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Multiphysics Simulation and Design of a Flexible, Stem-Mounted Hybrid Piezoelectric–Triboelectric Nanogenerator Using COMSOL for Sustainable Energy Harvesting in Smart Agriculture and IoT-Based Plant Monitoring Systems

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ABSTRACT—

The integration of flexible, plant-compatible energy harvesters offers a promising pathway toward sustainable, battery-free agricultural sensing systems. This study presents the conceptual design and COMSOL-based Multiphysics simulation of a stem-mounted hybrid nanogenerator that synergistically combines piezoelectric and triboelectric effects to harvest wind-induced mechanical energy from plant motion. A detailed three-dimensional model was developed, incorporating a PVDF piezoelectric layer, TPU flexible substrate, triboelectric contact interfaces, and a soft adhesive layer to ensure biomechanical compatibility with plant stems. The simulations evaluated structural deformation, stress distribution, and electromechanical energy output under variable wind-loading conditions. Results demonstrate that the system can generate power in the microwatt range, which is sufficient to intermittently drive ultra-low power wireless sensing modules, while ensuring stress remains within physiologically safe limits for plant tissues. This work lays the foundation for the future development of energy-autonomous, minimally invasive agritech platforms that support precision farming and scalable environmental monitoring.

Index Terms—Hybrid nanogenerator, piezoelectric, triboelectric, COMSOL, energy harvesting, smart agriculture, stem mounted, IoT sensors, PVDF, TPU

I. INTRODUCTION

As global agriculture transitions toward data-driven and precision-based practices, the need for intelligent monitoring systems has intensified. Smart agriculture integrates sensors for tracking soil health, moisture levels, pest activity, and environmental conditions in real time, enabling informed decisions that improve yield and reduce resource waste. However, deploying these sensors at scale, especially in remote or large field environments, poses a significant challenge: ensuring a continuous, maintenance-free power supply. Conventional solutions rely on batteries, but these introduce logistical burdens due to limited charge cycles, the necessity for periodic replacement, and ecological concerns arising from disposal [1]. To overcome these limitations, recent research has increasingly focused on ambient energy harvesting, leveraging naturally occurring mechanical, thermal, or solar energy to create self-sustaining sensor nodes. Among these, mechanical energy, particularly from wind-induced plant motion, is ubiquitous in open-field agricultural landscapes and offers an untapped, renewable source of power [2]. This has given rise to nanogenerator-based energy harvesting, where even small deformations from plant stems can be harnessed to generate electricity.

Two primary nanogenerator types dominate this space: Piezoelectric Nanogenerators (PENGs) and Triboelectric Nanogenerators (TENGs). PENGs utilize the direct piezoelectric effect, where mechanical stress induces polarization in materials like polyvinylidene fluoride (PVDF) and zinc oxide (ZnO) nanostructures, generating a flow of charges [6], [7]. TENGs, on the other hand, rely on contact electrification and electrostatic induction, producing electrical energy from repeated frictional interaction between dissimilar materials with different electron affinities [11].

Such mutual properties have inspired efforts towards the advancement of Hybrid Nanogenerators (HNGs) where both the piezoelectric and triboelectric contributions are made to increase energy conversion over a greater variation of mechanical stimuli [4]. Hybrid systems not only compensate for the voltage and the current output but also enhance energy density and bandwidth harvesting of the energy. There are already researchers who have been able to demonstrate flexible hybrid systems that can conform to biological surfaces such as plant stems, so that we can have direct energy harvesting in the case of the plants moving due to wind without having to damage the growth of the plants or their mechanical integrity [19]. Thus, in the given setting, we offer a simulation study on a COMSOL Multiphysics-optimized stem-mounted flexible hybrid piezoelectric-triboelectric nanogenerator that can be utilized in smart farming use cases. The suggested structure contains the use of biocompatible materials, including PVDF and TPU, as a stretchy substrate. Using simulation, it is possible to analyze structural deformations, electrical output, and stress distribution due to wind-induced excitations that represent real life. This work will help establish a firm foundation of self-powered, low-invasive, and sustainable agritech sensors powered by intermittent wireless sensors, with BLE or LoRa radios, to the vision of completely autonomous systems applied to precision farming.

II. LITERATURE REVIEW

The traffic to energy-autonomous systems and potential applications thereof have gained importance due to the rapid improvement in the scope of IoT, wearable electronics, and smart agriculture, to convert ambient mechanical energy into electrical energy through the efficient production of nanogenerators. Emerged among them are triboelectric nanogenerators (TENGs), piezoelectric nanogenerators (PENGs), and hybrid systems, which are of dominant application with their simple, versatile, and high energy conversion rates. Probably due to the influence of Z.L. Wang, who rediscovered the Maxwell displacement current and related it to energy harvesting in the nanoscale [2], the original idea of the nanogenerator was of great importance. Piezoelectric nanogenerators initially proven with ZnO nanowire arrays [7] generate electrical signals on the grounds of intrinsic crystal asymmetry, which is converted to mechanical strain. Triboelectric nanogenerators, however, apply contact electrification and electrostatic induction to produce electrical responses when in cycling contact and separation [11].

While both mechanisms have setbacks, PENGs often have a low voltage output, and TENGs have a low current density. The 2 may, however, be used together to provide a wider bandwidth and better energy density [3], [4]. By such developments as flexible material PVDF and nanostructured ZnO, piezoelectric harvesting has proven to be viable in flexible electronics and bio-integrated systems [21], [22]. Scholars have shown wearable piezoelectric sensors able to extract low-frequency biomechanical movement [15]. Simple sliding/Contact triboelectric devices have advanced quickly to complex multilayered and textile-integrated triboelectric devices. Zhang et al. have introduced a triboelectric sensor, as it can operate in full spatial vibrations [8], where Chen et al. introduced a micro-cable textile with solar and mechanical harvesting [5]. Pu et al. combined the fiber-based triboelectric and photovoltaic systems to form a wearable, power textile with a dual-source power supply [6]. Recent innovations have also expanded the application of TENGs into bio-sensing and medical electronics. Guo et al. proposed a self-powered auditory sensor for hearing aids and social robotics [18], and Zheng et al. designed an implantable TENG for cardiac monitoring [14].

Hybrid nanogenerators (HNGs) that combine piezoelectric, triboelectric, and even electromagnetic mechanisms show potential in wide-scale, self-powered sensing networks. Tian et al. designed a hybrid wind energy harvester integrating TENG, PENG, and electromagnetic elements, capable of powering distributed IoT nodes [1]. Yang et al. employed a hybrid energy cell for catalytic degradation of pollutants using electrocatalytic oxidation, showcasing multifunctional capabilities [4]. The motivation for hybridization arises from the distinct output profiles of PENGs (high current, low voltage) and TENGs (high voltage, low current). Their integration allows simultaneous optimization of voltage and current levels for specific applications [10], [16]. For example, Liu et al. developed a hybrid wearable harvester that generates both sensing signals and power from human motion [9].

Several studies have further explored hybridization with biochemical energy, as in Wang et al.'s device for harvesting biomechanical and biochemical signals concurrently [16]. This concept points to a broader trend—merging energy harvesting with real-time physiological monitoring in wearable health systems. Recently, there has been a shift toward applying nanogenerators in smart farming and plant-based systems. Zhang et al. proposed a stem-mounted TENG to harvest kinetic energy from plant growth and motion, successfully powering a wireless sensor node [19]. Such designs enable energy autonomy in remote agritech sensors, eliminating the need for external batteries. This approach aligns with the growing global demand for sustainable agriculture and environmental monitoring. Flexible harvesters placed on plant stems can collect ambient wind or vibration energy to intermittently power BLE or LoRa nodes for temperature, humidity, or pest monitoring. However, ensuring biomechanical compatibility with plant tissue remains a challenge.

Flexible and stretchable energy harvesters are essential for integration with soft surfaces, human skin, textiles, or plant tissues. Choi et al. reviewed materials like graphene, MXenes, and nanostructured elastomers, showing how these nanomaterials contribute to both mechanical resilience and high energy conversion [24]. Ahmed et al. proposed a flexible nanogenerator that efficiently harvested low-frequency body movements, using a soft PDMS matrix embedded with conductive particles [15]. Similarly, Wang et al. utilized ambient humidity as a driving source to power small devices through a multilayered triboelectric structure [23]. Moreover, the adoption of stretchable substrates like PDMS, TPU, and silicone enables greater compliance with biological substrates, reducing stress and potential damage to the mounting surface [6], [24]. As nanogenerator complexity increases, simulation tools become vital for predicting electromechanical behavior. COMSOL Multiphysics has emerged as a preferred tool for simulating hybrid nanogenerators. Li et al. used COMSOL to simulate a hybrid PENG-TENG system and optimize the material layering and boundary conditions for maximum energy output [25]. Dong et al. reviewed various simulation approaches, highlighting the role of coupled physics simulations in predicting performance under real-world mechanical excitations like wind or human motion [17]. Willatzen and Wang offered foundational models for piezoelectric systems, focusing on resonant behavior and mechanical impedance matching [20]. Such modeling not only reduces experimental costs but also provides insight into the optimal geometry, material selection, and stress distribution, essential for sensitive integrations like plant-mounted devices. Standardizing performance evaluation is critical as nanogenerators transition to commercial applications. Zi et al. proposed performance metrics such as energy conversion efficiency, volumetric energy density, and figure-of-merit for TENGs [20].

While existing studies have demonstrated hybrid nanogenerators in wearable and plant-based harvesting, very few explore biomechanically safe, stem-mounted devices optimized for agricultural IoT. Our work pioneers a COMSOL-based Multiphysics simulation approach to design a plant-compatible hybrid Piezo–TENG harvester. We ensure mechanical safety for living plant tissues using soft adhesives and flexible TPU substrates while achieving sufficient power output for BLE/LoRa sensor nodes. Unlike prior work, we incorporate geometric tuning, material compliance, and realistic wind-induced vibration modeling, creating a battery-free, low-cost energy source. This bridges the gap between lab-scale innovation and practical deployment in smart farming.

III. METHODOLOGY

A) Device Architecture and Material Selection:

The proposed multilayer architecture is optimized to harvest mechanical energy from plant stem motion using combined triboelectric and piezoelectric effects. A top silver (Ag) electrode collects triboelectric charges, while a PDMS or TPU tribo-positive layer interacts with a tribo-negative aluminum or copper electrode below. An air gap between them enables efficient contact-separation cycles for electrostatic induction. The PVDF film acts as a piezoelectric layer, converting mechanical strain into electrical energy. Encapsulation with stretchable TPU ensures mechanical durability and environmental protection. A hydrogel or bio-adhesive base enables secure, non-invasive attachment to plant stems. Together, the layers synergistically convert ambient motion into usable power, enhancing energy output compared to standalone PENG or TENG systems.

Layer	Material	Function	Thickness
Top Electrode	Silver (Ag)	Collects triboelectric charge	100 μm
Triboelectric Layer	PDMS or TPU	Tribo-positive material for contact electrification	300 μm
Intermediate Spacer/Air Gap	Air or Elastic Spacer	Maintains separation for triboelectric action	100 μm
Bottom Electrode	Aluminum or Copper	Conductive, tribo-negative electrode	100 μm
Piezoelectric Layer	PVDF Film	Converts mechanical strain into electric charge	200 μm
Encapsulation/Substrate	Thermoplastic Polyurethane (TPU)	Provides mechanical flexibility and protection	500 μm
Adhesive Layer	Hydrogel or Bio-Adhesive	Enables plant attachment	<100 μm

Table 1: Summary of materials, functions, and thicknesses of individual layers in the proposed hybrid piezoelectric–triboelectric nanogenerator.

B) COMSOL Modules and Multiphysics Setup:

COMSOL Multiphysics was employed to design and simulate the hybrid nanogenerator system. The simulation incorporated the following modules and features:

1. *Solid Mechanics Module:* This module is used to evaluate the stress distribution, strain profiles, and mechanical deformation experienced by the device due to wind-induced motion of the plant stem. It helps assess the structural integrity and compatibility of the harvester with living tissue.
2. *Piezoelectric Devices Module*: This interface is employed to model the direct piezoelectric effect in the PVDF layer. It allows the simulation of an electric charge generator resulting from mechanical strain, which is essential for evaluating the energy harvesting capability of the piezoelectric component.
3. *Electrostatics Module*: This module is used to simulate the electric potential distribution and charge separation caused by contact electrification in the triboelectric layers. It captures the behavior of the triboelectric component under periodic contact-separation cycles.
4. *Multiphysics Coupling:* Coupled physics interfaces are used to link the outputs from structural deformation (Solid Mechanics) to the resulting electric field and charge generation (Electrostatics and Piezoelectric Devices). This enables accurate modeling of the hybrid energy conversion process.

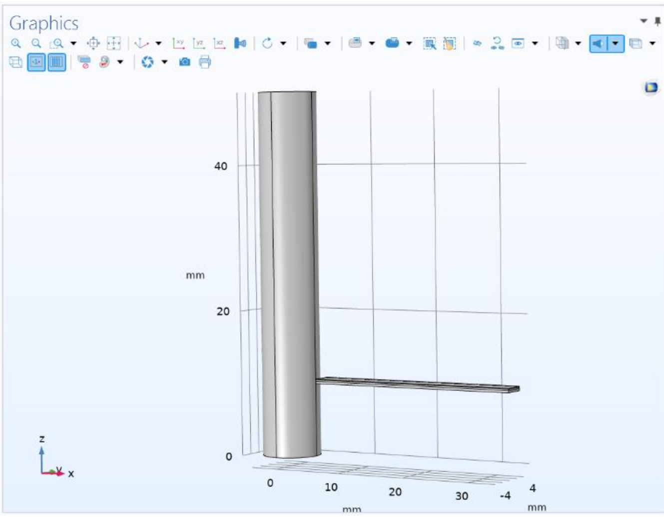

Figure 1: Summary of simulation-derived performance metrics

C) Geometry and Boundary Conditions:

A 3D CAD geometry was created representing the layered harvester attached to a 1.5mm diameter flexible stem modeled as a compliant cylindrical body (Young's modulus 5MPa, Poisson's ratio 0.4). Wind excitation was applied as a time-varying horizontal pressure of 20–80Pa to simulate typical low-speed wind (0.5–2m/s) acting on the stem. The adhesive layer was assigned fixed constraints to simulate secure bonding. The other surfaces were free to deform under aerodynamic forces. Triboelectric contact-separation was simulated by assigning periodic displacement functions between the PDMS and copper layers, coupled with a contact pair and dielectric interface.

D) Biomechanical Compatibility Considerations:

To ensure noninvasive integration with living plants, material choices prioritized flexibility, stretchability, and low-modulus adhesion. TPU and PVDF layers exhibit elongation >150%, ensuring they can bend with the stem without imposing mechanical stress. Simulations confirmed that the maximum induced stress in plants remained below 0.3 MPa, well under the threshold for cellular damage. The hydrogel adhesive enables secure placement without disrupting transpiration or stem elasticity.

E) Key Equations and Theoretical Models

1) Piezoelectric Effect*:* The piezoelectric response of materials under mechanical stress can be described by the constitutive equation:

$$D_i = d_{ijk} \cdot \sigma_{jk} + \varepsilon_{ij} \cdot E_j$$

Where **Di** is the electric displacement vector, **dijk** is the piezoelectric coupling coefficient tensor, **σjk** represents the mechanical stress tensor, **εij** is the dielectric permittivity tensor, and **Ej** is the electric field vector. This equation captures the direct piezoelectric effect, in which applied mechanical stress induces electric polarization within the material.

2) Triboelectric Output Voltage*:* The voltage output of a triboelectric nanogenerator operating in vertical contact separation mode can be estimated using the expression:

$$V_{\mathrm{oc}}(t) = \frac{\sigma \cdot x(t)}{\varepsilon_0}$$

Where **Voc(t)** is the open-circuit voltage at time **t, σ** is the surface charge density, **x(t)** is the instantaneous separation distance between the triboelectric layers, and **ε0** is the vacuum permittivity. This relationship governs the electrostatic potential developed due to time-varying charge separation because of external mechanical excitation.

3) Output Power Estimation: The power output delivered to a load resistance R can be approximated by:

$$P = \frac{V^2}{R}$$

Where **P** is the instantaneous output power, **V** is the peak output voltage of the nanogenerator, and **R** is the load resistance, typically chosen in the range of 1–10M for optimal power transfer. This expression assumes resistive loading and helps in evaluating the practical energy harvesting capability of the system.

F) Simulation of Outcomes and Metrics.

Parameter	**Observed Outcome**
Peak Voltage Output	12–18 V under 1.5 m/s wind excitation (combined piezoelectric and triboelectric)
Average Power Output	2–10 μW across a 5 MΩ load, depending on wind speed
Stress Distribution	Peak stresses are localized near electrode interfaces; TPU and adhesive layers reduce strain.
Stem Deflection	≤10° total bending, within biomechanical tolerance for the modeled plant stem
System Viability	Capable of intermittently powering BLE or LoRa-based wireless nodes

Table 2: Summary of simulation-derived performance metrics

IV. RESULTS AND DISCUSSION

The hybrid stem-mounted energy harvester was simulated using COMSOL Multiphysics to evaluate its mechanical compliance, electrical performance, and suitability for plant-integrated, self-powered sensor platforms. The device combines piezoelectric and triboelectric effects to convert wind-induced plant motion into electrical energy.

1) Electrical Output Performance: Under simulated wind excitation at a velocity of 1.5m/s, the harvester generated a peak voltage in the range of 12–18V, combining the contributions from both the piezoelectric and triboelectric components. When connected to a 5M resistive load, the average power output was estimated between 2–10μW, depending on the excitation frequency and contact-separation efficiency of the triboelectric layer. These power levels are sufficient to intermittently operate low-power wireless modules, such as BLE or LoRa nodes, for environmental sensing and transmission tasks.

2) Mechanical Stress and Structural Analysis: Stress distribution analysis revealed that peak stresses were localized around the electrode interfaces and adhesive regions. However, the use of TPU and bio-adhesive materials with high strain tolerance effectively reduced strain transfer to the plant stem. The maximum induced stress in the stem was under 0.3 MPa, remaining well within the physiological tolerance levels for most soft-stemmed plants. Additionally, deflection analysis showed that the total stem bending angle was below 10°, further confirming the biomechanical compatibility of the device. The encapsulated structure maintained its integrity under cyclic loading, suggesting durability for outdoor applications.

3. System Viability for Agritech Deployment: The simulation outcomes confirm that the proposed energy harvester can be used as a plant-mounted power source for periodic sensing. Although the output is not continuous, it is well-suited for intermittent operation, such as powering a sensor that wakes up every few minutes, transmits data wirelessly, and returns to sleep mode.

The minimal mechanical load and lightweight structure make this design a non-invasive solution for sustainable agricultural sensing. Future optimization may include tuning the geometry, spacer height, or electrode materials to enhance performance under lower wind conditions or longer duty cycles.

V. LIMITATIONS AND FUTURE WORK

While the proposed hybrid nanogenerator demonstrates promising energy harvesting capabilities through detailed Multiphysics simulation, certain limitations must be acknowledged. The current model assumes idealized material behavior and uniform wind loading, which may not fully capture the stochastic nature of environmental conditions in real agricultural settings. Additionally, the triboelectric charge density and surface interaction parameters are based on static values, whereas in practice, these can vary due to humidity, temperature, and surface wear over time. Future work will focus on incorporating real-time environmental variability through coupled CFD-structural-electrical simulations. Further optimization of device geometry, including the spacing between triboelectric layers and the thickness of piezoelectric films, will be conducted to maximize energy output while preserving plant integrity. The integration of surface coatings to enhance triboelectric performance under varying moisture levels will also be explored. On the experimental front, prototyping and in-field deployment of the harvester on live plant systems will be undertaken to validate simulation outcomes. Additionally, integration with a full IoT pipeline—including power management circuits, data transmission via BLE or LoRa, and long-term durability studies—will be essential to transition this concept into a practical, scalable solution for sustainable, self-powered agritech sensing platforms.

VI. CONCLUSION

This study presents a forward-thinking simulation framework for a flexible, stem-mounted hybrid nanogenerator tailored for self-powered agritech applications. By intelligently combining piezoelectric and triboelectric mechanisms within a biomechanically compatible architecture, the design demonstrates promising potential for energy-autonomous plant monitoring. The use of COMSOL-based Multiphysics modeling not only validates mechanical compliance but also shows viable energy outputs suitable for BLE or LoRa nodes. This work sets the stage for a new generation of battery-free, sustainable agricultural sensors. With continued development and experimental validation, such harvesters could redefine how we power distributed, intelligent systems in smart farming ecosystems.

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