The two triboelectric layers should be chosen in varying tendencies for gaining or losing electrons. A differential voltage is produced when the tribonegative and tribopositive materials interact. These materials can be polymers, bio materials organic or inorganic materials. In Fig. 8 a list of various tribopositive and tribonegative materials are shown. In order to collect the generated charges, conductive layers are adhered to the triboelectric layers. The electrodes can be configured in various patterns depending on the TENG mode. The triboelectric layers and the electrodes are supported by flexible or rigid substrates that provide mechanical stability and adaptability [54, 69, 96, 97].

There are four basic modes of operation for TENGs and are based on different charge-generation methods. Each mode has a fundamental structure and certain benefits that are used for particular applications. Figure 9 provides an illustration of the various modes of TENGs. Vertical contact-separation mode (VCS) is characterized by periodic contact and separation between the tribopositive layer and tribonegative layer (Fig. 10).

During contact electrons are transferred between the layers and upon separation an electric potential difference

occur, driving the electron flow through the external circuit [100]. In the lateral sliding mode (LS) the layers slide against each other and create a dynamic charge distribution due to friction. This relative motion generates an electric potential difference that drives current flow [101]. In the single-electrode mode (SE), a single triboelectric layer interacts with a grounded object. The charge generated on the layer induces a potential difference with the electrode, producing a current in the external circuit [102]. In the freestanding triboelectric-layer mode (FST), a freely moving triboelectric layer alternately approaches and separates from fixed electrodes, generating an alternating electric potential difference [102]. A TENG device, for example in any configuration is neutral and can be defined by a lumped parameter [103]. Table 1 lists the different modes of TENGs working mechanisms, and their advantages, disadvantages and the different factors affecting the working of different modes.

After the fabrication these NGs, to safeguard these device from environmental degradation such as moisture, mechanical stress, contaminants and external factors a protective encapsulation layers are made [102]. When the device is finally paired with an external load, thermal or mechanical energy is successfully converted to electrical energy [106]. The electrical power produced can either be used directly for charging small electronic devices or saved in energy storage devices like capacitors and batteries [48, 84].

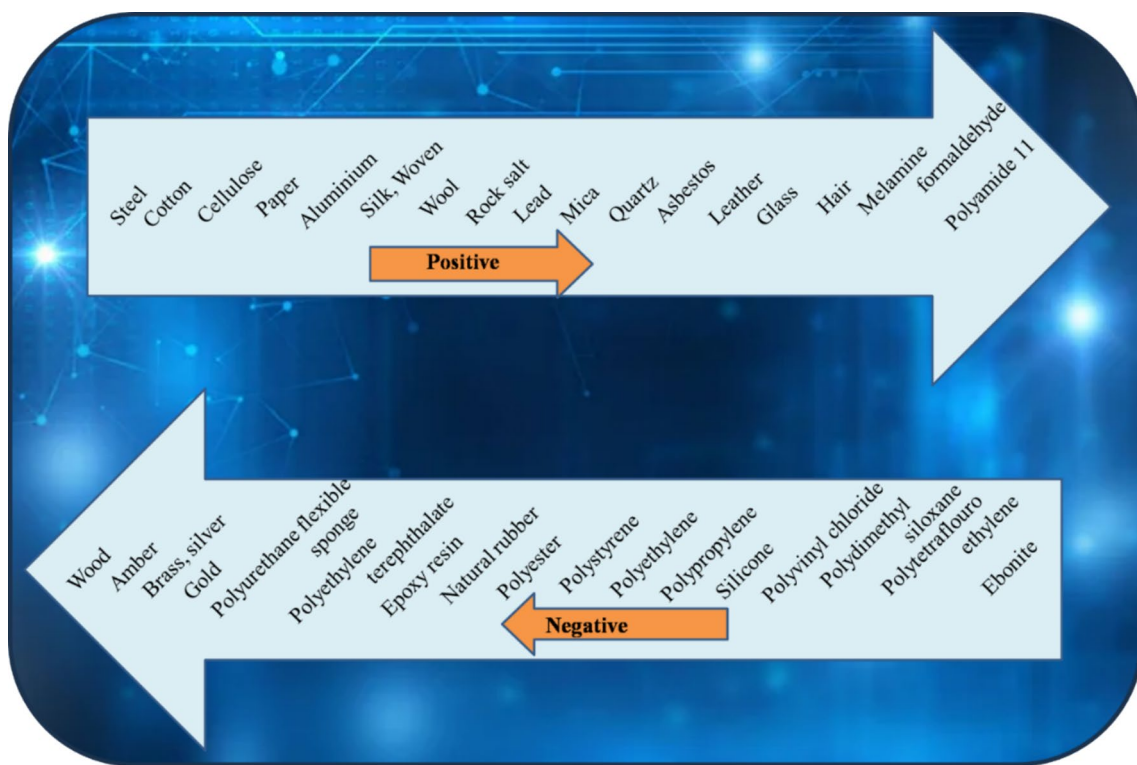


Fig. 9 Triboelectric series of materials [98]

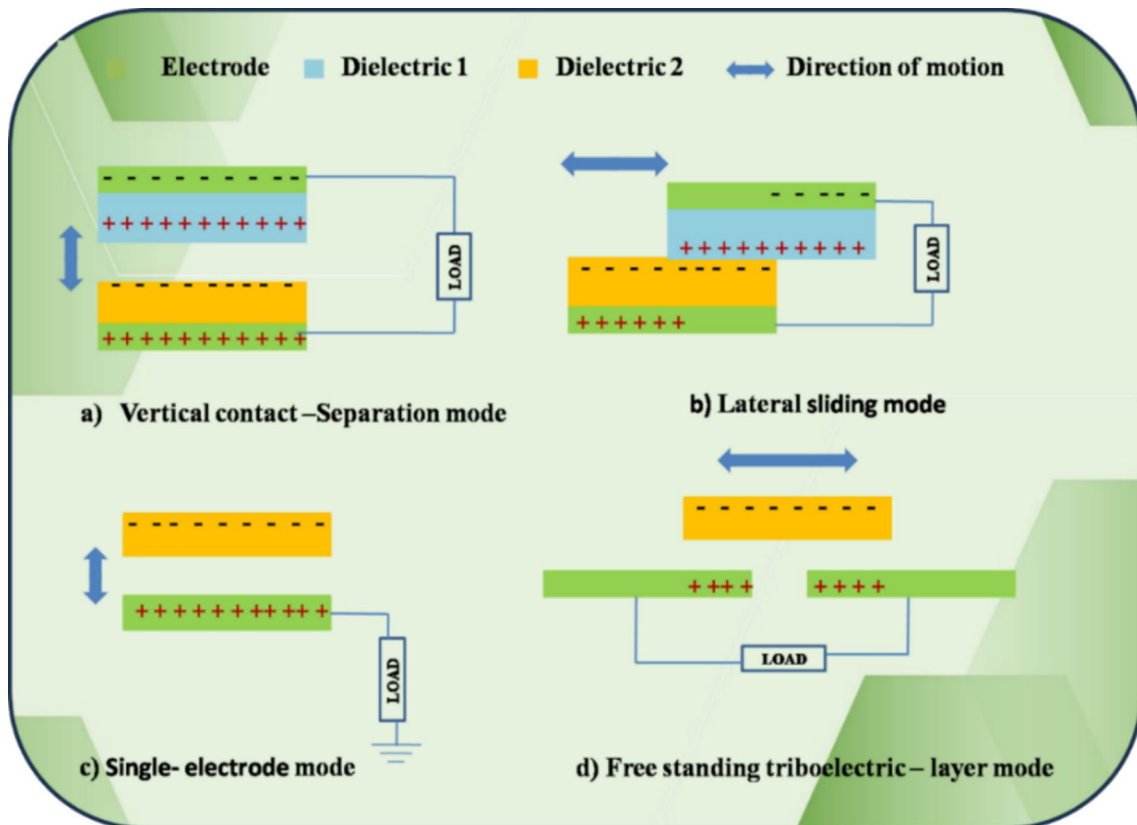


Fig. 10 Schematic of the TENGs four operational modes [99]

Table 1 Specifications of VCS, LS, SE and FST modes of TENGs [102, 104, 105]

Mode	Operating principles	Benefits	Limitations	Factors
Vertical contact- separation	Two materials periodically come into and out of contact, generating charge through contact electrification and electrostatic induction	Simplified framework and high output	Comparatively large device size and poor long-term stability due to mechanical wear	Material properties, contact force and separation distance
Lateral sliding	Charge generation occurs due to relative lateral motion between two surfaces with different triboelectric affinities	Continuous energy harvesting and high charge density	Requires continuous sliding motion and potential wear	Surface roughness, friction coefficient and sliding velocity
Single-electrode	One triboelectric layer interacts with external objects while being connected to a reference ground	Simplified framework	Lower charge transfer efficiency, needs grounding	Dielectric constant, grounding efficiency and surface potential
Freestanding triboelectric-layer	A dielectric layer which is moving, induces charge redistribution between two stationary electrodes	High output power	Large device size, weak longevity	Electrode spacing, movement frequency and dielectric properties

Hybrid nanogenerators

A device that combines multiple energy harvesting systems to transform different sources of energy into electrical power is a hybrid NG. By utilizing various ambient energy sources including mechanical, thermal, solar or electromagnetic energy a hybrid NG seeks to maximize energy harvesting efficiency and output. For HNG there is an increase the total energy conversion efficiency by capturing a wider spectrum of ambient energy sources by integrating several energy collecting techniques. The device capture different forms of energy based on the availability of several energy sources and ensure a more stable power supply. Small-scale electronic devices and biosensors can be powered independently by absorbing energy by different means like body motions, vibrations and ambient environmental motion [107–109].

Materials and their aspects for nanogenerators

The material properties are fundamental to the performance and functionality of a NG for reliable long-term operation, the material must possess high resistance to mechanical fatigue and stress, ensuring durability under continuous use. The voltage generated can be affected by various structural designs and materials [110–112]. It is also important for materials to maintain stability during repeated mechanical interactions and to avoid degradation over time. High entropy has gained significant traction in materials research throughout two decades and it has more recently been used to nanomaterials. Materials with high entropy, defined by the addition of five or more utilize entropy to encourage the creation of compositionally complex single-phase materials as opposed to phase-segregated alternatives by combining more principal elements in approximately equal amounts

[75]. High-entropy materials combine several elements in nearly equimolar ratios to produce distinct defect patterns and adjustable features that improve mechanical strength, piezoelectric responsiveness and stability in NGs. These substances increase the energy conversion efficiency as well as long-term robustness of nanogenerators, increasing their dependability for wearable and IoT applications.

High dielectric constant materials significantly contribute to improving energy storage and enhancing output performance. The development of innovative non-toxic conductive polymer-based materials like hydrogels to greatly enhance the efficiency of NGs, opening new avenues for practical and commercial implementation [9, 43, 76, 77]. In HNGs for seamless integration and compatibility, the material interfaces is important. The materials ensure efficient energy transfer and maintain the overall structural stability. Through the precise selection and design of materials with improved properties, NGs can achieve optimal performance across diverse applications.

Pyroelectric nanogenerator

With a large pyroelectric coefficient and improved performance, Lead zirconate titanate (PZT) is a promising material for PyENGs. Common pyroelectric materials includes crystalline materials like BaTiO₃, Lithium niobate (LiNbO₃) and polymers like PVDF [113]. Pyroelectricity can be enhanced by doping PVDF nanocomposite thin films with ZnO nanoparticles [114]. SiGe alloys are compatible with semiconductor manufacturing techniques, hence exhibit strong thermoelectric properties and are suitable for integration into microelectronic devices [1]

Skutterudites based on Cobalt antimonide (CoSb₃) compounds demonstrate excellent mechanical strength and thermoelectric efficiency in intermediate temperature ranges, making them suitable for waste heat recovery and power generatio [115]. Half-Heusler alloys composed of

environmentally friendly and thermally stable materials are widely employed in industrial and automotive waste heat recovery applications due to their high thermoelectric performance [38]. Tin selenide (SnSe) is a next-generation material which shows a maximum figure of merit (FOM) and thermoelectric efficiency at high temperatures [39]. These diverse materials offer a range of possibilities for advancing TEG devices for specific applications, specifically enhancing energy harvesting efficiency [80].

Thermoelectric nanogenerator

Thermoelectric materials chosen for TEGs are based on their stability, efficiency, and capacity to function at different temperatures. TENGs are effective across low, medium and high-temperature regimes, making them versatile for diverse applications. Bismuth Telluride (Bi_2Te_3), Half-Heusler, Lead telluride (PbTe), Tin selenide (SnSe) crystals, Silicon germanium (SiGe) alloys and Skutterudite are materials with good thermoelectric properties [81, 115]. Quantum dots enhance the performance by leveraging nanoscale effects to optimize thermoelectric efficiency. At the nanoscale, material properties are tuned to suppress thermal conductivity while simultaneously improving electron transport. This supports the interplay between quantum confinement and phonon scattering to boost thermoelectric performance [116, 117]. Bi_2Te_3 is highly efficient for energy conversion at room temperature [88, 89, 118].

Flexible thermoelectric generators can be developed by printing Bi_2Te_3 nanoplates and reduced Graphene oxide (rGO) onto Polyimide [39, 119, 120]. PbTe is another material with exceptional thermoelectric performance in the 400–900 K temperature range, making it ideal for waste heat recovery applications [33]. Emerging materials, such as magnetic 2D tellurides, offers potential for flexible energy harvesting systems [12]. MXenes are also predicted to exhibit outstanding thermoelectric properties and are used in wearable electronics, energy storage, sensing, electrical applications, and biomedical sciences [34]. Aluminum trioxide (AlO_3) doped with Lanthanum aluminate (LaAlO_3) is also a promising nanostructured thermoelectric material [35].

Piezoelectric nanogenerator

BaTiO_3 is recognized for its strong piezoelectric response and high dielectric constant, is used for high-performance energy harvesting systems due to its superior thermal stability [1, 121]. Lead zirconate titanate (PZT) with its exceptional ferroelectric properties is applied in actuators where high sensitivity is essential [61]. The flexibility properties of PVDF make it promising material for PENGs.

These lightweight materials are preferred for wearable and flexible NGs [122]. Piezoelectric properties along with ease of fabrication into fibers and films make PVDF ideal for diverse applications.

Gallium nitride (GaN) and Aluminum gallium nitride (AlGaN) characterized by its high piezoelectric coefficient and excellent chemical stability is particularly suited for high-frequency applications contributing to the development of robust and efficient nanogenerators [94, 123, 124]. Enhancements in nanogenerator performance have been achieved by incorporating silver nanoparticles (Ag-NPs) into Polyvinylidene fluoride-hexafluoropropylene (PVDF-HFP) fibers which boosts their efficiency [53, 125]. Potassium sodium niobate (KNN), a lead-free and environmentally friendly material with high piezoelectric performance serves as a sustainable option for eco-friendly energy harvesting devices.

Novel materials like Boron nitride nanosheets (BNN) demonstrate higher piezoelectric responses PENG nanogenerators offer sustainable solutions in human-machine interfaces, sensors and biomedical applications [126–128]. The incorporation of 5–25 wt.% ZnO microparticles into a Polydimethylsiloxane (PDMS) matrix enhances flexibility and adaptability. Moreover, interfacing nickel oxide (NiO) and ZnO into heterojunction configuration further improves the electrical performance making them highly efficient for advanced applications [54, 97].

Triboelectric nanogenerator

A high-performance TENG requires careful consideration to choose the right triboelectric materials. The materials used for TENG mainly includes metals, polymers and inorganic materials [129]. The material selection for triboelectric generators plays a vital role since its fundamental to the functioning of the triboelectric generator and it directly affects the electrical properties of the NG [130]. The materials position in the triboelectric series determines the magnitude of the charge transfer.

Figure 8 presents various triboelectric materials arranged in increasing or decreasing order of their positivity and negativity. The combination of materials far apart in the series (e.g., polytetrafluoroethylene (PTFE) and aluminum) generates more charges. 2D MXenes are used to increase the flexibility of TENG [131]. Increasing the surface area through roughness or nanostructures enhances charge generation by amplifying the contact points. Perovskite-elastomers are used for gripper sensing and gesture recognition. The Kapton and Bi_2Te_3 film paired with a thermal insulating textile based TENG (TI-TENG) gives significant output power, dependable energy-harvesting capabilities and the capacity to power portable electronics [132]. Graphene oxide (GO)

and Molybdenum disulfide (MoS_2) gives a high output voltage in TENG [70]. Another promising material is carbon black that can be used for waste water treatment [133].

Cellulose, a common natural polymer holds great promise for creating sustainable TENGs [134]. GO used in TENGs helps in efficient charge transport to the back contact [40]. TENGs are also made of nature inspired materials like rose petals, fish tail, human skin and wood for its working [135]. In order to power wireless sensors in power transformers, a TENG can be attached, which gives an excellent outcome [136]. The property elastomers to maintain stable triboelectric output under deformation enable seamless integration into multifunctional devices [137].

Surface roughness on triboelectric layers, an important factor influencing charge generation, can be achieved through various techniques, including inductively coupled plasma etching, wet etching, electrospinning, lithographic techniques, electrodeposition, and casting [52, 59, 138, 139]. Material fabrication plays a pivotal role in enhancing NG efficiency and scalability. Solution-based methods have proven effective for producing high-yield, low-cost nanofilms suitable for commercial applications [53]. For instance, electrospinning creates nanoscale fibers with

enhanced surface morphologies improving the triboelectric performance of NGs.

Similarly, wet etching provides a scalable method for creating cost-effective patterned surfaces, while electrodeposition enables precise control over material thickness and uniformity. Despite these advantages, some techniques, such as lithographic methods, may involve higher costs and complexity, limiting their large-scale applicability. The interfacial state and stability significantly impact NG performance. Innovations such as the in situ sputtering of Ag to fabricate induction electrodes have improved compatibility and reduced interfacial resistance in TENGs, leading to enhanced energy conversion efficiency [103]. Additionally, low-cost electroplating processes have shown promise in fabricating TEGs, further demonstrating their potential for large-scale commercial deployment [140, 141].

As an example consider a TENG from polyacrylonitrile and ZnO material can be used in pressure sensor [143]. Different nanowires are synthesized and its comparison in NG performance is done, which shows the importance of selecting the material structure and size. Figure 11a–c shows the Scanning electron microscope (SEM) images of 200 polypropylene (PP) nanowires, (d–f) shows SEM images of 400 polypropylene nanowires and (g–i) SEM images of Nylon nanofibers.

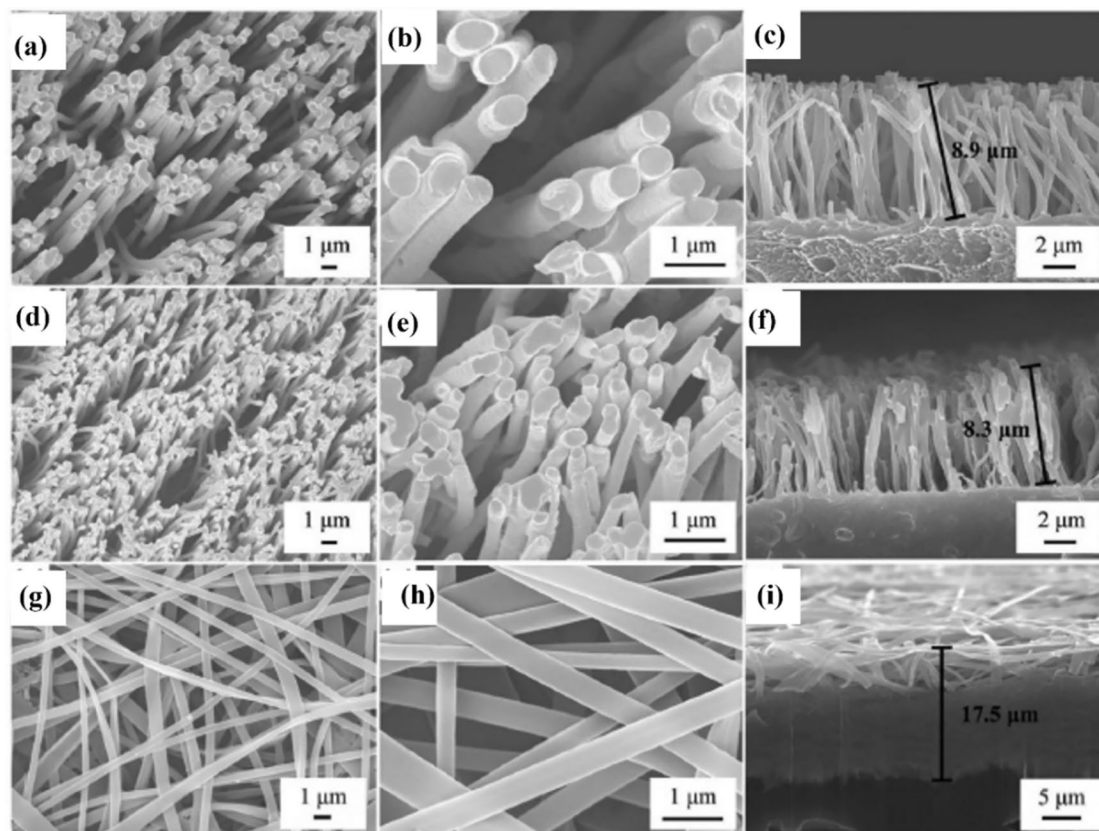


Fig. 11 a–c SEM images of 200 Polypropylene nanowires, d–f SEM images of 400 polypropylene nanowires and g–i SEM images of Nylon nanofibers. “Reprinted from [142] with permission from The Royal Society of Chemistry”

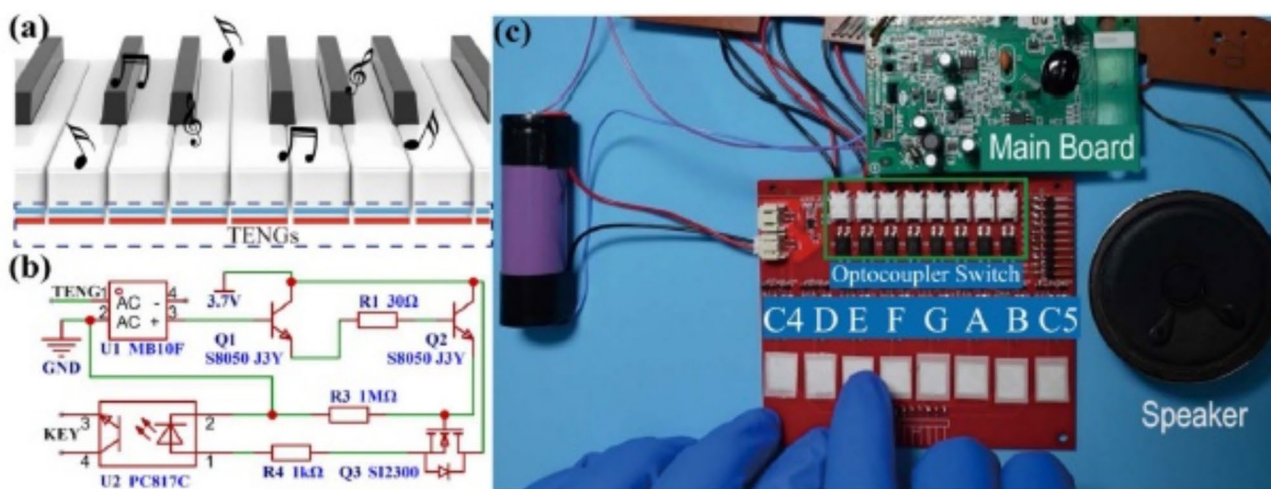


Fig. 12 a–c Schematic image and diagram of trigger signal and photograph of flat PP of 200 nm pore size TENG. Reprinted from [142] with permission from The Royal Society of Chemistry 4.5 Hybrid nanogenerators

Table 2 Electrical parameters of various materials used in PyENGs

References	Material	Stability [Cycles]	External load [MΩ]	Output power [mW]	Short circuit current I_{sc} [μA]	Power density [W/m ²]	Open circuit voltage V_{oc} [V]
[145]	BNT	5000	20	–	1.2	3.5	19
[146]	PVDF	–	50	8.3×10^{-3}	2.5	–	42
[41]	ZnO	200	–	–	–	–	$\sim 5 \times 10^{-3}$

Table 3 Electrical parameters of various materials used in TEGs

References	Material	Output current [μA]	Output voltage [V]	Stability [Cycles]	Open circuit voltage V_{oc} [V]	Output power [mW]
[147]	AZO+CuI	2.2	0.014	40	–	32×10^{-3}
[119]	rGO+Bi ₂ Te ₃	–	–	1000	0.014	1.72×10^{-3}
[148]	MXene	–	35.3×10^{-3}	–	–	33.5×10^{-6}

nanofibers. These different nanostructures are used in NG for switching circuits as shown in Fig. 12a–c. Hot pressing can be an effective method for creating regular-structured polypropylene (PP) nanowires. This polypropylene nanowire comes in two variants: 200 nm pore size PP and 400 nm pore size PP. Planar and nanowire-structured friction layer materials affects the TENG output. To improve the output performance, nylon nanofiber and polypropylene nanowire were combined to create a dual nanostructure TENG. The greatest I_{sc} , V_o and charge density of 63.3 mA, 1135 V and 161.5 cm^{-2} were attained by the 200 flat PP and nano nylon TENG respectively [142].

HNGs represent a transformative approach in energy harvesting, effectively integrating diverse materials to synergistically capture mechanical, thermal and solar energies (Table 2). Nanogenerator performance can be tuned for certain purposes by choosing and designing materials with specified features. HNGs are designed by integrating diverse materials to absorb energy from various sources more effectively [68, 69, 144]. Advancements in polymer materials, particularly hydrogels can significantly enhance

NG efficiency by increasing scalability and it can be easily tunable. These advanced polymers can be scalable for various applications. Their unique attributes not only promise improved performance but also hold substantial potential for widespread commercial applications in the near future [7, 63, 93].

Comparison of electrical parameters of various materials used in nanogenerators

Tables 3, 4, 5, 6 compares electrical parameters of various materials used for NG fabrication. Advanced nanomaterials through high surface area, mechanical flexibility and tunable composition improves the charge transfer, output voltage and current density of the device. Yet, optimizing energy conversion, scaling production and achieving seamless integration are challenging. Understanding how surface morphology, composition and nanostructure influencing different NG properties is essential. GO and Titanium carbide (Ti₃C₂Tx-MXene) with PET and Polyvinyl alcohol (PVA) provide moderate power density of 1.3 W/m^2

Table 4 Electrical parameters of various materials used in TENG

References	Material	Output current [μA]	Output voltage [V]	Stability [Cycles]	Short circuit current I_{sc} [μA]	Power density [W/m^2]	Open circuit voltage V_{oc} [V]	Output power [mW]	Current density [Acm^{-2}]
[149]	Polyimide	–	–	10,000	10.79	2.61	753	–	–
[66]	Aluminium	–	–	5,000,000	348	46.1	233	–	–
[142]	Nylon 11	–	1134	193 000	63.3	–	–	–	–
[1]	Zeolitic imidazolate	–	–	10,000	19	5	578	–	–
[150]	Cellulose	–	–	1200	3.78	1.894×10^{-7}	3.86	–	–
[151]		–	–	–	0.6	–	29	3×10^{-3}	–
[152]		–	–	30,000	967	300	350	2.1	–
[153]		8.2	122	–	–	–	–	440×10^{-3}	–
[154]	PTFE	–	–	3960 000	–	135×10^{-3}	–	–	–
[155]	Cu-PTFE	–	–	500 000	–	530×10^{-3}	1.6	–	–
[156]	PTFE	53.2	–	1,260,000	–	1.16	–	4.27	–
[157]	Acrylic	–	–	–	–	–	10,000	–	0.27×10^{-3}
[137]	Elastomers	–	–	10,000	20	3.8	848	–	–
[3]	Polyester fur+PTFE+Nylon	–	–	–	14	–	18,000	–	–
[140]	PTFE	–	–	5000	2	–	55	60×10^{-3}	–
[158]		25	1000	3000	–	–	–	–	–
[159]	PTFE	84.4	–	860 000	–	16.8×10^{-3}	–	–	–
[160]	PDMS	–	–	2500	4.5	0.162	33.6	–	0.74×10^{-3}
[161]	GO	–	–	–	–	1.3	87	–	1.4×10^{-6}
[162]		78	340	18,000	–	–	–	–	–
[163]	ZnO	–	–	–	–	–	~ 2	–	–
[2]		–	–	–	1.2	–	51	–	–
[131]	MXene	–	–	–	96	6.66	390	–	–
[29]		–	–	–	1.22	402.94×10^{-3}	54.37	–	–
[164]		15	670	–	–	0.28	–	–	–

Table 5 Electrical parameters of various materials used in PENGs

References	Material	Output voltage [V]	Short circuit current I_{sc} [μA]	Power density [$\mu\text{W}/\text{cm}^2$]	Open circuit voltage V_{oc} [V]	Output power [mW]	Current density [Acm^{-2}]	Stability (Cycles)
[165]	Samarium nitrate hexahydrate	–	320	–	–	–	290	21
[30]	ZnO	–	5.9×10^{-3}	–	–	10×10^{-3}	20×10^{-6}	–
[166]	ZnO & NiO	–	4.1	37.9	65	–	–	–
[167]	Ag	3	–	–	–	–	9×10^{-7}	–

and $6.66 \text{ W}/\text{m}^2$, respectively but, their current densities are relatively low. Silver-based PENG have moderate output of $0.9 \mu\text{A}$, 3 V showing their potential for small-scale energy applications.

Self-powered pyroelectric NGs driven by breathing offers solution for wearable devices. PVDF a flexible material light-weight makes it ideal for healthcare, fitness and diagnostics. But the performance may degrade due to sweat, moisture or extreme conditions, hence requiring protective coatings. The sensor tracks breathing patterns or other parameters like heart rate and oxygen saturation in healthcare applications. Sensitivity to rapidly changing or irregular breathing and integration with smart textiles or healthcare

IoT platforms can be explored [146]. The pyroelectric ZnO nanowire effectively have a heat flow conversion coefficient of $0.08 \text{ V m}^2/\text{W}$ which can be a promising material for self-powered pyroelectric NG, but more improved PyENG are required for the scalability and real-world uses [41].

Aluminum-doped zinc oxide (AZO) and cuprous iodide (CuI) are eco-friendly materials that can be used for energy harvesting systems and are architectural useful, such as in windows and as facades. The durability of these thin films under environmental stress, including UV radiation and mechanical wear need to be improved. The long-term stability of AZO and CuI thin films under prolonged UV exposure, humidity and weathering effects needs to be

Table 6 Various nanogenerators, their materials, applications and associated challenges based on the data obtained from Tables 3, 4, 5, 6

Nanogenerator	Materials/ Parameters	Applications	Challenges
TENG	Gas–solid	Energy harvesting from wind sand	Durability
TENG	Breathing driven	Medical devices like pacemaker	Low efficiency
TENG	Plant based	Wearable electronics	Material degradation and environmental sensitivity
TENG	GO	Stimuli enhanced environment monitors	Fragility
PENG	ZnO	Thermal energy and mechanical energy harvesting	Issues related to energy density
PENG	n-ZnO/p-NiO Interface	Mechanical energy harvesting	Sensitivity to UV exposure and humidity
PyENG	BNT	Mechanical energy harvesting	Sensitivity
PyENG	Samarium nitrate hexahydrate	Pressure sensor and self-powered electronic systems	Environmental sensitivity and durability
PENG	PVDF-HFP and Ag	Piezoelectric properties enhanced	Oxidation
PyENG	Sodium bisulfite and TiO ₂	Stable output for energy harvesting	Low power output and scale of power output
TENG	Zeolitic imidazolate	self-powered microelectronics	Durability
TEG	Semi-transparent TEG	For energy solution	Humidity effects and UV exposure
TEG	GO and Bi ₂ Te ₃	Flexible and wearable devices	Production issues

studied further [147]. Due to the high flexibility, robustness, and energy conversion efficiency of the produced BNT on PVDF PENG device, it is anticipated to be used for harvesting various mechanical movements present in daily life through large-scale technology. The PNG- powered a safety walker system based on self-illuminating bracelets was proposed, which can be used in everyday life to prevent road accidents and for many other applications [145].

The rGO along with bismuth telluride composite due to its lightweight and robust nature increase its applicability in structural and flexible electronics. The solution-based fabrication method reduces costs and enables large-area production supporting commercial viability. But the thermoelectric efficiency may decline under fluctuating thermal conditions limiting performance in high-temperature environments. Despite cost reduction, scaling up production of high-quality composites remains challenging [119].

ZnO nanosheet networks amplify triboelectric charge density, their mechanical stability makes them ideal for demanding environments contributing to sustainable energy solutions. Durability, scalability and output power for high-power applications should be enhanced [168]. The engineering of electrodes with 2D Titanium carbide mxene (Ti₃C₂T_x-MXene) sheets combined with chloride salts improves the electrical output of TENGs. MXenes offer mechanical flexibility and durability making them suitable for wearable energy systems. Their sensitivity to oxidation, complex fabrication process and potential environmental issues can limit efficiency [131]. Traditional air purification systems can be used in distant or resource-constrained areas because they need external power sources. As a solution to this problem a high-voltage self-powered direct current triboelectric TENG that can run an air purification module continuously is generated.

Development of these environmental NG captured and removed particulate matter proving a fully self-powered system capable of producing a steady, high-voltage output of 18 kV, where air filtration applications is feasible. The systems long-term durability under continuous operation, stability in performance under changing ambient conditions and humidity, and scalability for large-area purification management need to be studied [3]. TENG with optimized charge management, structural engineering and material selection that can deliver an ultra-high open-circuit voltage of roughly 10 kV is achieved. This shows that TENGs can be used for direct high-voltage applications without the need for extra power conditioning circuits and able to overcome intrinsic material and design limits. Operational safety at extremely high voltages, avoiding dielectric failure, controlling charge leakage and preserving steady performance under constant operation and changing environmental circumstances [157]. Nanofibers like Ag NPs and PVDF-HFP together improve the energy conversion efficiency. Both materials are cost-effective making this approach suitable for scalable and commercial applications.

Electrospinning provides precise control over fiber morphology enhancing device performance, but scaling can be an issue. But the Ag NP-doped nanofibers may degrade due to environmental factors like nanoparticle oxidation or changes in polymer matrix [167]. ZnO based PENG exhibit superior performance in smart electronics, biosensors and environmental energy harvesting systems. Achieving optimal interfacing between n-ZnO and p-NiO requires precise control of material properties and processing techniques. Polymer based NGs are highly flexible and can be integrated into portable systems. The effectiveness of energy conversion can be increased by doping, functionalization and also by exploring HNGs which, hence can be used for broader

Table 7 List of synthetic materials used in different nanogenerators

References	Material	NG	Application	Advantages	Disadvantages
[171]	PVDF	PENG, TENG, TEG	Cardiac pacemakers, biosensors	Biocompatible and flexible	Difficult processing
[172, 173]	PDMS	TENG, TEG	Wearable, sensors and patches	Biocompatible, stretchable and soft	Low triboelectric charge
[174]	Gelatin	TENG	Wound healing sensors	Biodegradable and non-toxic	Short lifespan
[175]	GO	TENG, TEG	Neural stimulation	Conductive, antibacterial	Processing complexity
[176]	MXenes	PENG, TENG	Smart bandages and ECG sensors	High conductivity and hydrophilic	Expensive
[177]	ZnO	PENG, TEG	Bone implant and energy harvesters	Strong piezoelectricity	Cytotoxic at high dose
[178]	Lead telluride	TENG	Thermoelectric power generators	High thermoelectric efficiency	Contains toxic lead and high processing cost
[76]	Iron	Hybrid	Magnetic components in magneto-electric NGs	Abundant and strong magnetic properties	Heavier, may corrode without proper protection
[179]	GaN	PEN	High-frequency and robust PENG	Excellent thermal stability and strong piezoelectric properties	Expensive, complex fabrication process
[180]	PZT	PEN, PyENG	High-performance PENG	Excellent thermal stability and strong piezoelectric properties	Expensive, complex fabrication process
[181, 182]	Kapton	TENG	Flexible substrates in NGs	Excellent thermal stability and flexibility	Expensive, process challenges
[183]	Nylon	TENG	Triboelectric layers in flexible NGs	High mechanical strength and flexibility	Performance degradation by moisture absorption

Table 8 List of biomaterials used in different nanogenerators

References	Material	NG	Application	Advantages	Disadvantages
[185]	Alginate	TENG	Flexible and biodegradable NGs	Biocompatible and easy gelation	Low mechanical strength and water sensitivity
[186]	Cellulose	TEG, PENG, PyENG	Flexible substrates and triboelectric layers	Abundant, biodegradable and renewable	Variability in properties and moderate electrical output
[56, 187]	Collagen	TENG, TEG, PENG	Implantable sensors and biomedical NGs	Excellent biocompatibility and natural origin	Mechanical weakness and prone to degradation
[188, 189]	Chitosan	PENG, PyENG	Biopolymer NGs, flexible and biomedical sensors	Biocompatible, biodegradable and low cost	Lower mechanical strength and modest piezoelectric output
[190]	Silk fibroin	PENG, TENG	Implantable electronics	Biodegradable and safe	Weak mechanical properties

real-world applications. The rGO and Bi₂Te₃ improves thermoelectric properties in NGs [57].

PENG based on a three-dimensional intercalation electrode (IENG) with numerous boundary interfaces within the piezoelectric material resulted in a rise in the total surface polarization charges, thereby contributing to an augmented current density. The IENG can produce a peak short-circuit current of 320 μA , with the corresponding current density of 290 $\mu\text{A cm}^{-2}$ being 1.93 and 1.61 times the record values for the PENG and TENG, respectively. Additionally, it can charge a 1 μF capacitor from 0 to 8 V in 21 cycles and the equivalent [165].

Samarium nitrate hexahydrate is used in a 3D intercalation electrode design that increases the effective contact area by penetrating the piezoelectric material and enhancing charge separation and transport efficiency. With its successful demonstration of a notable improvement in output power density and short-circuit current, this invention represents a substantial advancement towards implantable electronics devices. The research also highlight several difficulties,

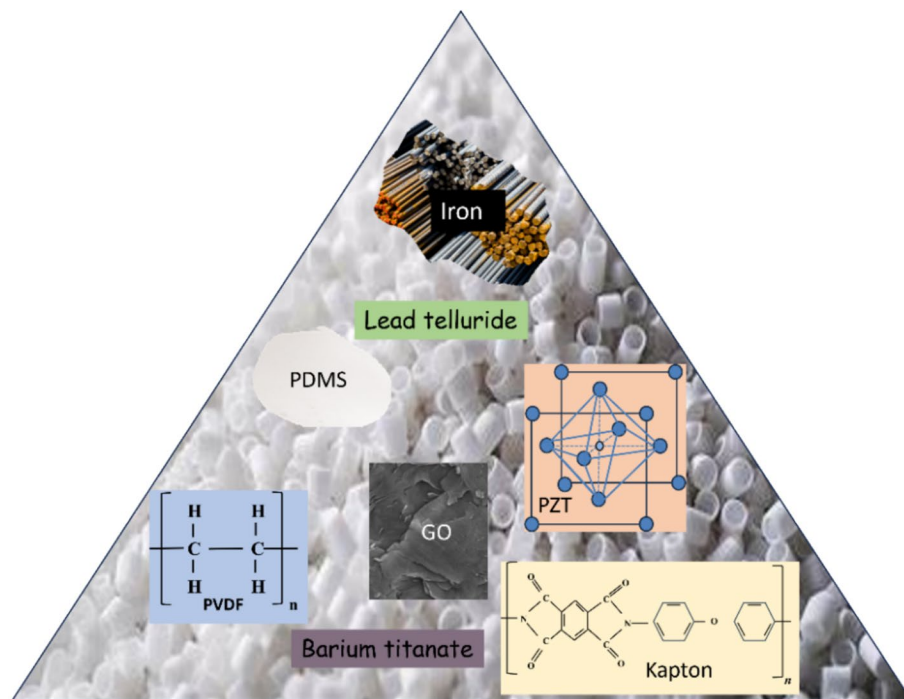
including the difficulty of creating stable 3D intercalated structures, preserving mechanical integrity in the face of recurrent deformation and guaranteeing long-term durability under continuous operation [165]. Table 7 lists various NGs, applications, challenges and different materials used in each NG. Due to the safe, biocompatible and sustainable, the biomaterial-based triboelectric nanogenerators (BM-TENGs) are very useful in individualized healthcare [134, 169, 170].

Tables 8 and 9 lists different synthetic and biomaterials used in different nanogenerators. The tables also mention the application, advantages and disadvantages of these materials. SiO₂ nanoparticles that are basically inorganic nanoparticles can be added into polymer composites to improves the energy conversion efficiency and its mechanical stability. These nanoparticles can be used in implant NGs and biosensors due to its biocompatibility. Its biocompatibility can be increased by surface modifications [184]

Cobalt Ferrite Nanoparticles poses excellent magnetic properties and can be used for targeted drug delivery and

Table 9 List of the proposed application of nanogenerators with specific field

References	Nanogenerator application	Area	Specific field
[82, 84, 191–193]	Biomedical applications	Smart textiles, implantable medical devices and wearable devices	Biosensors, heartbeat sensors, blood presser sensors and sensors for prosthetics
[9, 104, 194]	IoT	Smart homes, and agriculture	Monitoring pollution, weather and traffic
[16, 70, 195–197]	Smart electronics	Smart sensors, flexible and stretchable electronics	Smart watches, smart fabrics, smart cities and infrastructure monitoring
[48, 198]	Environmental applications	Space, sea and environment monitoring	Wind energy harvesting and soil monitoring

Fig. 13 Different synthetic materials used for nanogenerator fabrication

hyperthermia by surface functionalization to make sure it has a safe cytotoxicity level [199]. Carbon nanotubes are used in biomedical applications after functionalization and purification. Carbon nanotubes (CNTs) can efficiently conduct electricity and also withstand stress and deformation [55].

Figure 13 represents various synthetic materials used for NG fabrication. GO is used for flexible NGs, its oxygenated groups help in further functionalization in order to increase biocompatibility for implant technology. Molybdenum silicon nitride (MoSiN_4) is a promising material of superior mechanical, optical and electrical properties, high strength and mobility help in effective conversion of mechanical energy into electrical energy. Due to its distinct structure and adjustable characteristics, it can be used for flexible device construction. The properties and functions of 2D materials greatly increased by the design and synthesis of van der Waals layered materials and van der Waals layered materials. By passivating the surface of 2D non-layered molybdenum nitride with elemental silicon, a novel van der Waals layered material, MoSi_2N_4 , was created. These

materials are promising for electrical and optoelectronic devices [200, 201].

Various materials like amino acids, peptides, chitosan, alginate, gelatin, silk and cellulose are investigated for NG fabrication because of their biocompatible properties. But the durability and electrical parameters are constrained. Cellulose is a promising material for NGs. Nanocellulose is a biodegradable and abundant material which can be used for bio based nanogenerators. It can serve as the friction layer for nanogenerators. Surface characterization, including contact angle and surface potential measurements, further optimizes triboelectric performance [202]. Lignin nanomaterials offer a sustainable alternative to fossil-based chemicals, leveraging their structural diversity and biodegradability for high-value applications. The lignin is a strong tribonegative material, which can be used in TENG [203]. Starch, a widely available natural polymer, holds great potential for eco-friendly functional electronics due to its low cost, processability and biodegradability. Silicone foam-based designs based on corn starch gives better electrical output for TENGs [204, 205].

Figure 14 shows different biocompatible and biodegradable materials used for self-powered NG fabrication. The schematic diagram shows a conceptual framework for using various biological and renewable resources as structural elements or active layers for NGs. These include the collagen-rich prawn and fish skins, which offer intrinsic flexibility and piezoelectric qualities, the egg membrane and crab shell, which offer hierarchical structures perfect for mechanical energy conversion; and the soft, breathable substrates of wool and cotton, which are used in wearable applications. Furthermore, natural rubber offers endurance and elasticity, while the leaves of sugarcane plants provide lignocellulosic frameworks with exceptional mechanical strength. In line with the concept of green energy generation, this strategy paves the path for a sustainable energy future by producing energy devices in biomedical and environmental settings and biodegradable.

Modeling and simulation of nanogenerators

The development of NGs is a multidisciplinary process requiring systematic steps, including theoretical analysis, material selection, equivalent electrical circuit design, simulation, structural design and fabrication [206]. Each step is important for ensuring optimal device performance and efficiency. To boost the understanding of energy conversion mechanisms theoretical models are developed using various

simulation tools such as COMSOL, ANSYS, MATLAB and CAD [207–215]. Analyzing and simulating materials used in NGs, combined with precise geometric modeling, forms the foundation for the NG design and optimization. This approach is applicable to a wide spectrum of NGs like triboelectric, thermoelectric, piezoelectric, pyroelectric, and electromagnetic NGs, offering benefits and challenges [216–218].

By optimizing characteristics including material composition, layer thickness, surface morphology and device architecture prior to production, this method enables researchers to methodically investigate a large design space. In addition to speeding up development and lowering experimental expenses, this predictive method makes it possible to spot performance snags and uncover creative design approaches that are challenging to accomplish with just tests. Additionally, modeling and simulation help to close the gap between basic science and real-world applications by directing innovations in self-powered, scalable, highly effective and environmentally friendly devices. They serve as knowledge-driven innovation helping the progress from theoretical prototypes to dependable, practical technologies. Simulation tools are indispensable in understanding and optimizing NG behavior. COMSOL Multiphysics is extensively used for providing detailed insights into the electric field and charge transfer processes [97]. MATLAB is another widely used tool for NGs. These models enable researchers to predict device performance and identify areas

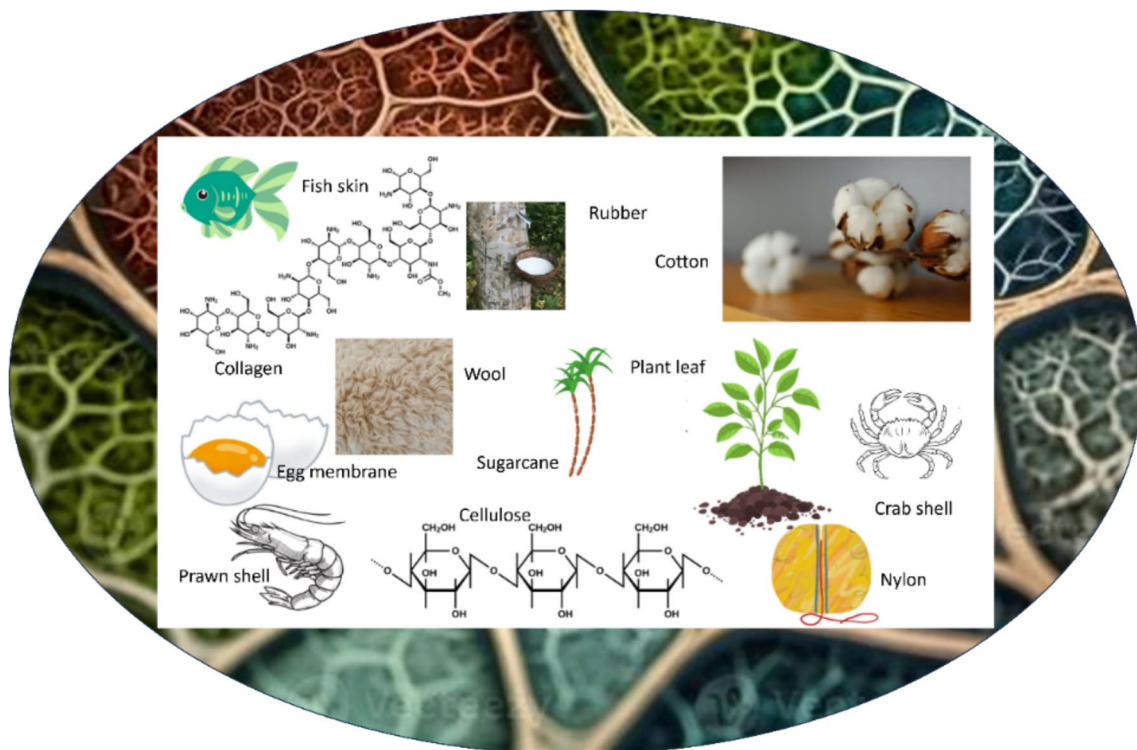


Fig. 14 Biomaterials for biocompatible nanogenerator fabrication

for improvement under varying operational conditions [32, 219]. Recently, a novel CAD tool was developed to give a better theoretical framework for NGs [210]. This innovative tool offers rapid optimization by considering motion parameters such as angle and distance. Unlike traditional COMSOL simulations, which can be computationally intensive the CAD tool provides results within seconds significantly accelerating the design process [104]. The boundary conditions imposed in various application scenarios, which are all urgent issues that need to be resolved, in order to get the simulation results closer to the actual situation [52].

Triboelectric nanogenerator

Figure 15 explains the effects of droplets on a Solid–Liquid TENG (S–L TENG) during the harvesting of energy. The process of droplets and charge transfer can be summed up as follows: step (1) based on the electric-double-layer hypothesis the triboelectric layer induces charges on its surface when it comes into contact with droplets. Step (2) the droplets rebound since it is hydrophobic in nature and a current is created during the rebound process. Step (3) the droplets bounce back and spreads to maximize their contact area. As fresh drops fall, steps (2) and (3) are repeated. Additionally, investigates the connection between triboelectric signals, droplet volume, and droplet dropping velocity [52, 220]. The S–L TENG's overall electricity conversion efficiency is limited by the viscous mechanisms that cause

energy dissipation. Researchers have used molecular dynamics simulations to analysis the viscous surface at the microscopic level in order to better understand its behavior. These investigations show how the changes in ion type and concentration affects the processes of charge transfer in dielectric materials and also how electrostatic field changes throughout the course of the operational cycle.

The interactions between liquids and dielectric surfaces during friction have been investigated. The results suggest that charge transfer is dominated by ionic species and the initial charge density on the dielectric layer is mainly determined by the interaction of electronegativity and static electric forces. Furthermore, it has been also observed that the production of free radicals during droplet–electrolyte interactions influence charge dynamics [221]. The behavior of these radicals depends on different physicochemical factors. The polarization of the electrons in processes Fig.15 (a) to (b) will finally result in a specific rise in potential, sustaining the maximum output [52].

In order to create a theoretical model of the S–L TENG potential distribution mechanism using COMSOL software. on the friction power production layer's surface, it's possible to determine the adsorption status of various ion types with functional groups using molecular dynamic simulation. But using such models in COMSOL Multiphysics is still difficult to provide genuine bidirectional coupling between electrostatic and fluid flow fields. In addition, for theoretical formulations equations like Maxwell stress-based surface

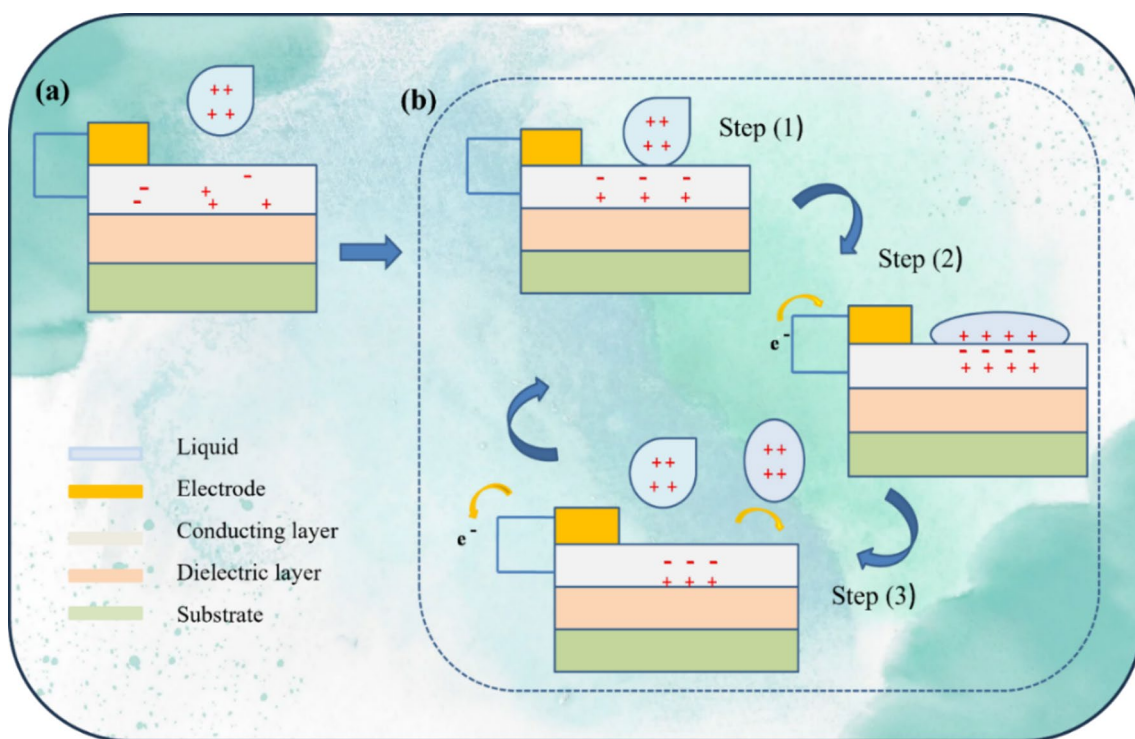


Fig. 15 Charge distribution process of a droplet TENG theoretically modeled [52]

tion, must be incorporated into the governing flow equations.

Piezoelectric nanogenerator

M 13, a virus with piezoelectric properties is very promising for biocompatible NGs. As a biofuel harvester, it has gained significant interest from the scientific community. To mimic the vertical assembly of a monolayer of M13 COMSOL has been used. The results of the simulations indicate a 2.3 V voltage and 134 nA current as shown in Fig. 16. These findings will help improving device fabrication. To provide the required energy to the intended load, additionally adjust the input acoustic stimulation frequency and amplitude [79].

Using the first law of thermodynamics it is possible to formulate the piezoelectricity phenomena. The formula predicts that the additional thermal energy and external work applied to a closed system will change systems internal energy. The equation is given by

$$dW + dQ = dW_{electrical} + dW_{mechanical} + dQ \quad (4)$$

$$dU = E_{md}D_m + T_{ij}dS_{ij} + \theta d\sigma \quad (5)$$

where dW denotes the external work done on the system and dQ represent the changes in the systems thermal energy.

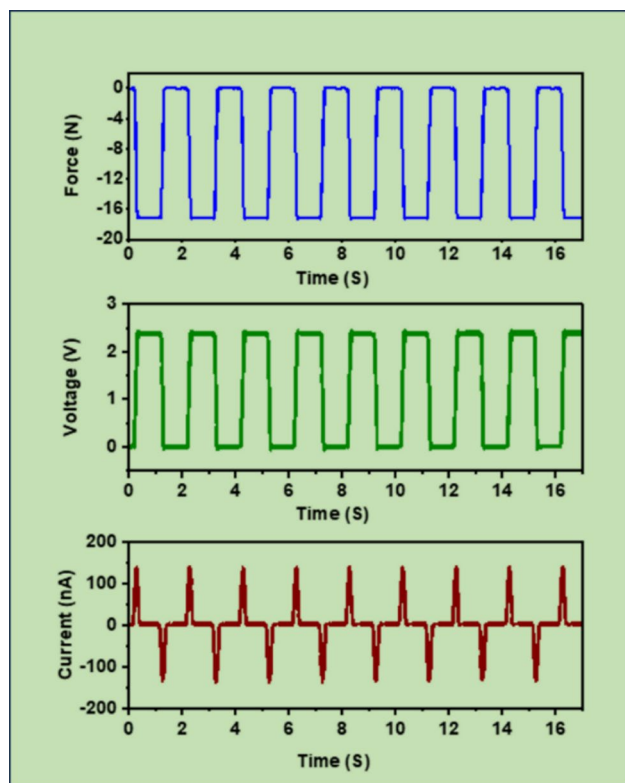


Fig. 16 Vertical loading COMSOL simulation results for the 6H-M13 phase, that is vertically aligned [222]

dU says about the changes in the internal energy. T_{ij} and S_{ij} represents the mechanical strain and stress. The electrical field intensity and electrical flux density are represented by E_m and D_m , the temperature and entropy per unit volume are denoted by θ and σ , respectively. The internal energy changes can be expressed by the equation, the Gibbs free energy, which is defined by

$$G = U - E_m D_m - T_{ij} S_{ij} - \theta \sigma \quad (6)$$

Can be used to study the system where the intensive state variables E_m , T_{ij} , and θ are specified in (3).

In a closed system, the Gibbs energy is minimized when the system is at thermodynamic equilibrium. Consequently, the derivative of G should be zero which means that

$$dG = D_{md}E_m - S_{ij}dT_{ij} - \sigma d\theta = 0 \quad (7)$$

By fixing a chosen set of intense variables as follows, we may calculate the values of D_m , S_{ij} , and σ from (7). The extensive state variables are connected to the intensive state variables. Assuming isothermal circumstances, $d\theta=0$, we can use Taylor series expansion to ignore all derivative terms of orders greater than one by assuming that there are slight changes for other state variables. The changes in the extensive state variables can be as follows. Dielectric Material Law is represented by the first term on the right and the direct piezoelectric effect is represented by the second term. In Eq. (6), the Inverse Piezoelectric Effect is represented by the first term on the right and the Hooke's law is represented by the second term. The linearized constitutive equations for piezoelectric material under isothermal conditions can be obtained by assuming zero values for the state variables initial conditions [222].

Pyroelectric nanogenerator

Ferroelectric materials like PVDF, PZT and BTO has spontaneous polarization and shows both pyroelectric and piezoelectric properties. PVDF' polymer have a strong mechanical flexibility and biocompatibility and hence is suitable for wearable technology despite of its low pyroelectric coefficient. PyNG based on PVDF was developed wher cold and hot water are used as a thermal energy source, A thin polyvinyl chloride (PVC) layer of 30 μm thickness was coated on the surface of device in order to stop oxidation and water conductivity. The PyNG's output performance has improved from 6 to 11 μA as the hot flow increases. The internal polarization of PyENG has also enhanced by mechanically deformation. The output performance of this mechanically deformed PyNG has an output of 100 V and 190 V. The temperature of the hot water rises from 40 to 80 $^\circ\text{C}$. A finite

element method by using COMSOL multiphysics software was used for PyENG simulation. Due to partial contact with the flows their arise a heat loss from the PVC thin film. The simulated electrical potential distribution of cross-sectional PVDF film for PENG gives a maximum output of 774 V, which is much greater than the experiment results [223].

Thermoelectric nanogenerator

The potential application of the metal-assisted nanoporous silicon chemical etching fabricated is a new material for TEGs. It was observed that the seebeck coefficient and FOM would increase and thermal conductivity would decrease in nanoporous materials. A spin-on dopant approach which increase the internal was employed to further increase the devices performance. when compared to bulk silicon a maximum power density of $1.12 \mu\text{W}/\text{cm}^2$, the synthesised nanoporous silicon-based TEGs showed a FOM values that are 4.2 times greater for n-type and also 12 times larger for p-type The experimental findings are compared with COMSOL simulation for validation. In both experiment and simulation, a clear temperature gradient was observed from the hot top electrode to the cold substrate, which confirms the effective heat flow which is the important for of TEGs. Nanoporous silicon when compared to bulk exhibits better consistent and controlled temperature distribution throughout the active region.

Applications of NGs extend beyond material development and include their integration into electronic circuits, such as driving and power management systems. Computational models provide a robust framework for predicting NG behavior under different scenarios, enabling researchers to explore design variations without the need for time-consuming experimental trials [108].

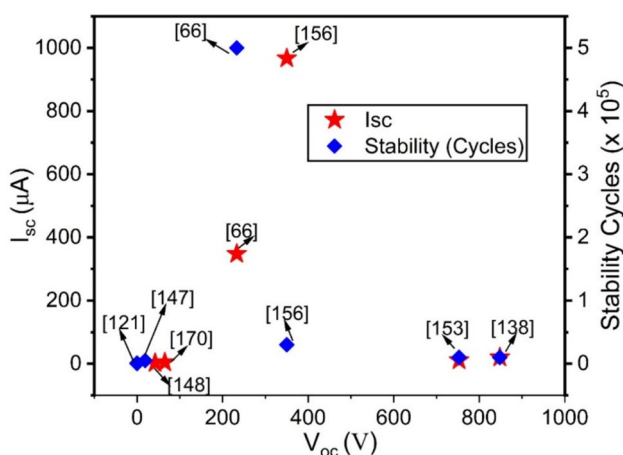


Fig. 17 The comparative analysis of different nanogenerators based on open circuit voltage, short circuit current and stabile. The comparative analysis of different nanogenerators based on power density and efficiency

From the benchmark analysis of NGs it is observed that it is an innovative technology for powering independently operating electronic systems and collecting ambient energy for the surroundings. TENGs typically show higher output voltage and have greater material choice while PENGs show better sensitivity to mechanical stimuli. Although TEGs have constant output it heavily depends on temperature gradients and material figure-of-merit. Recently to improve energy conversion efficiency and power density, HNGs that incorporate several energy conversion mechanisms have been developed. When compared to single-mechanism devices, these hybrid architectures greatly enhance electrical output performance by collecting different ambient energy. Despite these developments the NGs has a drawback of low power density, sensitivity to the environment, material deterioration and scaling issues. The frequent mechanical operation can result in wear and long-term performance degradation. Environmental factors such as humidity, temperature fluctuations and surface contamination can lower charge density and device stability. In order to increase efficiency, durability and practical applicability of NG the current research focuses on improved materials, nanostructured surfaces, hybrid energy harvesting systems and also scalable production techniques.

To precisely benchmark nanogenerator performance and also to determine the appropriate energy harvesting methodologies for particular applications, a multi-parameter should be considered. It is important to evaluate nanogenerators beyond open circuit voltage and short circuit current in order to compare them effectively. The practical performance of this energy harvesting devices is also determined by factors like power density, energy conversion efficiency, impedance matching and also operating circumstances. It is observed that under mechanical stress, PENG devices usually show modest voltage and output current, but TENG can produce high voltage but frequent internal impedance. But TEG generate continuous power under a temperature gradient.

The PyENG produce electricity by means of cyclic variation in temperature. For wearable applications, the PENG has a moderate power density and good stability under mechanical stress. TENG on the other hand, has a very high internal impedance that prevents effective energy transfer even though it can produce high voltage and power density. The efficiency of TENG and PENG is reported as approximately 50 & 30% respectively [181, 182, 224, 225]. From Fig. 17 PENG, PyENG, and TEG devices show relatively lower voltage but nevertheless contribute to a variety of energy harvesting capabilities, TENG devices are display higher voltage output and have greater stability cycle [226, 227].

Power management circuit and energy storage integration for nanogenerators

Even though the NGs can efficiently convert the mechanical, thermal and environmental energy into electrical signals, their direct output is usually low. Power management circuits are therefore essential to transform and control the produced energy into a stable signal and can be used for electronic devices application. A rectifier circuit is connected to NG output for the circuit to transform alternating current into direct current. Voltage control and impedance matching circuits are used to optimize energy transfer and enhance overall energy harvesting efficiency. The produced energy is stored in energy storage devices like capacitors, supercapacitors and also in rechargeable batteries. Integrating nanogenerators with supercapacitors and lithium-ion batteries can power sensors, wearable electronics and IoT devices in a self-powered system. Figure 18 shows a flow chart representing different steps involved in the integration of NG.

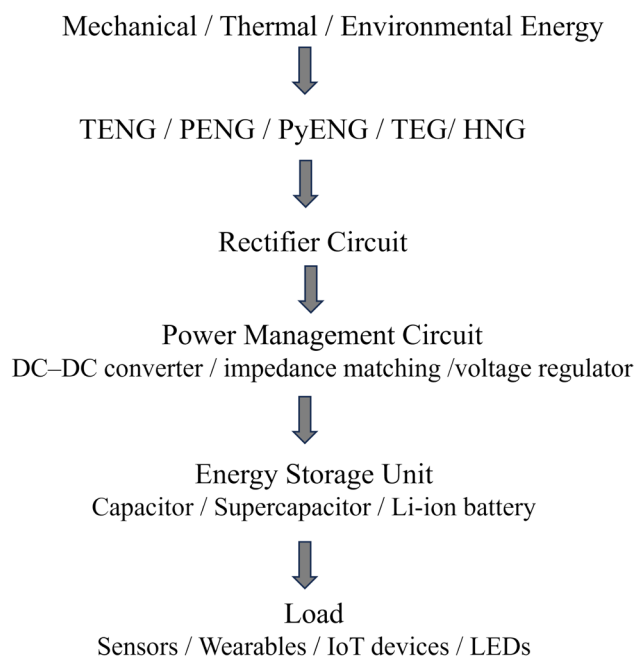


Fig. 18 Flow chart representing the steps in the integration of NG

Applications of the different nanogenerators

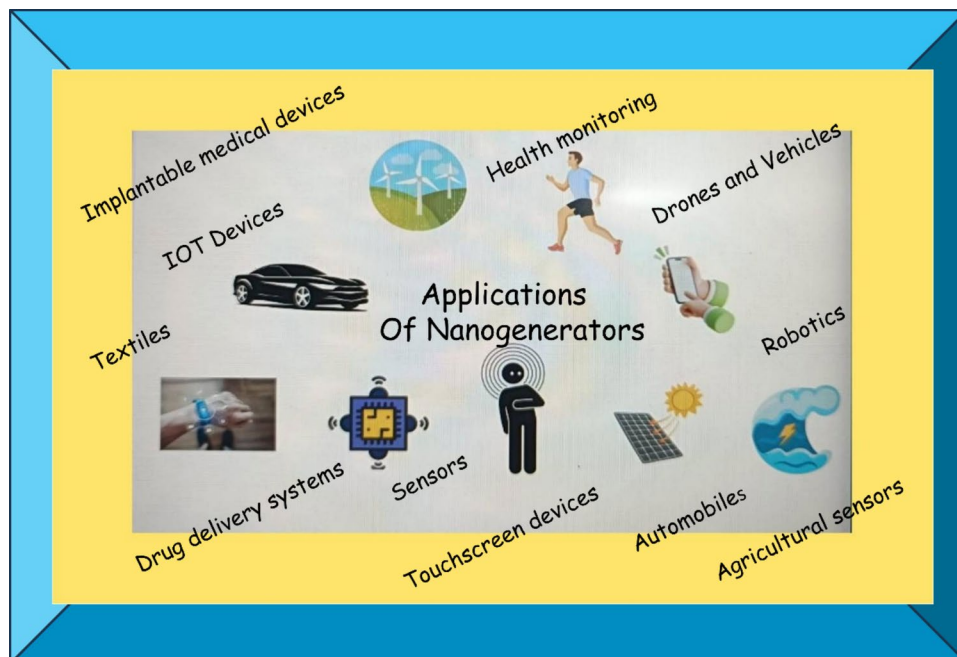
The metaverse is a new paradigm used for virtual interactions. These helps in the creation of revolutionary functional materials and devices for extended reality (XR) applications. XR gadgets when combined with soft robotic systems and wearable electronics. Virtual reality (VR) systems can incorporate NGs to produce immersive, self-powered experiences. They can be utilized in VR headsets, gloves and

outfit [228, 229]. Figure 19 lists various applications of NGs in various fields.

Pyroelectric nanogenerators

The compact design flexibility and ability to work at the nanoscale make PyENG an exciting area of research for sustainable energy solutions. By leveraging the pyroelectric effect, PyENGs offer a sustainable approach of harvesting thermal energy from dynamic temperature variations

Fig. 19 Various applications of nanogenerators



[83]. PyENGs offer practical and highly efficient solutions for harvesting and converting thermal energy for different applications [230]. The simplicity of their structure combined with their adaptability and potential make PyENGs useful for integration with nanoscale devices [231].

Thermoelectric nanogenerators

TEGs versatility makes them ideal for numerous applications including waste heat recovery, remote sensing and monitoring, wearable electronics and environmental monitoring [232]. In wastewater recovery systems, the capturing and converting heat from waste into electricity results in a significant enhancement of energy efficiency. TEGs also play an important role in remote sensing, where conventional energy supply is impractical. Powering sensors for real-time measurement of environmental data such as temperature, pollution and climate change parameters will help in environmental monitoring. Harnessing body heat to generate electricity for wearable devices enables self-powered health monitoring and personal electronics. Wearable thermoelectric generators (WTEGs) converts body temperature into electrical power [233]. Sensors, light-emitting diodes (LEDs) and biomechanical motion monitoring could all benefit from the use of TEGs as flexible power sources [25]. TEG can also be used to make wireless earphones [84]. By converting light and radioactive heat into electrical power the TEGs enhances the performance of electric vehicle batteries, glass industries and steel manufacturing industries [216].

Piezoelectric nanogenerators

PENGs have revolutionized biomedical engineering by enabling wearable sensors for biomonitors, where NGs serve as a continuous energy source reducing dependence on conventional batteries. Smart textiles integrated with PENGs are used for real-time motion tracking and electronic skin (E-skin) applications. PENGs with the IoT ecosystem enables self-powered switches, motion detectors and wearable electronics like self-charging smartwatches and fitness trackers. By leveraging ambient mechanical energy PENGs provide a sustainable power source for environmental monitoring systems [217].

PENGs in air and water quality sensors ensure continuous environmental assessment. These NGs also enhance vehicle intelligence by powering tire pressure monitoring systems, motion sensors and GPS tracking. The next generation of robotics also benefits from PENGs through self-powered robotic skins [234]. The piezoelectric materials are used in actuator, vibrator, resonator and transducer applications which necessitate the provision of a characteristics database

and scaling laws, hence enables the actuator or transducer designer to ascertain the response under operating settings [235]. There are drones which uses electric energy and are improved by the piezoelectric NG [236].

Triboelectric nanogenerators

TENG convert mechanical energy from different environmental forces, human motion, wind vibrations and water waves into electricity. By integrating advanced materials and nanoscale design, TENGs hold immense potential for addressing global energy challenges [22, 237, 238]. At present TENGs with free rotating discs are also used as energy converters in mechanical sensors [138]. TENGs offer immense potential to address energy challenges, positioning themselves as a pursuit of sustainable and decentralized power solutions for modern applications like power sources for sensors, wearable devices for health monitoring, energy harvesting from vibrations in vehicles or machinery and in environmental monitoring systems [111, 112].

Solid–liquid TENGs have diverse applications like harvesting energy from water energy to biomedical sensing [52]. There are also TENGs based on natural textiles which are good energy harvesters [198]. TENGs are used as pressure sensors in biomedical monitoring and also in automotive applications [239]. TENG are promising devices that are used in manipulators like soft robotics and industrial automation [26, 139]. A gas–solid flow-driven TENG demonstrates robust performance in harsh environments coupled with self-powered sensors for real-time environmental monitoring making it suitable for remote applications [140].

Wood-based TENG have been used to create a table tennis table which consists of monitoring features which helps in collecting sports data [141]. TENG as flexible sensors can be made with elastomers and these elastomers have ultra-high mechanical properties. Carbon nanotubes are mixed with an elastomeric substrate to produce flexible and elastic electrodes. These flexible electrodes can be used as a capacitive sensor with rapid response times that are capable of detecting human movement [137].

Wearable light-emitting devices made possible by newly developed light-emitting materials that can be used in displays, lighting, imaging, stimulation and therapy. A supplementary and affordable method of environmental sensing is offered by electronic skin, which has the ability to transform mechanical inputs into multimodal signals. Light-emitting composite films can be created for visual TENGs that are capable of producing electric and real-time photoemission signals from mechanical stimuli [240, 241].

Hybrid nanogenerators and the emerging nanogenerators

Omnidirectional energy harvesting can be challenging to accomplish because of vibration low frequency and random directions. An omnidirectional hybrid triboelectric–electromagnetic nanogenerator (OD-HNG) operates for harvesting the energy of omnidirectional vibrations and it is based on a tower spring. Electromagnetic nanogenerator (ENG) is hybridized with an electromagnetic generator to further boost the output of OD-HNGs. In order to achieve the goal to optimize space, TENGs are arranged in a multilayered structure. A 1000 μF capacitor can be charged to 1.75 V in 20 s when OD-HNG is put on a bicycle at a standard riding speed [242].

TVNGs are anticipated to address the issue of power supply due to their high current density, low matched impedance and continuous output. Wear in the friction interface significantly shorten TVNG lifespan and performance. A MXene solution is used as a lubricant increase to TVNGs output current density of 754 mA m^{-2} and a lifetime of 90,000 cycles is attained [243]. Table 9 summarizes the application areas where NGs can be useful. Ferroelectric nanogenerators are used in loudspeaker applications, wireless sensor network, touchscreen and acoustic applications [244]. The pyrophototronic effect, which has been widely applied in photodetectors is produced by combining pyroelectricity, semiconductors and optical stimulation [245].

The development of HNGs helps in collecting ambient energy from various sources and greatly enhances overall output performance. The current trend also includes the investigation of enhanced functional nanomaterials such as graphene, metal oxides, carbon nanotubes, MXenes and other 2-D have a great role in improving mechanical flexibility, electrical conductivity and charge transfer efficiency. The development of wearable and flexible NGs has increased the range of potential applications, in portable electronics and healthcare monitoring, where energy is directly extracted from human motion. The development of nanogenerators incorporation with IoT technology, makes the autonomous sensing networks possible. Additionally, new methods for collecting energy from humidity gradients and ionic diffusion processes have been developed using moisture-driven and osmotic nanogenerators.

Regarding long-term durability concern, the use of nanocomposites and self-healing materials is paying attention. Biocompatible and implantable nanogenerators are being investigated for their use in biomedical applications such as medical devices and implantable sensors. Large-scale energy harvesting ideas like blue energy systems using water flow and ocean waves, are showing promise for sustainable energy producing. While thermoelectric nanogenerator

research focuses on increasing the Seebeck coefficient and figure-of-merit for an improved efficiency. PVDF-based systems with conductive fillers helps to improve piezoelectric properties of NG. Future nanogenerators are designed in such a way that the systems can collect energy from several sources at once and combine with energy storage systems like batteries and supercapacitors to create self-charging power units. Fabrication techniques like electrospinning, solution-casting methods and roll-to-roll processing will help in nanogenerator commercialization. The practical application of nanogenerator technologies will depend on the development of standardized benchmarking techniques and also performance indicators, in addition to advancements in cost-effectiveness environmental stability and durability.

The repeated mechanical deformation can result in structural fatigue and decreased performance, long-term durability and mechanical stability of nanogenerators continue to be key problems. In addition, during continuous operation, device dependability be impacted by the inherent fragility of polymer matrices and nanostructured materials. Over time, performance decline may also be accelerated by environmental changes, moisture absorption and material deterioration. It is still difficult to achieve uniform nanostructures and stable device topologies on a wide scale, making scaled fabrication and production consistency problematic.

Humidity and environmental conditions are mainly two important factors that can change the surface charge density of triboelectric materials and lower the output performance of TENGs. High humidity can lower triboelectric charge retention and result in charge leakage and it lowers the voltage and power density. The contact and separation can cause friction between triboelectric surfaces which can lead to tribo-layer wear, which can damage the surface shape and lower the efficiency of charge generation. Mechanical fatigue in flexible electronics is a factor which is of a reliability concern. Over time, performance may degrade due to the cracks in the active materials and also in electrodes occurred by constant bending, stretching and compression. Inadequate adhesion and repeated mechanical stress can cause interfacial delamination between various layers which reduces electrical conductivity and device stability. To reduce this the nanogenerators can be fabricated using flexible electrode, wear-resistant triboelectric materials and device should be encapsulated in order to protect from humidity and for surface engineering. These methods will help for the practical application of nanogenerators in wearable electronics, sensors and self-powered systems by increasing device lifetime.

Furthermore, they frequently have low power density and total energy conversion efficiency, which limits their capacity to provide enough power for useful electronic devices.

Since many active materials degrade when exposed to dampness, oxygen, and ultraviolet radiation, environmental sensitivity is another important concern. This can lead to oxidation, decreased charge transfer efficiency, and loss of electrical output. In some NGs like TENG the electrostatic charge accumulation and high internal impedance can produce high open-circuit voltages in the range of 10–18 kV. The output current is usually relatively low even though it produces extremely high voltage, which can lower the risk of dangerous electric shock. But incorporating such devices into real-world application still requires careful optimization and fabrication should be done carefully for the safety purpose. Dielectric breakdown and electrical discharge can occur when the electric field is stronger than the air and surrounding materials dielectric strength. Inadequate insulation can also result in electrostatic discharge and it could harm delicate electronic parts attached to the nanogenerator. For a safety operation, suitable insulation layers, encapsulation materials and voltage regulation circuits are needed. The integration of nanogenerators in wearable electronics, biomedical devices and self-powered systems always depends on these safety measures.

Conclusions

Nanogenerators is a transformative technology with great innovations in wearable, flexible, implantable and sensing applications. By bridging the gap between fundamental science and practical applications, NGs contributes to sustainable energy solution. Nanomaterials and high entropy materials strengthen the performance as well as the functionality of NG. Hybrid designs can definitely increase material compatibility for efficient, energy transfer and long-term stability. The integration of advanced fabrication methods and simulation tools will help to overcome current limitations. This review has provided an in-depth analysis of various NGs like TENG, PENG, TEG and PyENG and their advancements in innovative materials and operating principles. Each NG offers distinct advantages and limitations that make it suitable for specific applications. The selection of a NG typically depends on its intended application. NGs with different open-circuit voltages of 18 kV, 10 kV, 753 V and 578 V, as well as short-circuit currents of 348, 320 and 63.3 μA have been reported in various studies. Moreover, these devices can also have high operational lifetimes of 3,960,000, 1,260,000, 860,000 and 90,000 cycles. It is observed that triboelectric NGs deliver the maximum electrical output. All these NG devices need advanced nanomaterials for optimization in mechanical stability and functionality across various applications. TENGs can operate in harsh environments and hence are ideal for remote

and self-powered monitoring systems. PyENGs and TEG devices dependent on temperature fluctuations and requires optimized thermal-to-electric conversion and material properties in order to broaden their application in sustainable and multifunctional systems. Even though the nanogenerator technologies have advanced in different field, a number of significant obstacles are there in implementation. To advance nanogenerators towards useful and sustainable energy harvesting systems, future research should focus on increasing power output and energy densities, strengthening material robustness, an implementing efficient encapsulation to devices and establishing large-scale fabrication processes. Even though these techniques greatly increase charge production and energy conversion efficiency, improving power density through optimal device designs and by improving nano-structured surfaces continues to be a major research focus. It is certain that further research and development in this area will result in more adaptable, effective and versatile NGs which will eventually spur their acceptance in a variety of real-world applications.

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Author contribution Arguine Tes Raj conceived the study, conducted data extraction, quantitative analysis and wrote the original draft, reviewed and edited manuscript. Binola K Jebalin I.V carried out conceptual refinement and reviewed and edited manuscript. Ancy Michel and A. Angelin Delighta contributed to data interpretation and reviewed and edited the manuscript. Maria E Messing conceived data interpretation and reviewed and edited the manuscript. D. Nirmal provided conceptual guidance and supervised the review process.

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Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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