

**DEVELOPMENT OF DUAL  
PIEZOELECTRIC/TRIBOELECTRIC NANOCOMPOSITES  
FOR SENSING AND ENERGY HARVESTING  
APPLICATIONS**

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**DEPARTMENT OF ELECTRICAL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY DELHI  
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FOR SENSING AND ENERGY HARVESTING  
APPLICATIONS

by

NADEEM TARIQ BEIGH

DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

In fulfilment of the requirements of the degree of Doctor of Philosophy

to the



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# THESIS CERTIFICATE

This is to certify that the thesis titled **Development of Dual Piezoelectric/Triboelectric Nanocomposites for Sensing And Energy Harvesting Applications**, submitted by **Nadeem Tariq Beigh(2018EEZ8567)**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy(Ph.D.)**, is a bonafide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dhiman Mallick

**Prof. Dhiman Mallick**

Department of Electrical Engineering,  
Indian Institute of Technology Delhi.

Place: New Delhi

Date: March 11, 2024

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*"Allah will raise in rank those of you who have faith and those who have been given knowledge"*  
(Holy Quran 58:11)

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## ABSTRACT

**KEYWORDS:** Piezoelectric Energy Harvesters/Sensors, Triboelectric Energy Harvesters/Sensors, Photopatternable Nanocomposites, Self-Powered Sensing, Hybrid Energy Harvesters/Sensors, Machine learning

The dawn of the Internet of Things (IoT) represents a monumental shift in the way we connect and interact with devices and the environment around us. One pivotal factor in the rapid growth of IoT is the significant contribution of low-power electronics. These energy-efficient components enable the deployment of IoT devices that can operate on minimal power resources, enhancing their reliability and scalability. As a result, IoT applications have flourished across various sectors, from smart homes and cities to industrial automation and healthcare, ushering in a new era of connectivity and data-driven insights that continue to reshape our world. However, the surge in IoT nodes has exponentially increased the number of wireless, remotely placed "IoT nodes" that should operate independently with minimal maintenance. The dependence on batteries is not feasible for the predicted growth of IoT technologies as it limits its multi-domain expansion. Since sensors are a vital component of IoT node, transforming the passive-energy consuming sensors into active-self powered sensors(or harvesters) provides a suitable solution and creates a transformative shift towards a greener world. Tapping the "always available" mechanical energy in the form of biomechanical and ambient vibrations opens up new avenues for self-powered sensing. The low-frequency ( $< 200$  Hz) vibrational energy can be efficiently harvested using a flexible piezoelectric, and triboelectric harvesters built from a diverse set of materials, including polymer nanocomposites and nano-filler combinations.

The majority of the published research on piezoelectric or triboelectric harvesters discusses the methodologies that are CMOS incompatible, expensive, complex, single transduction, and restricted to a small area harvesting/sensing. However, there are no reported studies on the development of novel material and their optimization as a CMOS compatible, simple, low-cost, dual transduction, and large area harvester/sensor that is suitable for self-powered IoT nodes. This thesis explores a series of research works associated with dual transduction nanocomposites and their process optimization to develop energy harvesters/sensors for extracting ambient and biomechanical energy. This thesis uncovers the possibility of dual transduction in photopatternable and non-photopatternable nanocomposites with applications in energy harvesting, impact loss compensation, machine learning integrated sensors, etc.

This thesis reports the following significant findings:

1. The optimization of photopatternability and piezoelectricity in %weight ratio varying

ZnO/SU-8 and BTO/SU-8 nanocomposites. The thesis uncovers the optimum weight ratio value of 15% and 20% for ZnO/SU-8 and BTO/SU-8 nanocomposites, respectively. At these values, they show optimum results with good piezoelectric response and UV transmittance, allowing reliable lithography of the nanocomposites. This optimization allows the development of flexible biomechanical energy harvesters with output power of  $223\mu W$  and  $642\mu W$  for ZnO/SU-8 and BTO/SU-8, respectively.

2. The exploration of inherent triboelectric nature of BTO/SU-8 nanocomposites and the effect of %weight ratio on its triboelectric transduction. The performance enhancement techniques on the form of UV exposure and graphene doping are also presented. The 1% graphene doped 20% BTO/SU-8 shows a high triboelectric shift with a charge retention measure of 85mV that enables the design of a dual transduction energy harvester with an power density of  $0.65\mu W cm^{-2}$  at 0.75g acceleration amplitude.
3. The development of a novel pixelated tactile pressure sensor with dual transduction capabilities using the optimized 20% BTO/SU-8 composites as the active layer. The sensor shows a sensitivity of  $34 mV kPa^{-1}$  for deep linear region and  $2.7 mV kPa^{-1}$  for the linear region over a pressure range of 0–170 kPa. The sensor shows a negligible hysteresis with an average deviation of 2.7%. A sensor-ML integration is also presented that allows effective utilization of this sensor for hind foot deformity detection, activity monitoring and grip strength assessment with 98.5%, 98.3% and 93.75% model accuracy, respectively.
4. The concept of dual transduction in a single thin film is presented as a possible solution to impact losses in impact driven piezoelectric energy harvesters. The proposed impact driven energy harvesters is capable of compensating impact-induced energy loss by a 100% power integral recovery at  $< 1.5g$  acceleration amplitude by suitably designing the device that incorporates a dual piezoelectric/triboelectric transduction-based nanocomposite as the active layer. This hybrid design demonstrates 3.3 times power gain and the bandwidth broadening of  $5.4Hz$  at  $1g$ .
5. The exploration of dual transduction in BTO/P(VDF-TrFE) and the effect of %weight ratio on the  $\beta$ -phase as well as triboelectric shift. 15% weight ratio of BTO in 20%P(VDF-TrFE) nanocomposites film shows the highest piezoelectric co-efficient of 0.58nm/V. The addition of BTO in 20% P(VDF-TrFE) results in a triboelectric shift from a tribonegative to tribopositive nanocomposite. The surface potential shifts from -382.5mV to 495 mV in 20% P(VDF-TrFE) and 15% BTO/20% P(VDF-TrFE). The charge retention metric  $\Delta V_{200}$  also decreases from 150mV to 60mV in 20% P(VDF-TrFE) and 15% BTO/20% P(VDF-TrFE), indicating the improvement in charge retention in 15% BTO/20% P(VDF-TrFE).

## सार

**कीवर्ड:** पीजोइलेक्ट्रिक एनर्जी हार्वेस्टर/सेंसर, ट्राइबोइलेक्ट्रिक एनर्जी हार्वेस्टर/सेंसर, फोटोपैटर्नबल नैनोकम्पोजिट, स्व-संचालित सेंसिंग, हाइब्रिड ऊर्जा हार्वेस्टर/सेंसर, मशीन लर्निंग

इंटरनेट ऑफ थिंग्स (IoT) की शुरुआत हमारे उपकरणों और हमारे आस-पास के वातावरण से जुड़ने और बातचीत करने के तरीके में एक महत्वपूर्ण बदलाव का प्रतिनिधित्व करती है। IoT की तीव्र वृद्धि में एक महत्वपूर्ण कारक कम-शक्ति वाले इलेक्ट्रॉनिक्स का महत्वपूर्ण योगदान है। ये ऊर्जा-कुशल घटक IoT उपकरणों की तैनाती को सक्षम करते हैं जो न्यूनतम बिजली संसाधनों पर काम कर सकते हैं, जिससे उनकी विश्वसनीयता और स्केलेबिलिटी बढ़ जाती है। परिणामस्वरूप, IoT एप्लिकेशन स्मार्ट घरों और शहरों से लेकर औद्योगिक स्वचालन और स्वास्थ्य देखभाल तक विभिन्न क्षेत्रों में फले-फूले हैं, जिससे कनेक्टिविटी और डेटा-संचालित अंतर्दृष्टि के एक नए युग की शुरुआत हुई है जो हमारी दुनिया को नया आकार देना जारी रखता है। हालाँकि, IoT नोड्स में वृद्धि ने वायरलेस, दूर से रखे गए "IoT नोड्स" की संख्या में तेजी से वृद्धि की है, जिन्हें न्यूनतम रखरखाव के साथ स्वतंत्र रूप से काम करना चाहिए। IoT प्रौद्योगिकियों की अनुमानित वृद्धि के लिए बैटरियों पर निर्भरता संभव नहीं है क्योंकि यह इसके बहु-डोमेन विस्तार को सीमित करती है। चूंकि सेंसर IoT नोड का एक महत्वपूर्ण घटक हैं, इसलिए निष्क्रिय-ऊर्जा खपत करने वाले सेंसर को सक्रिय-स्वयं संचालित सेंसर (या हार्वेस्टर) में बदलना एक उपयुक्त समाधान प्रदान करता है और एक हरित दुनिया की ओर एक परिवर्तनकारी बदलाव पैदा करता है। बायोमैकेनिकल और परिवेशीय कंपन के रूप में "हमेशा उपलब्ध" यांत्रिक ऊर्जा का दोहन स्व-संचालित संवेदन के लिए नए रास्ते खोलता है। कम-आवृत्ति (<200 हर्ट्ज) कंपन ऊर्जा को लचीले पीजोइलेक्ट्रिक और पॉलिमर नैनोकम्पोजिट्स और नैनो-फिलर संयोजनों सहित सामग्रियों के विविध सेट से निर्मित ट्राइबोइलेक्ट्रिक हार्वेस्टर का उपयोग करके कुशलतापूर्वक काटा जा सकता है।

पीजोइलेक्ट्रिक या ट्राइबोइलेक्ट्रिक हार्वेस्टर पर अधिकांश प्रकाशित शोध उन पद्धतियों पर चर्चा करते हैं जो सीएमओएस असंगत, महंगी, जटिल, एकल ट्रांसडक्शन और एक छोटे क्षेत्र में कटाई/संवेदन तक सीमित हैं। हालाँकि, नई सामग्री के विकास और सीएमओएस संगत, सरल, कम लागत, दोहरे ट्रांसडक्शन और बड़े क्षेत्र हार्वेस्टर/सेंसर के रूप में उनके अनुकूलन पर कोई रिपोर्ट नहीं की गई है जो स्व-संचालित आईओटी नोड्स के लिए उपयुक्त है। यह थीसिस परिवेश और बायोमैकेनिकल ऊर्जा निकालने के लिए ऊर्जा हार्वेस्टर/सेंसर विकसित करने के लिए दोहरे ट्रांसडक्शन नैनोकम्पोजिट और उनकी प्रक्रिया अनुकूलन से जुड़े शोध कार्यों की एक श्रृंखला की पड़ताल करती है। यह थीसिस ऊर्जा संचयन, प्रभाव हानि क्षतिपूर्ति, मशीन लर्निंग एकीकृत सेंसर आदि में अनुप्रयोगों के साथ फोटोपैटर्नबल और गैर-फोटोपैटर्नबल नैनोकम्पोजिट में दोहरे पारगमन की संभावना को उजागर करती है।

यह थीसिस निम्नलिखित महत्वपूर्ण निष्कर्षों की रिपोर्ट करती है:

- I. %वजन में फोटोपैटर्नबिलिटी और पीजोइलेक्ट्रिसिटी का अनुकूलन ZnO/SU-8 और BTO/SU-8 नैनोकम्पोजिट का अनुपात अलग-अलग है। थीसिस अन- ZnO/SU-8 के लिए 15% और 20% के इष्टतम वजन अनुपात मान को कवर करता है और क्रमशः बीटीओ/एसयू-8 नैनोकम्पोजिट। इन मूल्यों पर, वे दिखाते हैं अच्छी पीजोइलेक्ट्रिक प्रतिक्रिया और यूवी संप्रेषण के साथ इष्टतम परिणाम,

नैनोकम्पोजिट्स की विश्वसनीय लिथोग्राफी की अनुमति देना। यह अनुकूलन लचीले बायोमैकेनिकल ऊर्जा हार्वेस्टर के विकास की अनुमति देता है ZnO/SU-8 और BTO/SU-8 के लिए 223 $\mu$ W और 642 $\mu$ W की आउटपुट पावर.

- II. उन्होंने बीटीओ/एसयू-8 नैनोकॉम की अंतर्निहित ट्राइबोइलेक्ट्रिक प्रकृति की खोज की-सकारात्मकताएं और इसके ट्राइबोइलेक्ट्रिक ट्रांसडक्शन पर% वजन अनुपात का प्रभाव। यूवी एक्सपोजर के रूप में प्रदर्शन बढ़ाने की तकनीकें और ग्राफीन डोपिंग भी प्रस्तुत की जाती है। 1% ग्राफीन को 20% डोप किया गया बीटीओ/एसयू-8 चार्ज प्रतिधारण माप के साथ एक उच्च ट्राइबोइलेक्ट्रिक शिफ्ट दिखाता है 85mV का जो दोहरे पारगमन ऊर्जा हार्वेस्टर के डिज़ाइन को सक्षम बनाता है 0.75g त्वरण आयाम पर 0.65 $\mu$ W/cm<sup>2</sup> की शक्ति घनत्व के साथ।
- III. दोहरे के साथ एक नवीन पिक्सेल युक्त स्पर्श दबाव सेंसर का विकास अनुकूलित 20% बीटीओ/एसयू-8 कंपोजिट का उपयोग करके ट्रांसडक्शन क्षमताएं सक्रिय परत के रूप में. सेंसर 34 mV kPa<sup>-1</sup> की संवेदनशीलता दिखाता है गहरे रैखिक क्षेत्र और दबाव पर रैखिक क्षेत्र के लिए 2.7 mV kPa<sup>-1</sup> 0-170 केपीए की सीमा। सेंसर एक के साथ नगण्य हिस्टैरिसिस दिखाता है 2.7% का औसत विचलन. एक सेंसर-एमएल एकीकरण भी प्रस्तुत किया गया है पिछले पैर की विकृति का पता लगाने के लिए इस सेंसर के प्रभावी उपयोग की अनुमति देता है, 98.5%, 98.3% और के साथ गतिविधि निगरानी और पकड़ शक्ति मूल्यांकन क्रमशः 93.75% मॉडल सटीकता।
- IV. एक पतली फिल्म में दोहरे पारगमन की अवधारणा को इस प्रकार प्रस्तुत किया गया है प्रभाव चालित पीजोइलेक्ट्रिक ऊर्जा हानि में प्रभाव हानि का संभावित समाधान- वेस्टर्स। प्रस्तावित प्रभाव चालित ऊर्जा हार्वेस्टर काम करने में सक्षम है-100% पावर इंटीग्रल रिकवरी द्वारा प्रभाव-प्रेरित ऊर्जा हानि को दंडनीय बनाना डिवाइस को उपयुक्त रूप से डिज़ाइन करके <1.5 ग्राम त्वरण आयाम पर- एक दोहरी पीजोइलेक्ट्रिक/ट्राइबोइलेक्ट्रिक ट्रांसडक्शन-आधारित नैनोकॉम को कॉर्पोरेट करता है- सक्रिय परत के रूप में स्थित। यह हाइब्रिड डिज़ाइन 3.3 गुना शक्ति प्रदर्शित करता है लाभ और बैंडविड्थ 1g पर 5.4Hz का विस्तार।
- V. बीटीओ/पी (वीडीएफ-टीआरएफई) में दोहरे पारगमन की खोज और  $\beta$ -चरण के साथ-साथ ट्राइबोइलेक्ट्रिक शिफ्ट पर% वजन अनुपात का प्रभाव। 15% 20%P(VDF-TrFE) नैनोकम्पोजिट फिल्म में BTO का वजन अनुपात दिखाता है 0.58nm/V का उच्चतम पीजोइलेक्ट्रिक गुणांक। में बीटीओ को शामिल किया गया 20% P(VDF-TrFE) के परिणामस्वरूप ट्राइबोइलेक्ट्रिक शिफ्ट ट्राइबोनगेटिव से होता है ट्राइबोपॉजिटिव नैनोकम्पोजिट। सतह की क्षमता -382.5mV से बदल जाती है 20% P(VDF-TrFE) और 15% BTO/20% P(VDF-TrFE) में 495 mV तक। चार्ज प्रतिधारण मीट्रिक  $\Delta V_{200}$  भी 150mV से घटकर 60mV हो जाता है 20% P(VDF-TrFE) और 15% BTO/20% P(VDF-TrFE) में, जो दर्शाता है 15% BTO/20% P(VDF-TrFE) में चार्ज प्रतिधारण में सुधार।

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## ABBREVIATIONS

|               |                                             |
|---------------|---------------------------------------------|
| <b>MEMS</b>   | Micro Electromechanical Systems             |
| <b>VEH</b>    | Vibrational Energy Harvesting               |
| <b>VEHs</b>   | Vibrational Energy Harvesters               |
| <b>BTO</b>    | Barium Titanate                             |
| <b>FEM</b>    | Finite Element Method                       |
| <b>IoT</b>    | Internet of Things                          |
| <b>AI</b>     | Artificial Intelligence                     |
| <b>ML</b>     | Machine Learning                            |
| <b>TEGs</b>   | Triboelectric Generators                    |
| <b>TENGs</b>  | Triboelectric Nanogenerators                |
| <b>PEGs</b>   | Piezoelectric Generators                    |
| <b>PENGs</b>  | Piezoelectric Nanogenerators                |
| <b>DC</b>     | Direct Current                              |
| <b>DC-TEG</b> | Direct-Current Triboelectric Generator      |
| <b>UV</b>     | Ultra Violet                                |
| <b>PP</b>     | Photo-Patternability                        |
| <b>PET</b>    | Polyethylene Terephthalate                  |
| <b>PDMS</b>   | Polydimethylsiloxane                        |
| <b>CNTs</b>   | Carbon Nanotubes                            |
| <b>PTFE</b>   | Polytetrafluoroethylene                     |
| <b>PVDF</b>   | Polyvinylidene Fluoride                     |
| <b>XRD</b>    | X-ray Diffraction                           |
| <b>SEM</b>    | Scanning Electron Microscopy                |
| <b>FESEM</b>  | Field Emission Scanning Electron Microscopy |
| <b>ZnO</b>    | Zinc Oxide                                  |
| <b>KPFM</b>   | Kelvin Force Probe Microscopy               |
| <b>PFM</b>    | Piezo Force Microscopy                      |
| <b>TrFe</b>   | Trifluoroethylene                           |
| <b>ITO</b>    | Indium Titanium Oxide                       |
| <b>Al</b>     | Aluminium                                   |
| <b>PCB</b>    | Printed Circuit Board                       |
| <b>EMGs</b>   | Electromagnetic Generators                  |
| <b>emf</b>    | Electromotive Force                         |
| <b>MEH</b>    | Mechanical Energy Harvesters                |

|                        |                                              |
|------------------------|----------------------------------------------|
| <b>UV-VIS</b>          | UV-Visible Infrared Spectroscopy             |
| <b>PR</b>              | Piezo-Response                               |
| <b>ADC</b>             | Analog-to-Digital Converter                  |
| <b>MUX</b>             | Multiplexer                                  |
| <b>CNN</b>             | Convolution Neural Network                   |
| <b>PMU</b>             | Power Management Unit                        |
| <b>AFM</b>             | Atomic Force Microscope                      |
| <b>MoS<sub>2</sub></b> | Molybdenum Disulfide                         |
| <b>Cu</b>              | Copper                                       |
| <b>GaN</b>             | Gallium Nitride                              |
| <b>PEH</b>             | Piezoelectric Energy Harvester               |
| <b>2-D</b>             | Two Dimensional                              |
| <b>3-D</b>             | Three Dimensional                            |
| <b>ode</b>             | Ordinary Differential Equations              |
| <b>DSO</b>             | Digital storage oscilloscope                 |
| <b>DCP</b>             | Dickson Charge Pump                          |
| <b>LED</b>             | Light Emitting Diode                         |
| <b>MOS</b>             | Metal Oxide Semiconductor                    |
| <b>RoC</b>             | Region of Compensation                       |
| <b>RoiL</b>            | Region of Impact Loss                        |
| <b>IDEH</b>            | Impact Driven Energy Harvester               |
| <b>H-IDEH</b>          | Hybrid Impact Driven Energy Harvester        |
| <b>P-IDEH</b>          | Piezoelectric Impact Driven Energy Harvester |
| <b>L-PEH</b>           | Linear Piezoelectric Energy Harvester        |
| <b>C-TEH</b>           | Compensating Triboelectric Energy Harvester  |
| <b>SOI</b>             | Silicon on Insulator                         |
| <b>PZT</b>             | Lead Zirconate Titanate                      |
| <b>NW</b>              | Nano Wire                                    |
| <b>NP</b>              | Nano Particle                                |
| <b>NF</b>              | Nano Filler                                  |
| <b>NG</b>              | Nano Generator                               |
| <b>GO</b>              | Graphene Oxide                               |
| <b>rGO</b>             | Reduced Graphene Oxide                       |
| <b>FET</b>             | Field Effect Transistor                      |
| <b>RIE</b>             | Reactive Ion Etching                         |
| <b>ANN</b>             | Artificial Neural Network                    |
| <b>SVM</b>             | Support Vector Machines                      |
| <b>PI</b>              | Power Integral                               |
| <b>IPA</b>             | Isopropyle Alcohol                           |
| <b>DI</b>              | De-Ionised                                   |

---

|                 |                                                 |
|-----------------|-------------------------------------------------|
| <b>EDS</b>      | Energy Dispersive Spectroscopy                  |
| <b>NIR</b>      | Near Infrared                                   |
| <b>ANN</b>      | Artificial Neural Network                       |
| <b>JCPDS</b>    | Joint Committee on Powder Diffraction Standards |
| <b>MFP</b>      | Micro Force Probe                               |
| <b>CMOS</b>     | Complementary Metal-Oxide Semiconductor         |
| <b>M-I-M</b>    | Metal-Insulator-Metal                           |
| <b>NPI</b>      | Nano Platelets                                  |
| <b>PEP</b>      | Piezoelectric Pressure Sensor                   |
| <b>TEP</b>      | Triboelectric Pressure Sensor                   |
| <b>PGT</b>      | Polyethyleneglycol Terephthalate                |
| <b>PTI</b>      | Piezo-Tribo Imparter                            |
| <b>IDC</b>      | Insulation-Displacement Connector               |
| <b>KNN</b>      | K-Nearest Neighbour                             |
| <b>MLP</b>      | Multi-Layer Perceptron Neural Network           |
| <b>RAM</b>      | Random Access Memory                            |
| <b>RMSPro</b>   | Root Mean Squared Propagation                   |
| <b>Q-Factor</b> | Quality Factor                                  |
| <b>FPC</b>      | Flexible Printed Circuit                        |
| <b>NPID</b>     | Normalized Power Integral Density               |
| <b>LTO</b>      | Lithium Tantalate                               |
| <b>LBO</b>      | Lithium Niobate                                 |
| <b>AlN</b>      | Aluminium Nitride                               |
| <b>Mo</b>       | Molybdenum                                      |
| <b>FTIR</b>     | Fourier Transform Infrared Spectroscopy         |
| <b>DMSO</b>     | Dimethyl sulfoxide                              |
| <b>Ag</b>       | Silver                                          |
| <b>Au</b>       | Gold                                            |
| <b>DMF</b>      | Dimethylformamide                               |
| <b>FPGA</b>     | Field Programmable Gate Arrays                  |
| <b>GUI</b>      | Graphical User Interface                        |

# NOTATIONS

|                   |                                           |
|-------------------|-------------------------------------------|
| $V_{surface}$     | Surface potential difference              |
| $Q$               | Charge                                    |
| $d_{ij}$          | Piezoelectric Strain Constant             |
| $\Delta\sigma$    | Applied Stress                            |
| $V$               | Voltage                                   |
| $\epsilon_{ij}^T$ | Permittivity at Constant Stress           |
| $s$               | Strain                                    |
| $T$               | Stress Vector                             |
| $S^E$             | Elastic Compliance                        |
| $D$               | Electrical Displacement                   |
| $E$               | Electrical Field                          |
| $g_{ij}$          | Piezoelectric Voltage Coefficient         |
| $\tan\delta$      | Dissipation or Loss Factor                |
| $Q_m$             | Mechanical Quality Factor                 |
| $k_{ij}$          | Electromechanical Coupling Coefficient    |
| $PD$              | Power Density                             |
| $P_{max}$         | Maximum Power                             |
| $\phi_{Tr}$       | Material Work Function                    |
| $e$               | Electronic Charge                         |
| $V_{OC}$          | Open Circuit Voltage                      |
| $V_{TENG}$        | Triboelectric Voltage                     |
| $C_{TENG}$        | Triboelectric Capacitance                 |
| $V_T$             | Thinner Volume                            |
| $V_{SU8}$         | SU-8 Initial Volume                       |
| $\rho_{SU8}$      | Density of SU-8                           |
| $\rho_T$          | Density of Thinner                        |
| $S_{RI}$          | % Solid content of SU-8                   |
| $S_I$             | % Solid content of Final Solution         |
| $\epsilon_{nc}$   | Permittivity of Nanocomposite             |
| $\epsilon_p$      | Permittivity of Polymer Matrix            |
| $V_f$             | Volume Fraction                           |
| $\Delta V_{200}$  | Change in Triboelectric Surface Potential |
| $\Phi_{SAM}$      | Work Function of Sample                   |
| $\Phi_{AFM}$      | Work Function of AFM                      |
| $J$               | Current Density                           |
| $J_e$             | Externally Generated Current Density      |
| $n \cdot J$       | Surface Normal Current Density            |
| $d$               | Thickness of the Nanocomposite            |
| $F_v$             | Applied Force                             |
| $C$               | Elasticity Tensor                         |

|              |                                         |
|--------------|-----------------------------------------|
| $\rho_v$     | Volumetric Charge Density               |
| $P_{pze}$    | Piezoelectric Polarization              |
| $g_i$        | Triboelectric Air Gap                   |
| $EGND$       | Common Ground Electrode                 |
| $ETRI$       | Triboelectric Electrode                 |
| $EPZI$       | Piezoelectric Electrode                 |
| $NB$         | Naive Bayes Classifier                  |
| $I_{pz}$     | Piezoelectric Current                   |
| $I_{tr}$     | Triboelectric Current                   |
| $I_{hyb}$    | Hybrid Current                          |
| $E_{nc}$     | Electric Field Across the Nanocomposite |
| $A$          | Effective Area of Contact               |
| $q(t)$       | Instantaneous Charge                    |
| $v(t)_{tr}$  | Instantaneous Triboelectric Voltage     |
| $R_t$        | Triboelectric Load Resistance           |
| $\delta$     | Thickness of Nanocomposite              |
| $E_{air}$    | Electric Field Across the Air Gap       |
| $z$          | Cantilever Free End Displacement        |
| $m_{eff}$    | Effective Mass of Cantilever            |
| $k_{eff}$    | Effective Cantilever Stiffness          |
| $c_b$        | Damping Ratio                           |
| $\Delta$     | Initial Triboelectric Gap               |
| $\theta$     | Piezoelectric Coupling Coefficient      |
| $K_{imp}$    | Effective Stiffness of Impact Electrode |
| $c_i$        | Damping Ratio of Impacting Electrode    |
| $C_p$        | Piezoelectric Capacitance               |
| $R_p$        | Piezoelectric Load Resistance           |
| $a$          | Acceleration Amplitude                  |
| $\zeta$      | Damping Coefficient                     |
| $\omega_d$   | Resonant Frequency                      |
| $t_d$        | Time Period of Oscillation              |
| $\alpha^2$   | Electromechanical Coupling Coefficient  |
| $\Delta PI$  | Change in Power Integral                |
| $PI_{CTEH}$  | Power Integral for CTEH                 |
| $PI_{PIDEH}$ | Power Integral for PIDEH                |
| $PI_{LPEH}$  | Power Integral for LPEH                 |
| $PI_{CTEH}$  | Power Integral for CTEH                 |
| $\alpha$     | $\alpha$ -Phase                         |
| $\beta$      | $\beta$ -Phase                          |