Bulletin of Pure and Applied Science
Physics, Vol.44D No.2,
July-December 2025 P.67-76
Original Research Article

Print version ISSN 0970 6569
Online version ISSN 2320 3218

Available online at www.bpasjournals.com

Boosting the Triboelectric Performance of PVA Using Carbon Derived from Banana Pseudostem

[1]Sindhu R.L.* and [2]Anitha Rani L.V.

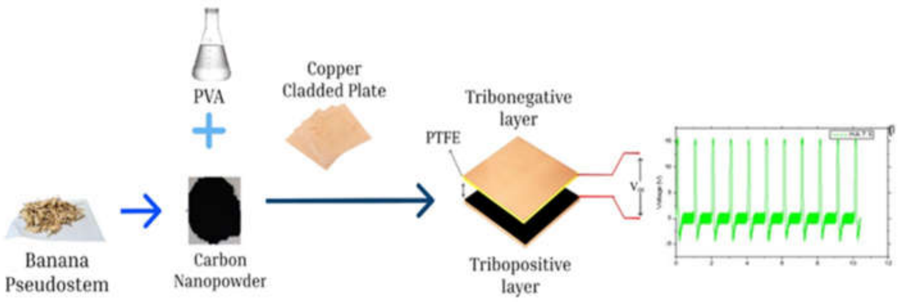
Author's Affiliations:
[1]Department of Physics, College of Engineering Trivandrum, Thiruvananthapuram, Kerala 695016, India.
[2]College of Engineering Trivandrum, Thiruvananthapuram, Kerala 695016, India.

***Corresponding author:**
Sindhu R.L.
Department of Physics, College of Engineering Trivandrum, Thiruvananthapuram, Kerala 695016, India.
E-mail: sindhuajai8@gmail.com

ABSTRACT

Triboelectric nanogenerators (TENGs) have emerged as the most promising technology for converting mechanical energy into useful electricity in efforts to investigate sustainable and energy-efficient energy harvesting systems. However, a major consideration is improving the output performance of polymer-based TENG devices. In this research, we present a green and cheap method for enhancing the triboelectric properties of polyvinyl alcohol (PVA) film by adding porous carbon derived from banana pseudostem. The pseudostem is an abundant agricultural waste from which the carbon powder is obtained. This bio-carbon is introduced into a PVA matrix to establish flexible composite films, which act as the tribo-positive layer in a vertical contact-separation mode TENG. The pseudostem carbon enhanced the dielectric constant, surface roughness, and charge trapping capacity of the PVA composite, thereby increasing the triboelectric outputs. At the optimum concentration of carbon powder, the TENG delivers a maximum output voltage of 25.523 volts, a maximum output current of 1.027 µA, and a maximum power density of 10.485 mW/m^2, all significantly better than PVA. This research opens up another avenue for environmentally friendly sustainability.

Graphical Abstract



KEYWORDS
TENG, Biomass, Carbon, Vertical contact separation mode, Triboelectric property, PVA, Tribopositive, Tribonegative, banana pseudostem

Received on 28.04.2025, Revised on 12.07.2025, Accepted on 20.07.2025

How to cite this article Sindhu R.L. and Anitha Rani L.V. (2025). Boosting the Triboelectric Performance of PVA Using Carbon Derived from Banana Pseudostem. *Bulletin of Pure and Applied Sciences- Physics,* 44D (2), 67-76.

INTRODUCTION

The urgent need for sustainable and portable power supplies on a global scale has led to intense research on self-powered energy systems. One technology that has been developed is the Triboelectric Nanogenerator (TENG). TENGs work through contact electrification and electrostatic induction and can harvest mechanical energy from various sources such as human motion, vibrations, airflow, or falling water droplets and convert that energy into usable electrical energy. TENGs rely on triboelectric layers, and the performance of TENG is dependent on the triboelectric layers used in fabrication. Material selection and surface engineering are critical to the development of these triboelectric layers [1-7Polyvinyl alcohol (PVA) is one material that has been studied previously in triboelectric nanogenerators (TENGs). PVA is low-cost, biodegradable, can form films, has a tunable chemistry for surface modification, and is mechanically flexible, which makes it an attractive material for studying TENGs. However, pure PVA has poor dielectric and poor electron affinity, unless low levels of plasticizers are added to improve the properties. The most effective way to mitigate these performance concerns is to add functional fillers to the PVA matrix [8-13]. Functional fillers are an effective means of enhancing the dielectric properties, charge trapping capability, and surface morphology, three important parameters when optimizing triboelectric performance.

Biomass-derived carbon materials offer an exciting and eco-friendly, and sustainable way to enhance the properties of materials in TENGs and other energy harvesting devices. One example of under-utilised agricultural waste is the pseudostem from a banana or plantain plant, which is an under-utilised source of lignocellulosic material. These biomass materials have the potential to form high-performing, eco-friendly fillers when processed into carbon materials [14,15,16]. In the current work, the materials used for the tribo-positive layer are PVA and carbon nanoparticles from the banana pseudo-stem. An eco-friendly triboelectric nanogenerator will be constructed since PVA and biomass-derived carbon have biocompatibility, hydrophilicity, and a stretchable nature. The novelty in the research project is the selection of biocompatible and biodegradable materials for the tribo-positive layer. The output power of a triboelectric nanogenerator with PVA-carbon composite (carbon from banana pseudo stem) as triboelectric positive layer and PTFE triboelectric negative layer is studied. The optimum concentration of carbon powder is determined. This research represents a sustainable option for a small energy requirement, with energy being harvested from renewable energy sources. The research will set out a sustainable option for small-scale power requirements when energy is harvested from renewable energy sources.

MATERIALS AND METHODS

The materials utilized in the present work are Polyvinyl alcohol, deionised water, hydrochloric acid, Polytetrafluoroethylene (PTFE)/Teflon tape, and copper-clad electrodes. All chemicals were used as received. The pseudostem used was obtained locally and washed in water to clean impurities and dirt. Teflon tape was used as the negative triboelectric material for each experiment.

Preparation of carbon from the banana pseudo-stem

The banana pseudo-stem was chopped into smaller pieces and washed with deionized water to remove soil and dust. The pseudo-stem was dried at 100 ⁰C for two days in a hot air oven to remove moisture. The dry pseudo-stem was ground into a fine powder and carbonized in a muffle furnace at 800 ⁰C for 4 hours. The carbon powder was then washed with 1M HCl and deionized water to remove the by-products formed during carbonization. The sample was filtered and dried in an oven at 80 ⁰C for 2 hours to remove any volatile species and moisture. The final sample was termed BPS powder.

Characterization of Carbon Powder

Powder X-ray diffraction determined the structural analysis of the synthesized powder. The X-ray diffraction pattern of the powdered sample was performed using a Bruker D8 ADVANCE with DAVINCI operating at 30 kV and 10 mA using Cu Kα radiation (λ=1.5418 Å). The diffraction pattern was recorded in the range of $10° \leq 2\theta \leq 79°$ with a step size of 0.02⁰.

The Fourier Transform Infrared Spectroscopy (FTIR) determined the presence of functional groups in the sample with a recorded wave number range of 4000 to 400 cm^{-1}. The prepared samples' FTIR spectra were recorded by Thermoscientific Nicolet iS50 instrument using the KBr pellet method.

The EDX analysis was performed to analyze the components in the carbon powder. The morphological study of the sample was done using SEM (Scanning Electron Microscopy) analysis, which was performed using a Carl Zeiss EVO 18 Research instrument.

Preparation of triboelectric layer

A PVA solution was prepared by dissolving 100 mL of deionized water and 6.67g PVA in a glass beaker while stirring continuously at 70⁰C for one hour, using a magnetic stirrer with a hot plate. Positive triboelectric layers were fabricated by applying this PVA solution onto copper-clad substrate electrodes. Fabrication of each positive triboelectric layer used cleaned and etched copper-clad plates that were cut to a 5cm x 5cm dimension. The PVA solution was then applied to the substrate plates using the Dr. Blade technique and allowed to dry in environmental conditions for 24 hours. Carbon generated from banana pseudo-stem (BPS) was taken in the proportions of 10, 15, 20, and 25 wt% to PVA powder, and uniformly combined with the prepared PVA solution. Subsequently, the solution was deposited on cleaned, etched copper clad plates to create the triboelectric layers BPS10, BPS15, BPS20, and BPS25. The negative triboelectric layer was made with the PTFE tape wound on copper-clad electrodes.

Output measurement using the TENG vibrator

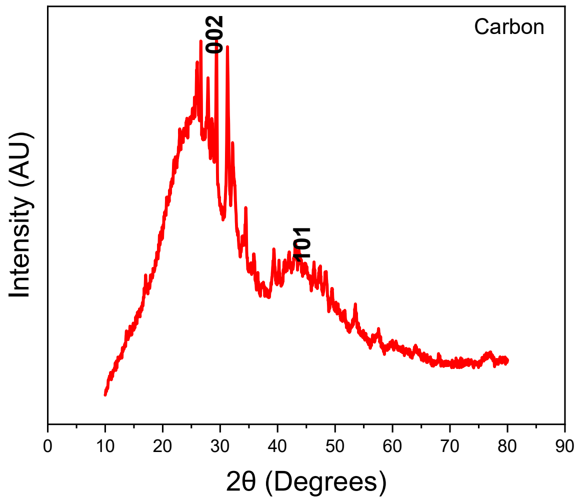
To create a TENG, there are always two triboelectric layers, one positive and one negative. In this study, the positive triboelectric layers were made by coating the prepared PVA solutions or PVA-banana pseudo-stem solutions onto copper-clad electrodes. The negative triboelectric layer was made from Teflon tape wound around the copper-clad substrate. The TENG was operated in vertical contact separation mode, utilizing an in-house fabricated TENG vibrator with two plate holders contacting each other at a frequency of 1 Hz. The distance between the plate holders was set initially at 2cm. The positive and negative triboelectric layers were attached to the plate holders, and the open circuit voltage and short circuit current were measured using a source meter (Keithley 2450), as shown in Figure 1.

Figure 1: Measuring TENG output with a Keithley 2450 sourcemeter

RESULTS AND DISCUSSION

Characterization of Carbon Nanoparticles

The XRD pattern of carbon obtained from the pseudo stem is shown in Figure 2. XRD of carbon shows a broad peak at 26^0 due to the (002) plane corresponding to graphitic planes. Another weak broader peak obtained around 43^0 represents in-plane diffraction from the hexagonal carbon rings. Peaks around 22^0-30^0 indicate silica, phosphorus, and calcium present in the biomass [17,18]. The average crystallite size of carbon nanoparticles is found to be 30.2 nm.



.

Figure 2: XRD pattern of carbon obtained from pseudo stem

The FTIR spectra of carbon obtained from the pseudo stem of the banana (Figure 3) show the following peaks. The spectrum shows the presence of carbon along with traces of elements like alumina, silica, and iron oxide[17,18,19].

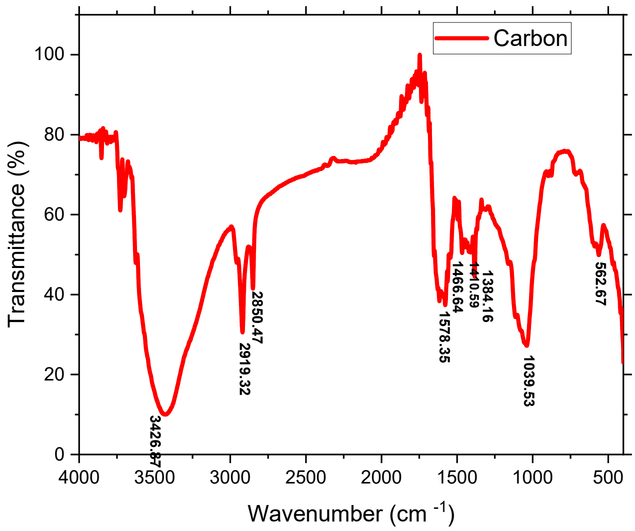
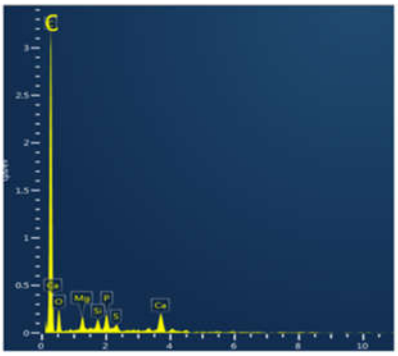


Figure 3: FTIR Spectrum of carbon obtained from pseudo stem

Table 1: FTIR peaks for carbon from pseudo stem

Sl. No.	Wavenumber	Band
1	3426cm $^{-1}$	OH stretching of hydroxyl groups
2	2919 & 2850 cm $^{-1}$	Corresponds to –C–H stretching of aliphatic or aromatic C–H groups
3	1578 cm $^{-1}$	C=C stretching of aromatic rings
4	1466 cm $^{-1}$	C–H bending vibrations from methyl ($-CH_3$) and methylene ($-CH_2-$) groups
5	1410 cm^{-1}	O–H bending of phenolic groups or C–H deformation in alkanes.
6	1384cm^{-1}	C–H deformation vibrations in the aliphatic compound
7	1039 cm^{-1}	C–O–C or C–O stretching of ether or alcohol groups
8	562 cm-1	Metal-oxygen (M–O) vibrations, which arise due to minerals like alumina, silica, and iron oxide

The EDX spectra (Figure 4) of carbon obtained from biomass show the presence of traces of oxygen, magnesium, silicon, phosphorus, sulphur, and calcium along with carbon. SEM image of carbon powder (Figure 5) shows the porous nature of biomass-derived powder.



Element	Weight %	Atomic %
C	80.48	86.81
O	13.03	10.55
Mg	1.23	0.66
Si	0.8	0.37
P	1.43	0.6
S	0.4	0.16
Ca	2.62	0.85

Figure 4: EDX analysis of carbon from the pseudo-stem

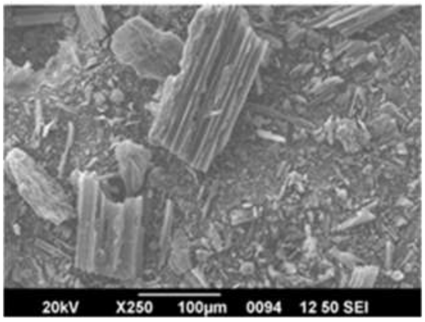
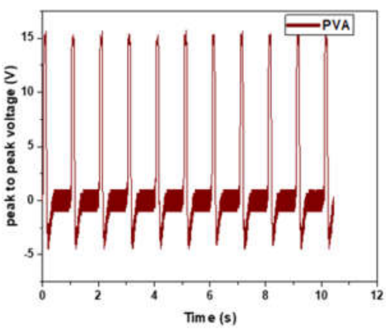


Figure 5: SEM image of carbon obtained from the pseudo-stem

Measurement of electrical output:

Figure 6 represents the peak-to-peak voltage and peak-to-peak current of the PVA sample as tribopositive layer. Figure 7 represents the peak-to-peak voltage of BPS10, BPS15, BPS20, and BPS25 samples, and Figure 8 represents the peak-to-peak current of these samples.



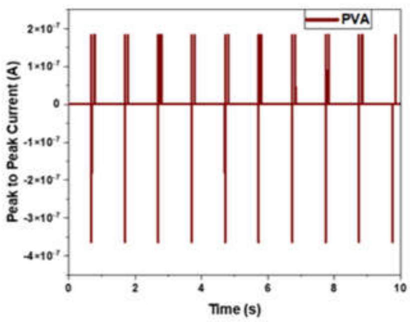


Figure 6: The variation of open circuit voltage and short circuit current with time for PVA

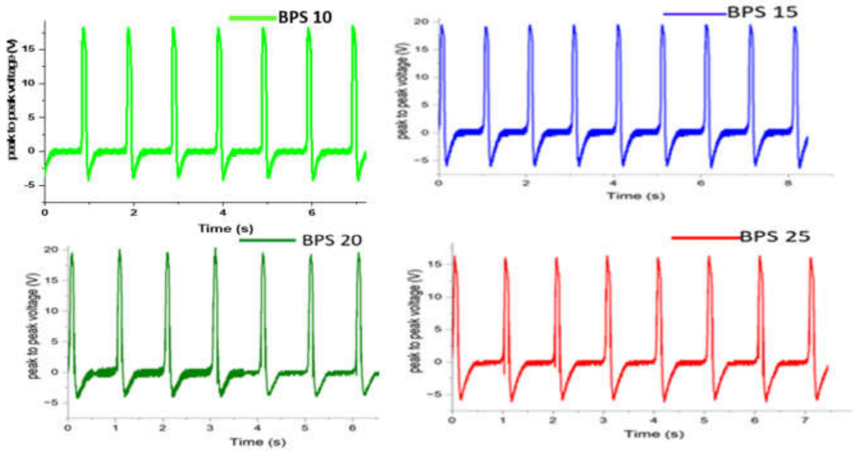


Figure 7: The variation of open circuit voltage with time for different concentrations of carbon powder

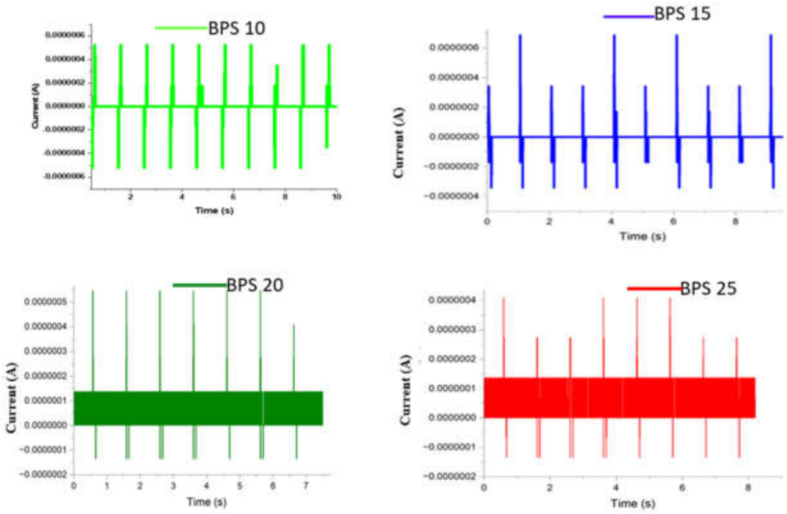


Figure 8: The variation of short circuit current with time for different concentrations of carbon powder

Table -2 depicts the peak-to-peak voltage, peak-to-peak current, and the power density obtained for the samples PVA, BPS10, BPS15, BPS20, and BPS25. With the addition of nanoparticles to the PVA in the tribo-positive layer, the power density increased. However, the power density achieves its maximum power density for the optimum concentration of nanoparticles. The banana pseudo-stem has a high fibre content, allowing for the production of a very porous carbon powder [19]. More pore volume means more surface roughness, increasing contact electrification. Carbon can increase surface charge density. In combination with biomaterials, they have a synergistic effect, and also increase the mechanical flexibility and durability of the composite film [22]. The carbon powder was produced through green or environmentally-friendly routes, allowing for a sustainable way to use waste biomass. The carbon powder was embedded into a polymer matrix formed with PVA to form a PVA-Carbon nanocomposite to create the tribopositive layer. The inclusion of nanoparticles enhances surface roughness, dielectric properties, and electron affinity for the triboelectric material. However, once the concentration of the nanoparticles increases to a point greater than their optimal concentration, power density decreases for higher concentrations of nanoparticles because the nanoparticles at high concentrations agglomerate, which results in charge being collected and also limits the effective surface area available for charge transfer.[20,21,4,23]. The variation of open circuit voltage and short circuit current with time is shown in Figures 7 and 8. Porous carbon has been effective at improving the dielectric constant, as well as developing micro and nanostructures. Additionally, an increase in surface roughness results in more contact points between the triboelectric layers. Therefore, at the optimum concentration of carbon powder (15 wt%), the output performance of the PVA-based triboelectric layer is maximum. At a higher concentration, the energy produced by the TENG was considerably lower due to the surface roughness affecting the contact between the triboelectric layers, which was caused by the increase in sample powder concentration. Moreover, the presence of carbon affects the dielectric constant and, beyond the optimum concentration, results in higher conductivity, which diminishes effective charge accumulation, subsequently lowering the output voltage[24-26].

Table 2: Electrical output obtained for various samples

Sl. No.	SAMPLE	V_{PP} (V)	I_{PP} (µA)	P(µW)	Power Density (mW/m2)
1	PVA	19.846	0.547	10.856	4.342
2	BPS 10	22.879	0.694	15.878	6.351
3	BPS 15	25.523	1.027	26.212	10.485
4	BPS 20	24.391	0.681	16.61	6.644
5	BPS 25	21.978	0.545	11.978	4.791

CONCLUSION

The study successfully demonstrates that the addition of biomass-derived carbon from banana pseudostem greatly improves the triboelectric behavior of a composite material and outperforms conventional materials based on PVA in the triboelectric nanogenerator (TENG) fabricated. The biomass carbon was produced through a controlled pyrolysis of the pseudostem, creating a porous structure and enhanced surface functionality that all contribute to higher charge generation, trapping, and retention inside the PVA material. These effects were attributed to a dielectric effect from the carbon particles, the surface roughness of the particles, as well as the improved electrical conductivity of the PVA-carbon composite. The TENG produced using the carbon-PVA composite generated larger output voltages, currents, and power densities relative to pristine PVA-based systems. An added benefit of the carbon composite material was the remarkable preservation of material characteristics of both flexibility and biodegradability. Therefore, this carbon-PVA composite opens a path for usage in flexible electronics and wearable sensors, as well as in devices for energy harvesting using a biodegradable material that meets sustainability demands. Apart from performance measures, this work suggests a sustainable solution by valorizing agricultural waste as high-value functional carbon material. The valorization of banana pseudostem aligns with global mandates for circular bioeconomy and zero-waste technology, at the same time, provides a new path for using biomass from the region in advanced material possibilities. In summary, carbon–PVA composite made from banana pseudostem offers an attractive route for next-generation green TENGs in terms of eco-friendliness, cost-effectiveness, and efficiency. Future efforts could focus on additional tuning of the carbon structure, surface chemistry, and loading concentration, expanding the limits of energy harvesting performance and applications.

REFERENCES

1. Ahmed, A., Qahtan, T., Owolabi, T., Agunloye, A., Rashid, M., & Mohamed Ali, M. S. (2024). Waste to sustainable energy based on TENG technology: A comprehensive review. *Journal of Cleaner Production, 448*, 141354. https://doi.org/10.1016/j.jclepro.2024.141354
2. Liu, D., Liu, J., Yang, M., Cui, N., Wang, H., Gu, L., Wang, L., & Qin, Y. (2021). Performance enhanced triboelectric nanogenerator by taking advantage of water in humid environments. *Nano Energy, 88*, 106303. https://doi.org/10.1016/j.nanoen.2021.106303
3. Khandelwal, G., Joseph Raj, N. P. M., & Kim, S.-J. (2020). Triboelectric nanogenerator for healthcare and biomedical applications. *Nano Today, 33*, 100882. https://doi.org/10.1016/j.nantod.2020.100882
4. Zhu, G., Lin, Z.-H., Jing, Q., Bai, P., Pan, C., Yang, Y., Zhou, Y., & Wang, Z. L. (2013). Toward large-scale energy harvesting by a nanoparticle-enhanced triboelectric nanogenerator. *Nano Letters, 13*(2), 847–853. https://doi.org/10.1021/nl4001053
5. Radhakrishnan, S., Joseph, S., Jelmy, E. J., Joseph, S., Santhanakrishnan, T., & John, H. (2022). Triboelectric nanogenerators for marine energy harvesting and sensing applications. *Results in Engineering, 15*, 100487. https://doi.org/10.1016/j.rineng.2022.100487
6. Munirathinam, P., & Chandrasekhar, A. (2023). Wearable triboelectric nanogenerator for real-time IoT-supported security applications. *Sustainable Materials and Technologies, 37*, e00700. https://doi.org/10.1016/j.susmat.2023.e00700
7. Walden, R., Kumar, C., Mulvihill, D., & Pillai, S. (2021). Opportunities and challenges in triboelectric nanogenerator (TENG) based sustainable energy generation technologies: A mini-review. *Chemical Engineering Journal Advances, 9*, 100237. https://doi.org/10.1016/j.ceja.2021.100237
8. Zhang, R., & Olin, H. (2020). Material choices for triboelectric nanogenerators: A critical review. *EcoMat, 2*, e12062. https://doi.org/10.1002/eom2.12062
9. Amini, S., Sagade, R. F., Ahmed, M., Madanahalli Ankanathappa, S., Chandrashekara Shastry, M. H., Shivanna, M., & Sannathammegowda, K. (2024). Investigating the annealing effects on the performance of polyvinyl alcohol-graphite-based triboelectric nanogenerator. *Sensors and Actuators A: Physical, 372*, 115309. https://doi.org/10.1016/j.sna.2024.115309
10. Reda, A. T., Weldemhret, T. G., Park, J. Y., Lim, S., Debele, N. T., Choi, S. S., Cho, C., & Park, Y. T. (2024). Synthesis and characterization of zinc basic salt–loaded PVA-PEI polymeric composite for antimicrobial activity and triboelectric nanogenerator applications. *Sensors and Actuators A: Physical, 370*, 115197. https://doi.org/10.1016/j.sna.2024.115197
11. Sun, W., Dong, J., Gao, X., Chen, B., & Nan, D. (2024). A study on the mechanisms and performance of a polyvinyl alcohol-based nanogenerator based on the triboelectric effect. *Materials, 17*(18), 4514. https://doi.org/10.3390/ma17184514
12. Cheedarala, R. K., & Song, J. (2021). Moderately transparent chitosan-PVA blended membrane for strong mechanical stiffness and as a robust bio-material energy

harvester through contact-separation mode TENG. *Frontiers in Nanotechnology, 3*, 667453. https://doi.org/10.3389/fnano.2021.667453

13. Yempally, S., Cabibihan, J. J., & Ponnamma, D. (2024). A facile approach to develop polyvinyl alcohol-based bio-triboelectric nanogenerator containing graphene-doped zinc oxide quantum dots. *Energy Technology, 12*, 2300992. https://doi.org/10.1002/ente.202300992

14. Zhou, J., Wang, H., Du, C., Zhang, D., Lin, H., Chen, Y., & Xiong, J. (2022). Cellulose for sustainable triboelectric nanogenerators. *Advanced Energy and Sustainability Research, 3*(5), 2100161. https://doi.org/10.1002/aesr.202100161

15. Du, G., Wang, J., Liu, Y., Yuan, J., Liu, T., Cai, C., Luo, B., Zhu, S., Wei, Z., & Wang, S. et al. (2023). Fabrication of advanced cellulosic triboelectric materials via dielectric modulation. *Advanced Science, 10*, 2206243. https://doi.org/10.1002/advs.202206243

16. Mishra, S., Supraja, P., Haranath, D., Kumar, R. R., & Pola, S. (2022). Effect of surface and contact points modification on the output performance of triboelectric nanogenerator. *Nano Energy, 104*, 107964. https://doi.org/10.1016/j.nanoen.2022.107964

17. Xie, Z., Guan, W., Ji, F., Song, Z., & Zhao, Y. (2014). Production of biologically activated carbon from orange peel and landfill leachate subsequent treatment technology. *Journal of Chemistry, 2014*, 491912. https://doi.org/10.1155/2014/491912

18. Deleanu, I., Stoica, A., Stroescu, M., Dobre, L., Dobre, T., Jinga, S., & Tardei, C. (2012). Potassium sorbate release from poly(vinyl alcohol)–bacterial cellulose films. *Chemical Papers, 66*, 138–143. https://doi.org/10.2478/s11696-011-0068-4

19. Venkatachalam, S., Luo, C., Stephan, A. M., Nahm, K.-S., Thomas, S., & Wei, B. (2007). Supercapacitors from activated carbon derived from banana fibers. *The Journal of Physical Chemistry C, 111*, 18195–18200. https://doi.org/10.1021/jp067009t

20. Huynh, N. D., Hyun-woo, P., Jeong-beom, J., & Deok-hyeon, C. (2018). Effect on TENG performance by phase control of TiOx nanoparticles. *Composites Research, 31*(6), 365–370.

21. Zhang, R., & Olin, H. (2022). Advances in inorganic nanomaterials for triboelectric nanogenerators. *ACS Nanosci Au, 2*(1), 12–31. https://doi.org/10.1021/acsnanoscienceau.1c00026

22. Mekbuntoon, P., Kaeochana, W., Prada, T., Appamato, I., & Harnchana, V. (2022). Power output enhancement of natural rubber-based triboelectric nanogenerator with cellulose nanofibers and activated carbon. *Polymers, 14*(21), 4495. https://doi.org/10.3390/polym14214495

23. Zhang, H., Zhang, P., Li, P., Deng, L., Zhang, W., Liu, B., & Yang, Z. (2022). Enhanced performance triboelectric nanogenerator based on porous structure C/MnO2 nanocomposite for energy harvesting. *Nano Research, 15*, 1–9. https://doi.org/10.1007/s12274-022-4326-2

24. Xu, Z., Chang, Y., & Zhu, Z. (2023). A triboelectric nanogenerator based on bamboo leaf for biomechanical energy harvesting and self-powered touch sensing. *Electronics, 13*(4), 766. https://doi.org/10.3390/electronics13040766

25. Jie, Y., Jia, X., Zou, J., Chen, Y., Wang, N., Wang, Z. L., & Cao, X. (2018). Natural leaf made triboelectric nanogenerator for harvesting environmental mechanical energy. *Advanced Energy Materials, 8*, 1703133. https://doi.org/10.1002/aenm.201703133

26. Feng, Y., Zhang, L., Zheng, Y., Wang, D., Zhou, F., & Liu, W. (2019). Leaves based triboelectric nanogenerator (TENG) and TENG tree for wind energy harvesting. *Nano Energy, 55*, 260–268. https://doi.org/10.1016/j.nanoen.2018.11.014

****