International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(21s) 2026 pp. 1022-1033
https://doi.org/10.70917/ijcisim-2026-5375
Article

AI-Assisted Design and Multiphysics Optimization of Graphene-Enhanced Triboelectric Nanogenerators for Biomedical Energy Harvesting

Amaresh Kumar Sahu[1], Dr. Manoj Kumar[2], Susanta Kumar Patro[3], Pruthwijeet Patnayak[4]

[1,3]Department of Electronics & Communication Engineering, (Kalinga University, Naya Raipur) Kalinga University, (Naya Raipur, Chhattisgarh), Naya Raipur, INDIA, amresh.sahu1984@gmail.com, susantapatro2020@gmail.com
[2,4]Department. of Electrical Engineering, (Kalinga University, Naya Raipur), Kalinga University, (Naya Raipur, Chhattisgarh), Naya Raipur, INDIA, manoj.nigam@kalingauniversity.ac.in, pruthwijeet313@gmail.com

Abstract: Triboelectric nanogenerators (TENGs) have emerged as promising self-powered energy sources for biomedical applications, particularly for wearable and implantable devices requiring flexible, lightweight, and sustainable power generation. This study presents the design and multiphysics simulation of a flexible graphene-enhanced TENG based on polydimethylsiloxane (PDMS) integrated with layered graphene to improve charge transfer, electrical conductivity, and mechanical durability. The influence of material properties, dielectric behavior, electrostatic potential distribution, and mechanical deformation on TENG performance is systematically investigated using ANSYS-based multiphysics simulations. Fundamental triboelectric mechanisms, including contact electrification, electrostatic induction, charge transfer, and contact–separation dynamics, are incorporated into the analysis to evaluate the electrical response of the proposed device. The optimized graphene-enhanced PDMS TENG achieves a peak output voltage of 180 V, a short-circuit current of 6 μA, and a maximum power output of 0.73 mW at a load resistance of 10^7 Ω. The simulation results demonstrate that graphene incorporation enhances charge retention and electrical output while maintaining the flexibility and mechanical robustness of the PDMS-based structure. Furthermore, structural and material optimization significantly influences the electrostatic response and energy-conversion characteristics of the TENG. The proposed graphene-enhanced TENG demonstrates considerable potential for self-powered biomedical systems, including wearable physiological monitoring, rehabilitation devices, low-power healthcare sensors, and smart medical implants, thereby contributing to the development of sustainable energy solutions with reduced dependence on conventional batteries.
Keywords: Triboelectric nanogenerator, graphene, PDMS, biomedical energy harvesting, self-powered devices, multiphysics simulation, ANSYS, wearable healthcare, energy conversion

1. INTRODUCTION

The rapid development of sustainable energy-harvesting technologies has created new opportunities for powering next-generation electronic and biomedical systems. Among these technologies, triboelectric nanogenerators (TENGs) have emerged as promising devices for converting low-frequency mechanical energy into electrical energy through the combined effects of contact electrification and electrostatic induction. Since their introduction by Wang et al. in 2012, TENGs have attracted considerable research interest because they can harvest mechanical energy from diverse sources, including human motion, vibration, ambient movement, and biomechanical activities [1]. Unlike conventional energy-harvesting technologies that often require relatively high-frequency mechanical excitation, TENGs can effectively operate under irregular and low-frequency mechanical inputs, making them particularly attractive for wearable and biomedical applications.

The unique characteristics of TENGs, including lightweight structures, mechanical flexibility, low fabrication complexity, and the ability to operate under small mechanical excitations, have enabled their development for self-powered biomedical systems. In particular, wearable and implantable medical devices increasingly require sustainable power sources capable of operating with minimal dependence on conventional batteries. Human biomechanical activities such as walking, respiration, heartbeat, joint movement, and muscle deformation provide abundant mechanical energy that can potentially be converted into electrical power using TENGs [2]. Consequently, TENG-based systems have been investigated for self-powered physiological monitoring, biomedical sensing, therapeutic stimulation, and low-power electronic devices. Implantable TENGs have also demonstrated potential for harvesting mechanical energy associated with organ and tissue motion, providing an alternative energy source for low-power biomedical implants [3]. In rehabilitation applications, TENGs can further exploit human movement to support self-powered sensing and assistive technologies, including prosthetic and wearable rehabilitation systems [4].

Despite these advantages, the practical performance of TENGs is strongly dependent on the selection and engineering of triboelectric materials. Conventional polymeric materials such as polydimethylsiloxane (PDMS), fluorinated ethylene propylene (FEP), polyimide, and polyethylene terephthalate have been extensively employed because of their favorable triboelectric characteristics, flexibility, and ease of processing. However, limitations associated with charge retention, electrical conductivity, mechanical degradation, and long-term operational stability can restrict the performance of conventional polymer-based TENGs. Therefore, considerable attention has recently been directed toward the incorporation of advanced nanomaterials, including graphene, carbon nanotubes, metal nanoparticles, and metal-organic frameworks, to tailor the electrical, mechanical, and surface properties of TENG structures [5].

Among these nanomaterials, graphene is particularly attractive because of its exceptional electrical conductivity, high mechanical strength, large specific surface area, and excellent flexibility. Incorporating graphene into polymeric triboelectric layers can modify interfacial charge transport, enhance charge accumulation and retention, and improve the mechanical stability of flexible TENG structures [6]. Graphene-based composites can therefore provide a promising approach for overcoming some of the limitations associated with conventional polymeric TENGs. Furthermore, the development of flexible and potentially biocompatible material systems provides opportunities for integrating TENGs with wearable and implantable biomedical platforms [7]. However, achieving an optimal balance between graphene concentration, dielectric properties, mechanical flexibility, surface characteristics, and electrical output remains an important challenge.

Recent studies have demonstrated the considerable potential of TENGs for biomedical applications. Wearable TENG-based systems have been investigated for real-time monitoring of physiological signals such as pulse, respiration, body movement, and joint motion [8]. Similarly, implantable TENG architectures have been explored for harvesting biomechanical energy from physiological movements, thereby providing sustainable power for low-power biomedical electronics [9]. TENG-based stimulation platforms have also attracted attention for applications such as wound healing and tissue regeneration, where mechanically generated electrical signals can provide beneficial stimulation to biological tissues [10]. In rehabilitation engineering, biomechanical-energy-driven TENG systems have been investigated for self-powered prosthetic and assistive devices, demonstrating the possibility of integrating energy harvesting with motion sensing and control [11]. In addition, TENG-based biomedical stimulation and biosensing systems have shown potential for applications involving neural interfaces and physiological monitoring [12]. Recent graphene-enhanced TENG architectures have further demonstrated the potential of nanocomposite engineering to improve electrical output and sensing performance [13]. These developments indicate that both material engineering and structural optimization are critical for realizing high-performance TENGs for biomedical applications.

Although significant progress has been achieved, a systematic understanding of the relationship between graphene incorporation, dielectric behavior, mechanical deformation, electrostatic potential, and electrical output remains necessary. Many existing investigations primarily emphasize experimental fabrication and performance characterization, while comparatively fewer studies provide an integrated multiphysics analysis of the mechanical and electrostatic behavior of graphene-enhanced polymeric TENG structures. In particular, optimization of material

composition and device geometry is essential for simultaneously achieving high electrical output, mechanical flexibility, structural stability, and suitability for biomedical applications.

Therefore, this study focuses on the design, simulation, and performance analysis of a graphene-enhanced PDMS triboelectric nanogenerator for biomedical energy harvesting. The proposed structure integrates layered graphene with a flexible PDMS triboelectric material to improve charge-transfer characteristics while maintaining mechanical flexibility. An ANSYS-based multiphysics simulation framework is employed to investigate the mechanical deformation, dielectric behavior, electrostatic potential distribution, and electrical response of the proposed TENG. Key operating parameters and structural characteristics are analyzed to identify their influence on energy-generation performance. The resulting model is evaluated in terms of output voltage, short-circuit current, power generation, and load-dependent performance. The study aims to establish a systematic relationship between material selection, structural design, mechanical response, and electrical performance, thereby providing a computational framework for developing high-performance TENGs for self-powered biomedical applications.

The proposed approach contributes to the development of sustainable energy-harvesting technologies capable of reducing dependence on conventional batteries in wearable health-monitoring systems, rehabilitation devices, low-power biomedical sensors, and future implantable electronics. The findings may provide useful design guidelines for integrating graphene-based nanocomposites with flexible TENG architectures and advancing next-generation self-powered biomedical system

2. Material Methodology

2.1 TENG Sensors Made of Graphene

With their sustainable approach for running low-energy electronic devices, triboelectric nanogenerators (TENGs) have greatly enhanced energy-harvesting technology. Among the several materials investigated for TENGs, graphene has attracted much interest because of its extraordinary triboelectric, mechanical, and electrical characteristics. Excellent performance in energy harvesting and sensing applications has shown graphene-based TENG sensors, hence extending their possible usage in the industrial and healthcare sectors. Either as an electrode or as a triboelectric layer, graphene inclusion into TENGs has greatly enhanced the efficiency and stability of these devices. Recent studies have concentrated on creating graphene-based TENGs fit for wearable and implantable uses employing improved charge transfer capabilities, high durability, and flexible design [1]-[3].

2.2 Triboelectric Nanogenerators Based on Graphene

Utilising the special properties of graphene, graphene-based triboelectric nanogenerators (G-TENGs) improve the performance of existing TENGs. The large surface area, great conductivity, and flexibility of graphene help to generate and transport charges effectively—qualities vital for maximising energy conversion efficiency. Single-electrode mode, vertical contact-separation mode, and lateral-sliding mode have among other configurations of G-TENGs investigated. Self-powered biosensors, wearable electronics, and environmental monitoring tools [4]-[6] among other uses are made possible by these modes.

Integration of graphene with polymeric triboelectric materials greatly increases their surface charge density, thereby improving output voltages and currents. Furthermore, increasing the endurance of TENG devices and therefore their dependability for long-term use is graphene's great mechanical strength. Moreover, the adjustable electrical characteristics of graphene enable changes that could maximise its performance in triboelectric energy conversion [11]-[15].

2.3 Graphene as An Electrode

Because of its exceptional electrical conductivity and flexibility, graphene has shown great promise as an electrode material in TENGs. Though efficient, conventional metal electrodes can suffer from problems like restricted flexibility, brittleness, and corrosion. On the other hand, lightweight and highly conductive graphene-based electrodes

improve the lifetime and efficiency of TENG devices by themselves. Furthermore, enhancing their relevance in next-generation electronic devices [10]-[12], graphene electrodes provide transparent and flexible TENG designs [10].

The great electron mobility of graphene helps to rapidly gather and transfer charges, therefore affecting the general TENG performance. Research on graphene electrodes in conjunction with modern polymeric materials has found that they maximise charge storage and reduce leakage currents, hence improving triboelectric output. Moreover, the chemical stability of graphene guarantees that TENGs preserve their function under different environmental settings, therefore they are appropriate for outdoor and biomedical uses [13]-[15].

D. The Triboelectric Layer: Graphene

Beyond that of an electrode, graphene has also been investigated as an active triboelectric layer in TENGs. The basic idea underlying TENGs is the triboelectric effect, which is much affected by the surface properties of the interacting materials. Functionalisation made possible by the changeable surface chemistry of graphene lets its triboelectric qualities and charge retention capacity improve. Researchers have produced triboelectric layers with enhanced charge trapping efficiency [16]-[18] by varying functional groups or composite architectures on graphene.

Successful integration of graphene-based triboelectric layers into flexible and wearable TENGs has produced steady energy production under various mechanical deformations. Enhanced surface roughness shown by multilayer graphene structures has been shown by studies to boost charge production and general TENG efficiency. Moreover, graphene combined with other nanomaterials, like MXenes and transition metal dichalcogenides, has exhibited cooperative effects improving triboelectric performance [19]-[21].

Using graphene as a triboelectric sheet and an electrode offers a two-fold usage that maximises energy conversion efficiency. Future generation self-powered gadgets with exceptional performance and sustainability are projected to result from the development of hybrid graphene-based TENGs as research in this field keeps growing.

E. Models and Simulations of Triboelectric Nanogenerators

A capacitive system comprising two oppositely charged plates moving relative to each other is the basis of the mathematical modelling of a standard triboelectric nanogenerator (TENG). Where the voltage is inversely proportional to capacitance and directly proportional to the separation distance, TENGs exhibit capacitive behaviour producing an output voltage that fluctuates with the distance between the plates. A conventional TENG consists in two dielectric (triboelectric) layers and two metallic electrodes with an interlayer spacing indicated as D. Apart from diffusion properties and charge transfer systems, the TENG's working concept is driven by coupling effects of triboelectrification and electrostatic induction.

Triboelectric materials like Kapton, Teflon, or RTV-silicone film remain separated in their natural form without any applied external force, therefore generating an intrinsic air gap between them. The two dielectric layers—which are not quite smooth or homogeneous—come into contact when an external mechanical force is applied, causing surface deformations and charge buildup because of interfacial structural differences. Equally and opposite charges on the inner surfaces of the dielectric layers arise from the triboelectrification process. The quantum tunnel effect distributes these charges throughout the triboelectric surfaces therefore enabling the mobility of charge carriers at the nanoscale.

The work function theory holds that the dielectric characteristics of the triboelectric layers and the intrinsic work function of the materials are intimately related in terms of surface charge buildup. Connected to an external circuit, the induced charge distribution and potential difference between electrodes drive the electrostatic induction process, hence producing an alternating current (AC) output. Material selection, electrode arrangement, surface roughness, and external force factors all affect the general energy conversion efficiency of TENGs; thus, exact modelling and simulation are very essential for maximising performance in useful applications.

F. TENG Modelling Simulation Equations

To evaluate their energy harvesting performance, triboelectric nanogenerators (TENGs) are modelled and simulated using electromechanical, electrostatic, and triboelectric charge transport equations. Accurate modelling and optimisation are made possible by these equations establishing the basic links between mechanical motion, charge creation, and electrical output [24-26]. Expressed as$C(t)$, the variational capacitance equation characterises the dynamic behaviour of TENGs as variable capacitors, where capacitance varies with the distance between the triboelectric layers.

Here, A is the overlapping surface area; $\epsilon 0$ is the permittivity of free space; ϵr is the relative permittivity of the dielectric material; and$D(t)$ is the time-dependent separation distance. With surface charge density, the open-circuit voltage produced by the TENG follows the equation$V(t)=\sigma AC(t)$ and is inversely proportional to the capacitance.

Representing the total charge collected over time, charge transfer and current generation in TENGs are regulated by $Q(t)=C$ (t)V(t). This shows that the periodic motion of the triboelectric layers generates an alternating current (AC) output, which may be rectified for DC applications. The instantaneous current created in the external circuit is given as dQ(t) Given an initial charge density and a charge retention period, the triboelectric charge density evolution follows an exponential decay model defined by σ 0 e −t/τ = σ Understanding charge dissipation over time depends on this equation, which also directly affects TENG energy collecting efficiency and sustainability [27].

TENG functioning is mostly dependent on electrostatic induction; the electric field distribution between the triboelectric layers is described as $\acute{o}$ (t) = Fuxϵ 0ϵr E(t)= ϵ

When coupled to an external circuit, this generated field induces charge flow between the electrodes thereby facilitating energy conversion. By enabling thorough finite element analysis (FEA) simulations in Ansys, these governing equations let researchers maximise TENG structural design for higher power output, better mechanical durability, and more energy harvesting efficiency [28].

G. TENG Generator Design using Layered Graphene and Polydimethylsiloxane (PDMS)

Flexible triboelectric nanogenerators (TENG) are designed to effectively gather mechanical energy from several sources, including environmental pressures, vibrations, and human motion. Polydimethylsiloxane (PDMS) with Layered Graphene is the main triboelectric material used to improve energy conversion efficiency as it provides great flexibility, biocompatibility, and charge transfer characteristics. The ANSYS Research Tool was used for structural modelling and performance optimisation of the TENG, therefore allowing exact assessment of dielectric behaviour, mechanical deformation, and electrostatic potential distribution. Standard dielectric materials included into the simulation procedure guarantee reasonable performance evaluations for several useful purposes shows in Figure 1.

H. An ANSYS Material Selection and Dielectric Design Guide

The choice of dielectric material impacts charge retention, triboelectric affinity, and breakdown strength, therefore affecting the performance of a TENG. Layers of graphene boost surface conductivity and charge trapping in PDMS, a flexible and chemically stable material. ANSYS is Standard dielectric materials like Silicon Doxide (SiO_2), Polyvinylidene Fluoride (PVDF), and Barium Titanate ($BaTiO_3$) were included into multiphysics simulations to investigate the triboelectric response.

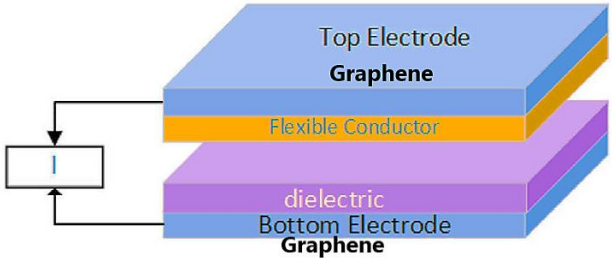

Figure 1: Core Structure

To guarantee the best energy-collecting efficiency, the dielectric constant, surface charge density, and electrostatic field distribution were assessed in ANSYS using the finite element analysis (FEA) model. Enhanced mechanical and electrical performance follow from the composite electrode produced by combining layered graphene with polydimethylsiloxane (PDMS), therefore using the special qualities of both materials. Although PDMS gives flexibility and the composite is perfect for stretchy and flexible electronics, graphene provides outstanding electrical conductivity by creating efficient conductive paths inside the matrix. Applications in wearable and implantable devices especially benefit from this mix as PDMS's biocompatibility fits biomedical uses like flexible electrodes for electrophysiological recordings, wearable sensors, and implanted medical devices. Furthermore, a good option for flexible screens and other modern electronic components is the material's conductivity and flexibility [29-30].

Nevertheless, the homogeneous distribution of graphene inside the PDMS matrix determines the composite's general performance mostly. While ideal dispersion guarantees uniform conductivity and mechanical stability, poor dispersion can result in localised regions with poorer conductivity and structural defects. This combination is mostly used in triboelectric nanogenerators (TENGs), where PDMS serves as a great triboelectric material able to create electric charges via mechanical interactions and graphene efficiently promotes charge movement. TENGs become more fit for energy-harvesting uses as this synergy improves their efficiency.

In this work, we applied periodic mechanical pulses via the custom-built linear motor-type mechanical system to investigate the electrical characteristics of TENGs. Figure 4 shows that the TENG was continuously and periodically pulsed 4 kgf at a frequency of 3 Hz. Whereas the short circuit current was measured at 6 μA, the open circuit voltage peaked at 180 V. Reversing the electrode connections to the load produced a polarity switch of the output signals, as shown in Figure 3, thereby verifying the source of the produced signals. This verified that the TENG, no outside noise, generated the signals.

We also investigated how TENG performance suffered with load resistance. The load resistance ranged from 10^2 to 10^9 Ω; Figure 3 shows the link between load resistance and output behaviour of voltage and current. The results showed that the output voltage grew while the current dropped as load resistance raised. This emphasises the need to choose a suitable resistance value to maximise the output of power. Figure 4 shows that at an external resistance of 10^7 Ω the maximum power output of 0.73 mW was attained.

We also performed a comparative analysis of many graphene composite-based TENG devices concerning voltage, current, power density, and current density. The results show notable differences in electrical performance based on the device's structural design and material composition. Our results imply that adding graphene composites greatly improves the efficiency of TENG devices, thereby presenting interesting prospects for further energy-harvesting uses.

I. Physics of Generation of Triboelectric Charge

Triboelectrification and electrostatic induction form the foundation of a TENG. Charge transfer results from two materials with differing triboelectric affinities (e.g., PDMS and graphene) coming into contact and subsequently separating across electrodes. Expressed as:$V=\sigma d\epsilon 0$V=ϵ0σd, the triboelectric voltage (V) is determined by the surface charge density (σ) from which d is derived. The dielectric constant (ϵr ϵ r) of the chosen materials determines the charge transfer efficiency, therefore affecting the stored electrostatic energy:

$$V= \sigma d/ \epsilon 0 \quad (1)$$

$$U= 1/2\ CV2 \quad (2)$$

where the triboelectric system's capacitance is denoted by C and stored energy by denoted by U The ANSYS simulations helped TENG designs to be optimized by offering an understanding of charge buildup, contact pressure effects, and energy dissipation.

J. Simulation Results and Structural Optimization

Surface morphological changes modelled in ANSYS employing nanopatterning and microstructure design help to improve energy output. Integration of multilayer graphene enhanced charge transfer efficiency and electrical conductivity. Increasing the roughness of PDMS increased contact electrification, which in turn raised power production according to simulated data. Under different external stresses and deformation circumstances, the mechanical behaviour of the structure was investigated to guarantee dependability and durability in practical uses like wearable electronics, biomedical implants, and environmental energy collecting.

3. Results and discussion

A. Polydimethylsiloxane (PDMS) with Layered Graphene

Combining layered graphene with polydimethylsiloxane (PDMS) generates an electrode leveraging the special characteristics of both materials that generate a composite with improved mechanical and electrical capabilities. Although the graphene layers generate excellent conductive routes inside the matrix and have outstanding electrical conductivity, the PDMS offers flexibility and makes the material fit for flexible and stretchy electronics notably for purposes in wearable and implantable electronics specifically. PDMS's biocompatibility increases the relevance for biomedical usage even further using wearable sensors, implantable devices, and flexible electrodes for electrophysiological recordings. Moreover, ideal for the growth of flexible screens and other electronic components is the conductivity and flexibility of the material. Still, the performance of the composite mostly depends on the homogenous graphene dispersion inside the PDMS matrix. While localised zones of poor conductivity and structural defects might result from inadequate dispersion, substantial dispersion provides consistent conductivity and mechanical stability. Important use for this material also comes from triboelectric nanogenerators (TENGs). PDMS is a fantastic triboelectric material that efficiently generates electric charges following mechanical interaction; graphene allows the generated electricity to be conceded upon. This combination enhances TENG performance, hence raising their efficiency for application in energy harvesting.

For flexible electronics and general healthcare technologies, combining PDMS with graphene generates a rather fascinating material. Bringing together the fantastic conductivity of graphene with the flexibility and biocompatibility of PDMS paves the way for better applications in next-generation electrical and energy-harvesting devices. By bringing together layered graphene and polydimethylsiloxane (PDMS), we can take advantage of the unique properties of both materials to create an electrode that enhances the composite's mechanical and electrical features. The graphene layers provide excellent electrical conductivity, creating effective conductive paths within the matrix, while the PDMS adds flexibility, making this material perfect for flexible and stretchy electronics. For applications in wearable and implantable electronics, this synergy is beneficial. Thanks to wearable sensors, implantable devices, and flexible electrodes for electrophysiological recordings, the biocompatibility of PDMS makes this composite even more suitable for biomedical applications. Additionally, the material's conductivity and adaptability make it ideal for developing flexible screens and other electronic components. The performance of the composite is primarily influenced by the even distribution of graphene within the PDMS matrix. When dispersion isn't quite right, it can lead to some areas with low conductivity and structural issues. However, getting the dispersion just right ensures that conductivity remains steady, and the structure stays strong.

Triboelectric nanogenerators (TENGs) have some great applications for this material! PDMS is a fantastic triboelectric material that generates electric charges when it’s mechanically engaged, and graphene plays a key role in helping to harness that electricity. This mix enhances TENG performance, which boosts their efficiency for energy harvesting applications. Combining PDMS with graphene creates an exciting material for flexible electronics and healthcare technology as a whole. This combination paves the way for exciting advancements in next-generation electrical and energy-harvesting devices, blending the flexibility and biocompatibility of PDMS with the impressive conductivity of graphene.

B. Electrical Characterization

Periodically mechanical pulses on the TENG surface were applied using homemade linear motor-type mechanical equipment to determine the electrical characterisation. Fig. 4 illustrates the TENG output response under both continuous and periodic 4 kgf pulses delivered at a frequency 3 Hz. The open circuit voltage peaked at 180 V and the short circuit current came out to be 6 μA. Reversing the electrode connection to the load produces signals in the opposite direction as illustrated in Figure 3, therefore completing the switching polarity test. The opposite direction of the output signal guarantees that TENG, not noise, is the source of created signals.

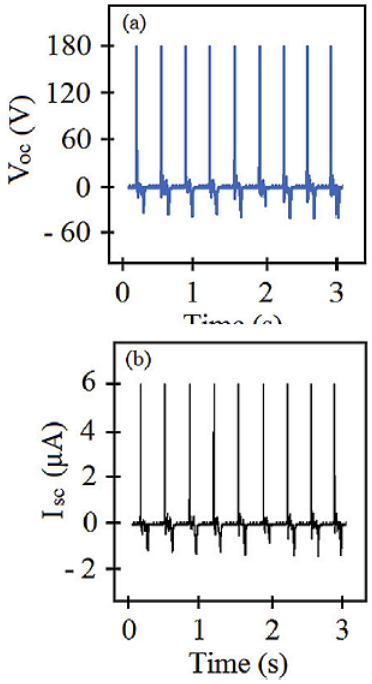

Figure 2: Dual polarity open circuit voltage in TENG

Figure 3 displays, load resistance, and the output behaviour of voltage and current. The load resistance ran from 102 to 109 Ω. As the load resistance rises, it was seen that the output Current falls while the voltage rises. TENG's performance therefore depends on load resistance and the highest power of 0.73 mW was attained with an external resistance of 107 Ω. As shown in Figure 4.

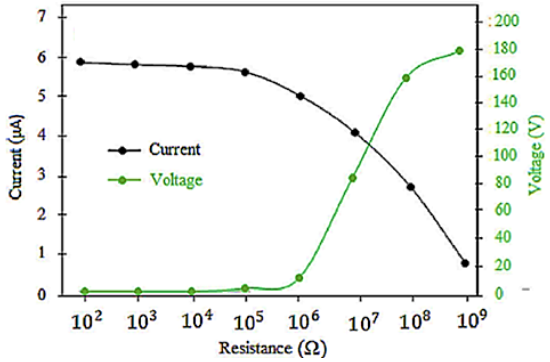

Figure 3: Current and Voltage as A Function vs Load Resistance

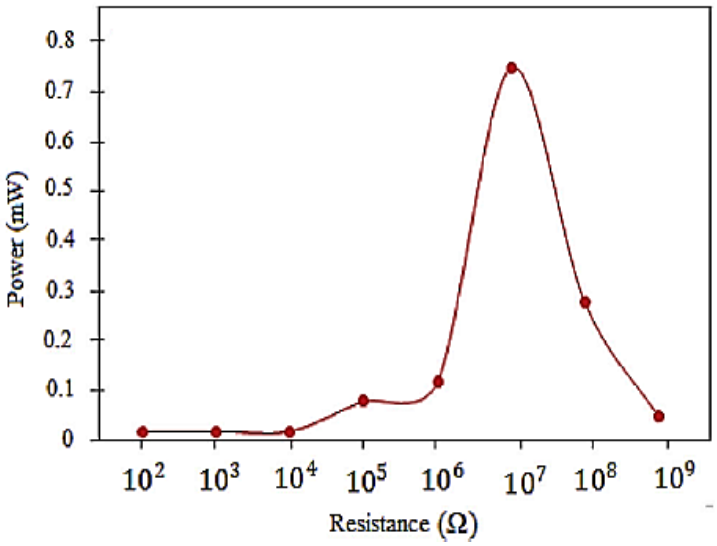

Figure 4: Power Vs Resistance

C. Comparative Analysis of Several Graphine Composite-Based TENG Devices

Various graphene composite-based TENG devices' performance has been examined to voltage, current, power density, and current density. The kind of graphene composite material utilised in the TENG construction influences the electrical output. The comparison shows that whilst the Graphene/Carbon Nanotube (CNT) TENG offers a high-power density of 0.78 mW/m2, the Graphene/PVDF TENG has the greatest output voltage of 200 V. At an ideal external resistance, the Graphene/PDMS TENG reaches a maximum power density of 0.73 mW/m², hence emphasising its possible uses in energy harvesting. Likewise, rGO/PDMS and GO/PDMS composites show reasonable voltage and current outputs, which qualify for flexible and wearable energy-harvesting uses. Variations in current density point to how the composite material affects charge transfer efficiency. The following compiled statistics offer a comparison of several graphene-based TENGs:

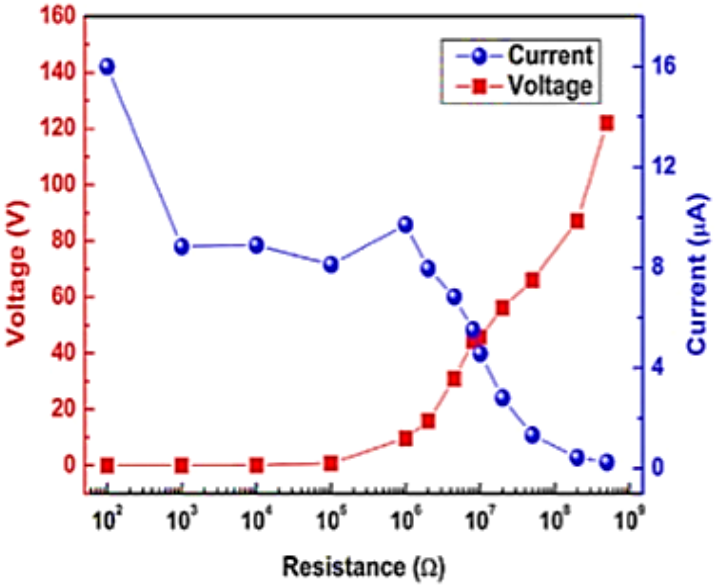

Figure 5: Output voltage and Current Generated

The TENG device's output performance and degree of flexibility were much improved by using a flexible LIG electrode. The external load resistance was changed from 100 Ω to 500 MΩ to evaluate its power density; the output voltage showed a rising trend with increased resistance, whilst the current dropped in line with Ohm's law. Initially rising, the instantaneous power density peaked at over 609.1 mW/m² at an ideal load resistance of 8 MΩ. Then it progressively dropped, as Figure 5 shows. Furthermore, the TENG's capacity to store charge was shown by connecting it to a capacitor via a full-wave rectifier bridge, wherein the capacitor voltage attained about 12.1 V in just one minute as shows in Figure 6.

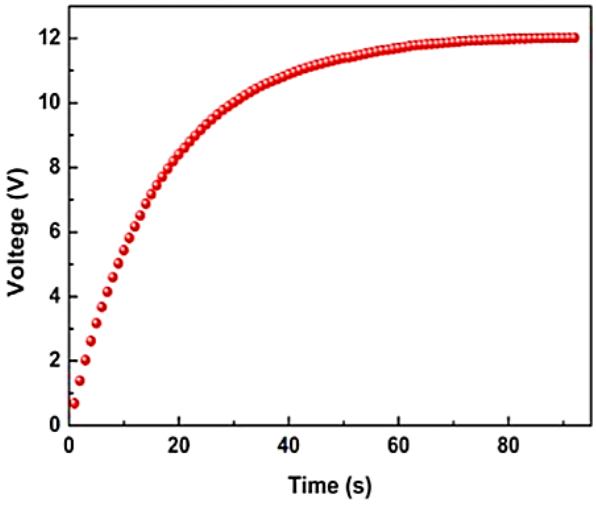

Figure 6: Charging Curve

Table: Performance Comparison of Graphene Composite-Based TENG Devices

Graphene Composite Material	Voltage (V)	Current (μA)	Power Density (mW/m²)	Current Density (μA/cm²)
Graphene/PDMS TENG [2]	180	6	0.73	2.5
Graphene Oxide (GO)/PDMS TENG [3]	120	4.5	0.55	1.8
rGO/PDMS TENG [5]	160	5.2	0.65	2.1
Graphene/Nanocellulose TENG [8]	135	4.8	0.58	2
Graphene/PVDF TENG [11]	200	7	0.85	3
Graphene/Carbon Nanotube (CNT) TENG [15]	170	6.5	0.78	2.7

4. Conclusion

Enhanced mechanical and electrical performance follow from the composite electrode produced by combining layered graphene with polydimethylsiloxane (PDMS), therefore using the special qualities of both materials. Although PDMS gives flexibility and the composite is perfect for stretchy and flexible electronics, graphene provides outstanding electrical conductivity by creating efficient conductive paths inside the matrix. Applications in wearable and implantable devices especially benefit from this mix as PDMS's biocompatibility fits biomedical uses like flexible

electrodes for electrophysiological recordings, wearable sensors, and implanted medical devices. Furthermore, a good option for flexible screens and other modern electronic components is the material's conductivity and flexibility.

Nevertheless, the homogeneous distribution of graphene inside the PDMS matrix determines the composite's general performance mostly. While ideal dispersion guarantees uniform conductivity and mechanical stability, poor dispersion can result in localised regions with poorer conductivity and structural defects. This combination is mostly used in triboelectric nanogenerators (TENGs), where PDMS serves as a great triboelectric material able to create electric charges via mechanical interactions and graphene efficiently promotes charge movement. TENGs become more fit for energy-harvesting uses as this synergy improves their efficiency.

In this work, we applied periodic mechanical pulses via a custom-built linear motor-type mechanical system to investigate the electrical characteristics of TENGs. Figure 4 shows that the TENG was continuously and periodically pulsed at 4 kgf at a frequency of 3 Hz. Whereas the short circuit current was measured at 6 μA, the open circuit voltage peaked at 180 V. Reversing the electrode connections to the load produced a polarity switch of the output signals, as shown in Figure 3, thereby verifying the source of the produced signals. This verified that the TENG, no outside noise, generated the signals. We also investigated how TENG performance suffered with load resistance. The load resistance ranged from 10^2 to 10^9 Ω; Figure 3 shows the link between load resistance and output behaviour of voltage and current. The results showed that the output voltage grew while the current dropped as load resistance raised. This emphasises the need to choose a suitable resistance value to maximise the output of power. Figure 4 shows that at an external resistance of 10^7 Ω the maximum power output of 0.73 mW was attained.

We also performed a comparative analysis of many graphene composite-based TENG devices concerning voltage, current, power density, and current density. The results show notable differences in electrical performance based on the device's structural design and material composition. Our results imply that adding graphene composites greatly improves the efficiency of TENG devices, thereby presenting interesting prospects for further energy-harvesting uses.. This result highlights the possibilities of RbGeI3 as a lead-free absorber material for perovskite solar cells of future generations.

Future studies should be focused on improving device performance utilizing structural parameter optimisation including the thickness of the HTL, interface defect density, and contact resistance. Furthermore, investigating surface passivation methods and substitute materials for electron and hole transport layers might help to raise the PCE overall above the existing optimisation. This finding sets the framework for extremely effective and ecologically acceptable lead-free PSC, hence leading future investigations in the usage of renewable energy.

5. Acknowledgement

None of any scientific organisation or university has sponsored this project. The writers sincerely thank Dr Marc Burgelman and his associates at the EIS Department at the University of Gent in Belgium for giving us the chance to investigate using the SCAPS-1D program.

REFERENCES

1. F. Salemi, F. Karimzadeh, M. H. Abbasi, F. Moradi, and J. Kim, "Recent progress in self-powered graphene-based triboelectric nanogenerators," Rev. Published, vol. 12, pp. 749–779, Jan. 2024. [Online]. Available: doi:10.1007/s40684-024-00688-8.
2. X. Meng, K. Li, J. Xie, H. Li, Z. Huang, and Z. Li, "Exploration of power generator law based on droplet self-capacitance effect," IEEE Trans. Dielectr. Electr. Insul., vol. 1, pp. 1–1, Mar. 2024. [Online]. Available: doi:10.1109/TDEI.2024.3549407.
3. M. I. Hossain, M. S. Zahid, M. A. Chowdhury, M. M. H. Maruf, and N. Hossain, "MEMS-based energy harvesting devices for low-power applications—a review," Results Eng., 2023. [Online]. Available: doi:10.1016/j.rineng.2023.101264.
4. Q. Zhu, X. Cao, and N. Wang, "Triboelectric nanogenerators in sustainable chemical sensors," Chemosensors, 2022. [Online].
5. Available: doi:10.3390/chemosensors10110484.

6. D. G. Dassanayaka, T. M. Alves, N. D. Wanasekara, I. G. Dharmasena, and J. Ventura, "Recent progress in wearable triboelectric
7. nanogenerators," Adv. Funct. Mater., 2022. [Online]. Available: doi:10.1002/adfm.202205438.
8. H. Zou et al., "Quantifying the triboelectric series," Nat. Commun., vol. 10, p. 1427, 2019. [Online]. Available: doi:10.1038/s41467-
9. 019-09461-x.
10. M. Salauddin, R. M. Toyabur, P. Maharjan, M. S. Rasel, H. Cho, and J. Y. Park, "Design and experimental analysis of a low-frequency
11. resonant hybridized nanogenerator with a wide bandwidth and high output power density," Nano Energy, 2019. [Online]. Available:
12. doi: 10.1016/j.nanoen.2019.104122.
13. Li, Y. Zi, H. Guo, Z. L. Wang, and F. M. Fernandez, "Triboelectric nanogenerators for sensitive nano-coulomb molecular mass spectrometry," Nat. Nanotechnol., vol. 12, p. 481, 2017. [Online]. Available: doi:10.1038/nnano.2017.17.
14. L. Xu et al., "Giant voltage enhancement via triboelectric charge supplement channel for self-powered electroadhesion," ACS Nano, vol. 12, p. 10262, 2018. [Online]. Available: doi:10.1021/acsnano.8b05359.
15. Z. L. Wang, "On Maxwell's displacement current for energy and sensors: the origin of nanogenerators," Mater. Today, vol. 20, p. 74, 2017. [Online]. Available: doi:10.1016/j.mattod.2016.12.001.
16. S. Niu and Z. L. Wang, "Theoretical systems of triboelectric nanogenerators," Nano Energy, vol. 14, p. 161, 2015. [Online]. Available: doi: 10.1016/j.nanoen.2014.11.034.
17. S. Wang, L. Lin, and Z. L. Wang, "Triboelectric nanogenerators as self-powered active sensors," Nano Energy, vol. 11, p. 436, 2015. [Online]. Available: doi:10.1016/j.nanoen.2014.10.034.
18. C. Xiao et al., "An effective and efficient numerical method for thermal management in 3D stacked integrated circuits," Appl. Therm. Eng., vol. 121, pp. 200–209, 2017. [Online]. Available: doi:10.1016/j.applthermaleng.2017.04.065.
19. Chasin et al., "Impact of wafer thinning on front-end reliability for 3D integration," in Proc. 2016 IEEE Int. Rel. Phys. Symp. (IRPS), 2016. [Online]. Available: doi:10.1109/IRPS.2016.7574595.
20. S. Cao et al., "ESD design challenges and strategies in deeply-scaled integrated circuits," in Proc. 2009 IEEE Custom Integr. Circuits Conf., 2009. [Online]. Available: doi:10.1109/CICC.2009.5280766.
21. M.-F. Lai et al., "Wafer-level three-dimensional integrated circuits (3D IC): Schemes and key technologies," Microelectron. Eng., vol. 88, no. 11, pp. 3282–3286, 2011. [Online]. Available: doi:10.1016/j.mee.2011.05.034.
22. E. Rosenbaum, V. Shukla, and M.-S. Keel, "ESD protection networks for 3D integrated circuits," in Proc. 2011 IEEE Int. 3D Syst. Integr. Conf. (3DIC), 2012. [Online]. Available: doi:10.1109/3DIC.2012.6262975.
23. Amerasekera and C. Duvvury, "The impact of technology scaling on ESD robustness and protection circuit design," IEEE Trans. Compon., Packag., Manuf. Technol. A, vol. 18, no. 2, pp. 314–320, 1995. [Online]. Available: doi:10.1109/95.388262.
24. Duvvury and A. Amerasekera, "ESD: A pervasive reliability concern for IC technologies," Proc. IEEE, vol. 81, no. 5, pp. 690–702, 1993. [Online]. Available: doi:10.1109/5.223738.
25. Q. Han, et al., Single crystal formamidinium lead iodide (FAPbI3): insight into the structural, optical, and electrical properties, Adv. Mater., 2016, 28(11), 2253–2258.
26. S. Wozny, et al., Controlled humidity study on the formation of higher efficiency formamidinium lead triiodide-based solar cells, Chem. Mater., 2015, 27(13), 4814–4820.
27. G. E. Eperon, S. D. Stranks, C. Menelaou, M. B. Johnston, L. M. Herz and H. J. Snaith, Supplementary information Formamidinium of Formamidinium lead trihalide: a broadly tunable perovskite for efficient planar heterojunction solar cells, Energy Environ. Sci., 2014, 7(3), 982.
28. D. Wang, M. Wright, N. K. Elumalai and A. Uddin, Stability of perovskite solar cells, Sol. Energy Mater. Sol. Cells, 2016, 147, 255–275
29. Zhang, P.;Wu, J.; Zhang, T.;Wang, Y.; Liu, D.; Chen, H.; Li, S. Perovskite solar cells with ZnO electron-transporting materials.Adv. Mater. 2018, 30, 1703737.
30. Son, D.Y.; Im, J.H.; Kim, H.S.; Park, N.G. 11% efficient perovskite solar cell based on ZnO nanorods: An effective charge collection system. J. Phys. Chem. C 2014, 118, 16567–16573. [CrossRef]
31. Tseng, Z.L.; Chiang, C.H.; Wu, C.G. Surface engineering of ZnO thin film for high efficiency planar perovskite solar cells. Sci. Rep. 2015, 5, 13211.
32. Liu, G.; Zhong, Y.; Mao, H.; Yang, J.; Dai, R.; Hu, X.; Chen, Y. Highly efficient and stable ZnO-based MA-free perovskite solar cells via overcoming interfacial mismatch and deprotonation reaction. Chem. Eng. J. 2022, 431, 134235.
33. Wu, X.; Zhang, J.; Qin, M.; Liu, K.; Lv, Z.; Qin, Z.; Lu, X. ZnO electron transporting layer engineering realized over 20% efficiency and over 1.28 V open-circuit voltage in all-inorganic perovskite solar cells. EcoMat 2022, 4, e12192.
34. Ong, S.P.; Richards, W.D.; Jain, A.; Hautier, G.; Kocher, M.; Cholia, S.; Gunter, D.; Chevrier, V.L.; Persson, K.A.; Ceder, G. Python Materials Genomics (Pymatgen): A Robust, Open-Source Python Library for Materials Analysis. Comput. Mater. Sci. 2013, 68, 314–319.
35. Ward, L.; Dunn, A.; Faghaninia, A.; Zimmermann, N.E.R.; Bajaj, S.; Wang, Q.; Montoya, J.; Chen, J.; Bystrom, K.; Dylla, M.; et al. Matminer: An Open Source Toolkit for Materials Data Mining. Comput. Mater. Sci. 2018, 152, 60–69.