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PERFORMANCE EVALUATION OF FREE-STANDING TRIBOELECTRIC GENERATOR (F-S TEG) USING DIFFERENT ELECTRODES AND TRIBOELECTRIC LAYERS

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ABSTRACT
Triboelectric Generators (TEGs) and Nano-generators represent promising alternatives in the realm of energy gathering technologies. TEGs have the ability of energy conversion from diverse sources such as human motion, water flow, and wind waves into electrical energy by leveraging the triboelectric effect. The functionality of TEGs/TENGs relies on the synergy of triboelectric charges and electrostatic induction, allowing them to generate both output voltage and current. These innovative devices have garnered substantial attention due to their potential applications in wearable electronics, self-powered sensors, and portable devices. TEGs/TENGs boast several advantages over traditional energy harvesting technologies, including high efficiency, cost-effectiveness, and flexibility. Ongoing research in this field is dedicated to enhancing their performance, reliability, and scalability, with the goal of seamless integration into various applications. The present study delves into the impact of triboelectric layer materials and electrode materials on the performance of free-standing triboelectric generators under different conditions. The investigation involved three types of electrode layers (Aluminium, copper, and graphite) paired with four types of triboelectric layers (PP, PVC, PTFE, and Kapton) to assess the efficacy of the proposed Free-Standing TEGs (F-S TEGs). The findings reveal that the use of aluminium or graphite electrodes can significantly enhance the triboelectric performance of free-standing triboelectric generators comprising Kapton, PTFE, PP, or PVC triboelectric layers.

KEYWORDS
Triboelectrification, electrode layers, triboelectric materials, free-standing triboelectric generator (FS-TEG).

INTRODUCTION
The triboelectric effect, an ancient and pervasive phenomenon dating back over 2600 years to ancient Greek civilization, is an ever-present occurrence in our daily lives, unfolding at any time and in any place. Despite its universal nature, this phenomenon has long been viewed as an unfavourable outcome, prompting a reconsideration of production methods and individual daily routines. In a transformative breakthrough in 2012, the triboelectric nanogenerator was introduced as a useful technology for energy harvesting and self-charged devices. [1] TENG exhibits the ability to convert irregular, distributed, and otherwise wasted mechanical energy into electric power through the synergistic interplay of contact electrification (CE) and electrostatic induction. This technology offers numerous advantages, including less expensive, a straightforward structure,

lightweight design, extra efficiency, and a wide range of engineering materials. Current research endeavours are concentrated on further improving the efficiency of TENG, with a persistent emphasis on mitigating its high impedance [2, 3]. To improve the output charge, a common approach involves modifying the shape of the Triboelectric Generator's (TEG) electrification surface layer. This method is employed to optimize the efficiency of the generator and improve its overall performance [4-9]. Research efforts are underway to explore mixed energy harvesters, includes triboelectric, electromagnetic, and piezoelectric-triboelectric nanogenerators [10-16]. TEG innovation has resulted in a wide range of applications, from energy-harvesting textiles [17, 18] and sensors [19, 20] to biological monitoring [18, 21]. Contact electrification can occur between insulators [1, 22], conductor and non-conductor [22, 23], and two conductors [24] in four types of rubbing mechanisms, contact – separation mode [25-27], sliding laterally mode [3, 28], single electrode [29, 30], as well as the mode of free-standing mechanism [31, 32]. By means of vertical contact-separation mode, the energy of mechanical motion converted into electricity through the repeated touching and releasing of the triboelectric layers with the presence of an external applied load. While lateral sliding rubbing mechanism generates an electrical energy through the rubbing layers of Triboelectric Generator. For mode of single-electrode mechanism it involves a substance in vertically connection with an electrode layer. Free-standing triboelectric generator (F-S TEG) exclusively working under sliding principle. The phenomenon of electrification involving similar materials has been studied and modeled by Apodaca et al. [30, 33-34], with a focus on the charge transfer on the atomic level of individual atoms. Henry et al. [35] have argued that there are heat generation related to the transfer of charges during asymmetrical rubbing. In contrast, Lowell et al. [36] have supported an explanation of asymmetrical rubbing that does not involve heat generation. Hu et al. [33] validated the idea of Lowell by reporting the output power for similar inorganic materials, incorporating surface modification to alter surface roughness.

Current research paper is concerned with designing and evaluating of triboelectric generator based on free-standing mode. The aim is to increase the generated voltage from daily small-scale motions. This approach opens avenues for further advancements in harvesting energy by means of triboelectric technology and its practical applications.

EXPERIMENTAL WORK

Free-Standing Triboelectric-Layer Mode.

The triboelectric generator of free-standing mode (F-S TEG) recently shows significant advantages, particularly in terms of wide range applications for gathering energy from moving objects or human motion or walking without the need for more electrodes. This mode stands out due to its ultra-robust nature and high energy conversion efficiency [37-39]. In this mode of operation, the generation of electricity relies on the relative positional changes of the charged layers between the electrodes, leading to a repeated alteration of the potential difference. The Triboelectric Generator (TEG) structure consist of a free-standing dielectric layer and two metal films, with these films serving dual roles as the triboelectric material and functioning as the two electrodes.

Construction and Testing of Free-Standing Triboelectric Generator.

To evaluate the proposed Free-Standing Triboelectric Generator (F-S TEG); test specimens were designed in form of rectangular layers with (10mm length x5mm width x0.5mm thickness). Each layer of the F-S TEG adhered to an electrode film, responsible for collecting and transferring electrons which generated from the rubbing of

triboelectric layers. The test samples incorporate three types of electrodes: Aluminium, copper, and graphite, alongside four types of triboelectric layers: Polypropylene (PP), Polyvinylchloride (PVC), Teflon (PTFE), and Kapton. Figure 1 illustrates a triboelectric generator based on the free-standing mode. 2mm separating distance between the layers has been maintained, facilitating the transfer of electrons generated from the rubbing action between different materials to move from one electrode to another. The current design of the F-S TEG aims to examine the impact of electrode and non-conductor layers on the output voltage of the proposed generator under specific conditions, including a constant reciprocating speed of 1 mm/sec and a contact pressure of 2 N/mm^2 for a duration of 60 seconds.

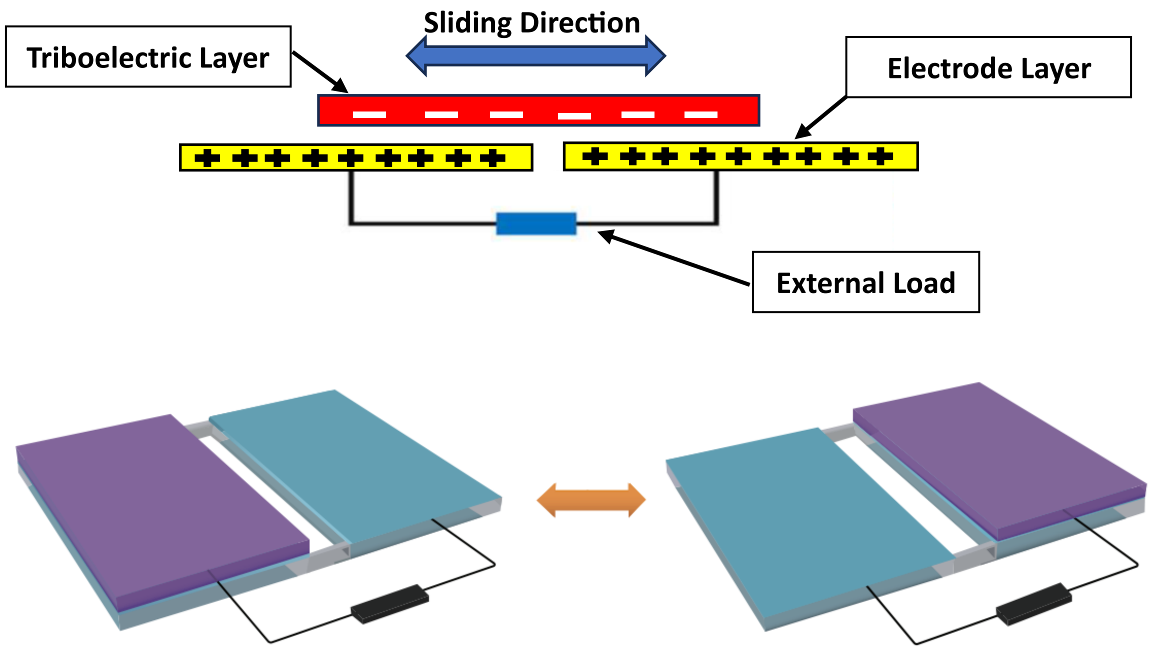


Fig. 1. Triboelectric generator based on free-standing mode and its operating principle.

RESULTS AND DISCUSSION

After the construction of free-standing triboelectric generators from different types of electrodes and polymeric layers and connecting the external load, the triboelectric layer for each type of TEG moving reciprocally from an electrode to the other and vice versa at a constant speed and contact load for 60 seconds and recording the output voltage using ultra-stable voltmeter then the results plotted against the time.

Triboelectric performance of F-S TEG using an electrode of aluminum film.

The following results show the effect of using aluminum electrodes on the triboelectric performance of triboelectric generators that consist of Kapton, PTFE, PP, or PVC based on free-standing mode. Figs. 2, and 3 show the effect of using PP or PVC plates as triboelectric layers moving on aluminum film on the generated voltage, as shown in Fig.2 the generated voltage increases for TEG consisting of the PP layer, reached 4 V after 8 sec. of sliding, also; for F-S TEG consisting of PVC, the output voltage increased with time to 2V. Figure 4 shows that using of PTFE layer slightly increases the output voltage for TEG to 2.3 V after 28 sec of repeated sliding on the aluminum electrode; while using Kapton film, Fig. 5, increases the voltage to 1.8 V after 20 sec. It seems that the combination of PP and aluminum leads to a high electrostatic charge that is collected using aluminum electrodes and then transferred through the external load. The previous results recommended the aluminum electrode with a Polypropylene triboelectric layer as a promising F-S TEG for energy harvesting applications.

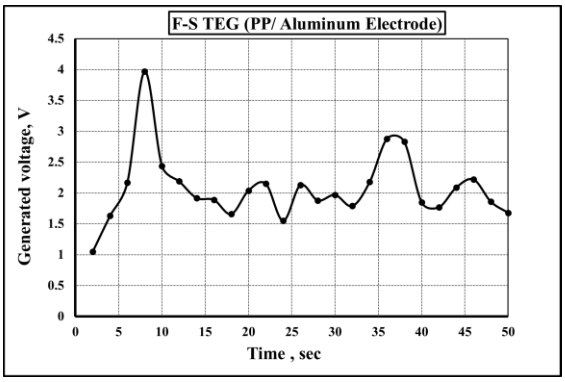


Fig. 2 Output voltage of TEG using Aluminium electrode on PP dielectric layers.

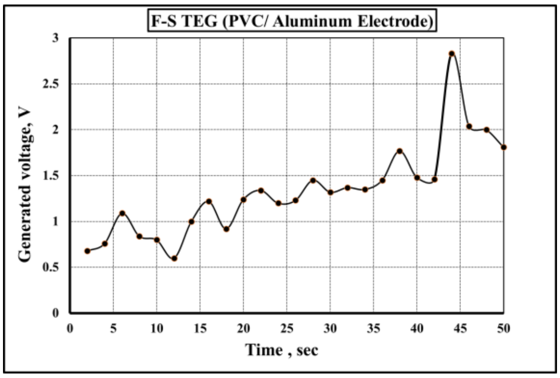


Fig. 3 Output voltage of TEG using Aluminium electrode on PVC dielectric layers.

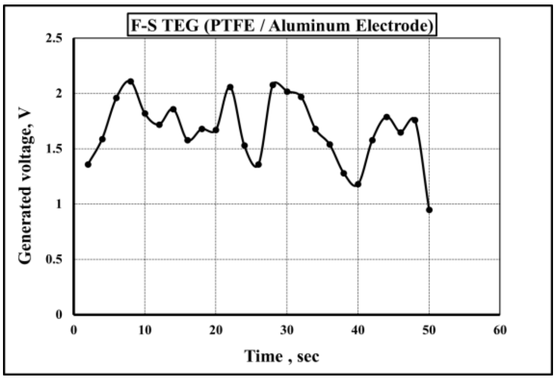


Fig. 4 Output voltage of TEG using Aluminium electrode on PTFE dielectric layers.

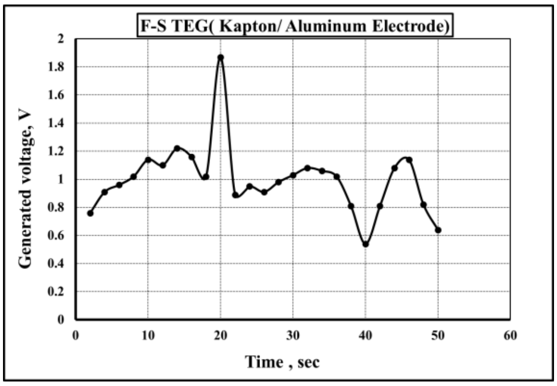
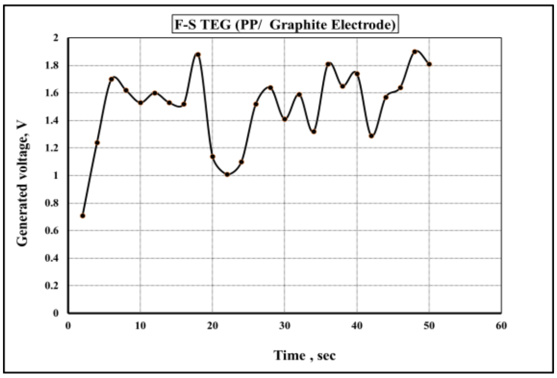


Fig. 5 Output voltage of TEG using Aluminum electrode on Kapton layers.

Triboelectric performance of F-S TEG using an electrode of graphite film.

Figures 6-9 shows the effect of using graphite electrodes on the output electricity from F-S TEG. It is noticed that the triboelectric layers of PVC – fig. 7- continually increase the output voltage to more than 3V after 22 sec. of sliding; while using (PP) increases the voltage slightly to 1.8V with increases of contact time to 50 sec. Free-standing TEG based on using Kapton film as triboelectric layer sliding on graphite electrode Fig. 8 shows remarkable improvement in the produced energy compared with TEG which consists of a PTFE layer sliding on the same electrode, the output voltage for Kapton F-S TEG sliding on graphite reached 2.5 V but; for PTFE layer the output voltage slightly increases to 1.9 V after 50 sec. as shown in fig.9. Among the proposed four types of triboelectric layers; PP and Kapton films show better results on graphite electrode layers.



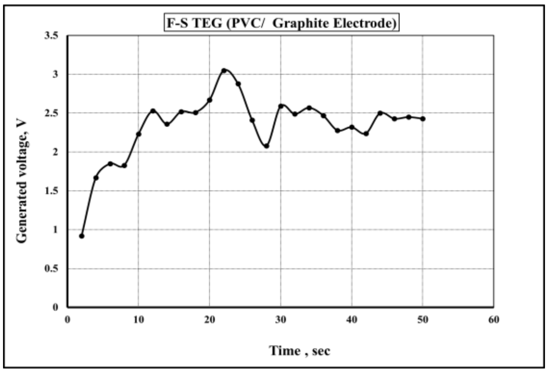
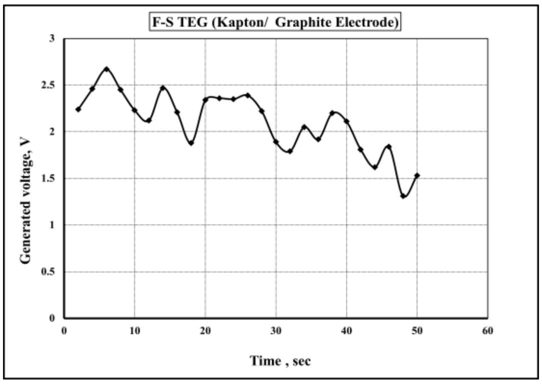


Fig. 6 Output voltage of TEG using Graphite electrode on PP dielectric layers.

Fig. 7 Output voltage of TEG using Graphite electrode on PVC dielectric layers.



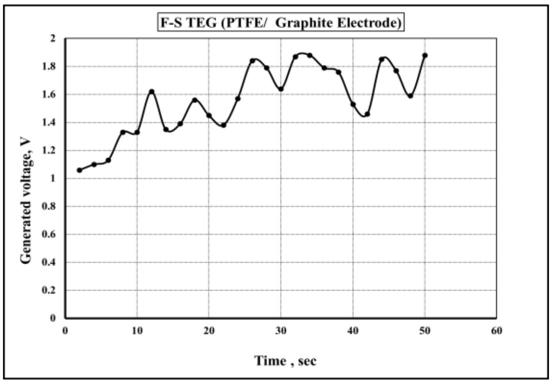
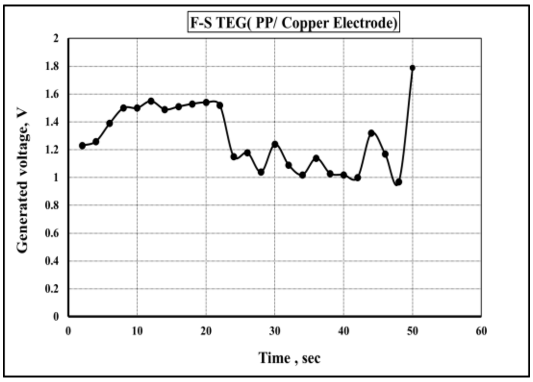


Fig. 8 Output voltage of TEG using Graphite electrode on Kapton dielectric layers.

Fig. 9 Output voltage of TEG using Graphite electrode on PTFE dielectric layers.



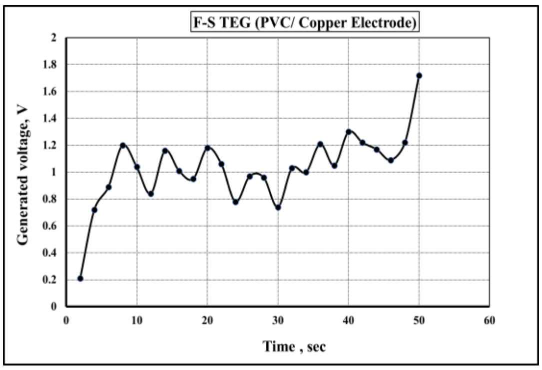
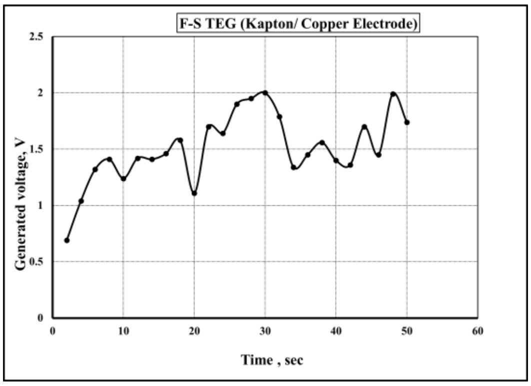


Fig. 10 Output voltage of TEG using Copper electrode on PP dielectric layers.

Fig. 11 Output voltage of TEG using Copper electrode on PVC dielectric layers.

Triboelectric performance of F-S TEG using an electrode of copper film.

Figure 10 -13 shows the effect of using copper electrodes for free-standing triboelectric generators. Triboelectric generators that consist of PP or Kapton layers show high output voltage of 1.8 V and 2 V respectively, while using PVC or PTFE increases the voltage to 1.6 V and 1.7 V respectively. In general, it seems that the aluminum or graphite electrodes help in rapidly collecting and transferring the generated charges more than copper film for all types of the proposed triboelectric layers.



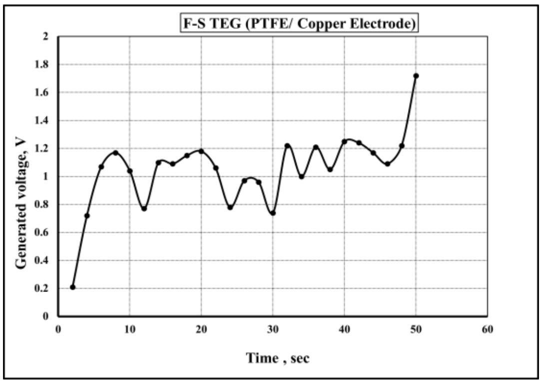


Fig. 12 Output voltage of TEG using Copper electrode on Kapton dielectric layers.

Fig. 13 Output voltage of TEG using Copper electrode on PTFE dielectric layers.

CONCLUSIONS

From the results of the experimental, it can be concluded that:

1- Using aluminium or graphite electrodes can enhance the triboelectric performance of free-standing triboelectric generators that consist of Kapton, PTFE, PP, or PVC triboelectric layers.

2- F-S TEG composed of PP layers sliding on aluminum electrodes shows the highest output voltage among the four types of triboelectric layers.

3- PTFE, Kapton, and PVC show good results in generated voltage by sliding on aluminum or graphite electrodes.

4- Copper electrodes show low output voltage for the proposed Free Standing Triboelectric generators with all types of polymeric triboelectric layers.

5- Based on this work it could be recommended to use F-S TEG consisting of PP and Aluminum electrodes for good energy harvesting applications.

REFERENCES

1- Fan, F.-R., Tian, Z.-Q., Wang, Z.L., “Flexible triboelectric generator”, Nano Energy. 1, pp. 328–334 (2012). https://doi.org/10.1016/j.nanoen.2012.01.004

2- Zhu, Y., Yang, B., Liu, J., Wang, X., Wang, L., Chen, X., Yang, C., "A flexible and biocompatible triboelectric nanogenerator with tunable internal resistance for powering wearable devices", Sci. Rep. 6, 22233 pp.1-10 (2016).
https://doi.org/10.1038/srep22233

3- Zhu, G., Chen, J., Liu, Y., Bai, P., Zhou, Y.S., Jing, Q., Pan, C., Wang, Z.L., "Linear-Grating Triboelectric Generator based on sliding Electrification. Nano Lett. 13, pp.2282–2289 (2013). https://doi.org/10.1021/nl4008985

4- Shin, S.-Y., Saravanakumar, B., Ramadoss, A., and Kim, S. J., "Fabrication of PDMS-based triboelectric nanogenerator for self-sustained power source application. Int. J. Energy Res., 40 pp.288–297. (2016)
https://doi.org/10.1002/er.3376

5- Yu, Y., Wang, X., "Chemical modification of polymer surfaces for advanced triboelectric nanogenerator development", Extreme Mech. Lett. 9, pp.514–530 (2016). https://doi.org/10.1016/j.eml.2016.02.019

6- Zheng, Y., Cheng, L., Yuan, M., Wang, Z., Zhang, L., Qin, Y., Jing, T., "An electrospun nanowire-based triboelectric nanogenerator and its application in a fully self-powered UV detector", Nanoscale. 6, pp.7842–7846 (2014). https://doi.org/10.1039/C4NR01934B

7- Wang, S., Lin, L., Wang, Z.L., "Nanoscale triboelectric-effectenabled energy conversion for sustainably powering portable electronics", Nano Lett. 12, pp.6339–6346 (2012).
https://doi.org/10.1021/nl303573d

8- Zhu, G., Zhou, Y.S., Bai, P., Meng, X.S., Jing, Q., Chen, J., Wang, Z.L., "A shape-adaptive Thin-Film-Based Approach for 50% highefficiency Energy Generation through Micro-grating Sliding Electrification", Adv. Mater. 26, pp.3788–3796 (2014). https://doi.org/10.1002/adma.201400021

9- Zhong, J., Zhong, Q., Fan, F., Zhang, Y., Wang, S., Hu, B., Wang, Z.L., Zhou, J., "Finger typing driven triboelectric nanogenerator and its use for instantaneously lighting up LEDs", Nano Energy. 2, pp.491–497 (2013). https://doi.org/10.1016/j.nanoen.2012.11.015

10- Wang, X., Yang, Y. "Effective energy storage from a hybridized electromagnetic triboelectric nanogenerator", Nano Energy. 32, pp. 36–41 (2017). https://doi.org/10.1016/j.nanoen.2016.12.006

11- Wang, X., Yang, B., Liu, J., Zhu, Y., Yang, C., He, Q., "A flexible triboelectric-piezoelectric hybrid nanogenerator based on P(VDFTrFE) nanofibers and PDMS/MWCNT for wearable devices", Sci. Rep. 6, 36409 pp. 1-10, (2016). https://doi.org/10.1038/srep36409

12- Xue, C., Li, J., Zhang, Q., Zhang, Z., Hai, Z., Gao, L., Feng, R., Tang, J., Liu, J., Zhang, W., Sun, D., "A Novel Arch-shape Nanogenerator based on piezoelectric and Triboelectric Mechanism for Mechanical Energy Harvesting", Nanomaterials. 5, pp.36–46 (2015).
https://doi.org/10.3390/nano5010036

13- Jung, W.-S., Kang, M.-G., Moon, H.G., Baek, S.-H., Yoon, S.-J., Wang, Z., Kim, S.-W., Kang, C.-Y., "High output piezo/triboelectric hybrid generator", Sci. Rep. 5, 9309 pp. 1-6, (2015).
https://doi.org/10.1038/srep09309

14- Huang, L., Bai, G., Wong, M.-C., Yang, Z., Xu, W., Hao, J., "Magnetic-assisted noncontact triboelectric nanogenerator converting mechanical energy into electricity and light emissions", Adv. Mater. (Deerfield Beach Fla). 28 pp. 2744-2751, (2016). https://doi.org/10.1002/adma.201505839

15- Han M., Chen X., Yu B., Zhang H., "Coupling of Piezoelectric and Triboelectric Effects: from Theoretical Analysis to Experimental Verification", Adv. Electron. Mater., 1, 1500187. Pp. 1-6 (2015)
https://doi: 10.1002/aelm.201500187
16- Chen, X., Han, M., Chen, H., Cheng, X., Song, Y., Su, Z., Jiang, Y., Zhang, H. "A wave-shaped hybrid piezoelectric and triboelectric nanogenerator based on P(VDF-TrFE) nanofibers", Nanoscale. 9, pp. 1263–1270 (2017). https://doi.org/10.1039/C6NR07781A
17- Zhu, M., Huang, Y., Ng, W.S., Liu, J., Wang, Z., Wang, Z., Hu, H., Zhi, C. "3D spacer fabric based multifunctional triboelectric nanogenerator with great feasibility for mechanized largescale production", Nano Energy. 27, pp. 439–446 (2016). https://doi.org/10.1016/j.nanoen.2016.07.016
18- Zhao, Z., Yan, C., Liu, Z., Fu, X., Peng, L.-M., Hu, Y., Zheng, Z., "Wearable Technology: Machine-washable Textile Triboelectric Nanogenerators for Effective Human respiratory monitoring through Loom weaving of metallic yarns" Adv. Mater. 28, pp.10266–10276 (2016).
https://doi.org/10.1002/adma.201670325
19- Fan, F.-R., Lin, L., Zhu, G., Wu, W., Zhang, R., Wang, Z.L., "Transparent triboelectric nanogenerators and self-powered pressure sensors based on micropatterned plastic films" Nano Lett. 12, pp.3109–3114 (2012).
https://doi.org/10.1021/nl300988z
20- Chen, J., Zhu, G., Yang, W., Jing, Q., Bai, P., Yang, Y., Hou, T.-C., Wang, Z.L., "Harmonic-resonator-based triboelectric nanogenerator as a sustainable power source and a self powered active vibration sensor" Adv. Mater. 25, pp. 6094–6099 (2013).
https://doi.org/10.1002/adma.201302397
21- Lai, Y.-C., Deng, J., Zhang, S., Niu, S., Guo, H., Wang, Z., "Singlethread-based wearable and highly stretchable Triboelectric Nanogenerators and their applications in Cloth-based self-powered human-interactive and Biomedical Sensing" Adv. Funct. Mater. 27, pp. 1-8 (2016).
https://doi.org/10.1002/adfm.201604462
22- Liang, Q., Zhang, Z., Yan, X., Gu, Y., Zhao, Y., Zhang, G., Lu, S., Liao, Q., Zhang, Y., "Functional triboelectric generator as self-powered vibration sensor with contact mode and non-contact mode" Nano Energy. 14, pp.209–216 (2015). https://doi.org/10.1016/j.nanoen.2014.07.010
23- Kim, W., Hwang, H.J., Bhatia, D., Lee, Y., Baik, J.M., Choi, D., "Kinematic design for high-performance triboelectric nanogenerators with enhanced working frequency" Nano Energy. 21, pp. 19–25 (2016).
https://doi.org/10.1016/j.nanoen.2015.12.017
24- Zhang, A., Liu, W., Zhang, Y. "On the mechanism and optimization of triboelectric nanogenerators" Nanotechnology. v.26, no. 42 pp.1-7 (2015).
https://doi.org/10.1088/0957-4484/26/42/425401
25- Soin, N., Zhao, P., Prashanthi, K., Chen, J., Ding, P., Zhou, E., Shah, T., Ray, S.C., Tsonos, C., Thundat, T., Siores, E., Luo, J., "High-performance triboelectric nanogenerators based on phase-inversion piezoelectric membranes of poly(vinylidene fluoride)-zinc stannate (PVDF ZnSnO3) and polyamide-6 (PA6)" Nano Energy. 30, pp. 470–480 (2016).
https://doi.org/10.1016/j.nanoen.2016.10.040
26- Zhu, G., Pan, C., Guo, W., Chen, C.-Y., Zhou, Y., Yu, R., Wang, Z.L., "Triboelectric-generator-driven pulse Electrodeposition for Micropatterning" Nano Lett. 12, pp. 4960–4965 (2012).

https://doi.org/10.1021/nl302560k
27- Zhu, G., Lin, Z.-H., Jing, Q., Bai, P., Pan, C., Yang, Y., Zhou, Y., Wang, Z.L., “Toward large-Scale Energy Harvesting by a nanoparticle-enhanced Triboelectric Nanogenerator”, Nano Lett. 13, pp. 847–853 (2013). https://doi.org/10.1021/nl4001053
28- Wang, S., Lin, L., Xie, Y., Jing, Q., Niu, S., Wang, Z.L. “Sliding triboelectric nanogenerators based on in-plane charge-separation mechanism” Nano Lett. 13, pp. 2226–2233 (2013).
https://doi.org/10.1021/nl400738p
29- Kaur, N., Bahadur, J., Panwar, V., Singh, P., Rathi, K., Pal, K., “Effective energy harvesting from a single electrode based triboelectric nanogenerator”, Sci. Rep. 6, 38835 pp.1-9 (2016).
https://doi.org/10.1038/srep38835
30- Yang, Y., Zhang, H., Chen, J., Jing, Q., Zhou, Y.S., Wen, X., Wang, Z.L., “Single-electrode-based sliding triboelectric nanogenerator for self-powered displacement vector sensor system,” ACS Nano. 7, pp. 7342–7351 (2013). https://doi.org/10.1021/nn403021m
31- Wang, S., Xie, Y., Niu, S., Lin, L., Liu, C., Zhou, Y.S., Wang, Z.L., “Maximum Surface Charge Density for Triboelectric Nanogenerators Achieved by Ionized-Air Injection: Methodology and theoretical understanding”, Adv. Mater. 26, pp.6720–6728 (2014). https://doi.org/10.1002/adma.201402491
32- Niu, S., Liu, Y., Chen, X., Wang, S., Zhou, Y.S., Lin, L., Xie, Y., Wang, Z.L., “Theory of freestanding triboelectric-layer-based nanogenerators”, Nano Energy. 12, pp.760–774 (2015).
https://doi.org/10.1016/j.nanoen.2015.01.013
33- Hu, W., Wu, W., Zhou, H., “Wind-blown sand electrification inspired Triboelectric Energy Harvesting based on homogeneous inorganic materials contact: A theoretical study and prediction”, Sci. Rep. 6, 19912 pp. 1-9 (2016).
https://doi.org/10.1038/srep19912
34- Apodaca, M.M., Wesson, P.J., Bishop, K.J.M., Ratner, M.A., Grzybowski, B.A., “Contact electrification between identical materials” Angew. Chem. Int. Ed. 49, pp. 946–949 (2010).
https://doi.org/10.1002/anie.200905281
35- Honegger, E., Henry, P.S.H., “Generation of Static on Solid Insulators” Journal of the Textile Institute Proceedings 48, no.1 pp. 5–25. (2009). https://doi.org/10.1080/19447015708688112
36- Lowell, J., Truscott, W., “Triboelectrification of identical insulators. II. Theory and further experiments” J. Phys. D. 19, p.1281(1986).
https://doi.org/10.1088/0022-3727/19/7/018
37- Wang S., Y. Xie, S. Niu, L. Lin, and Z. L. Wang, “Freestanding triboelectric-layer-based nanogenerators for harvesting energy from a moving object or human motion in contact and noncontact modes,” Advanced Materials, vol. 26, no. 18, pp. 2818– 2824, (2014).
38- Guo H., J. Chen, M. H. Yeh et al., “An ultra-robust high-performance triboelectric nanogenerator based on charge replenishment,” ACS Nano, vol. 9, no. 5, pp. 5577–5584, (2015)
39- Lin, Zhiming & Yang, Jin., “Recent Progress in Triboelectric Nanogenerators as a Renewable and Sustainable Power Source”, Journal of Nanomaterials. pp. 1-24. (2016).