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Triboelectric Nanogenerators Based on Agricultural Husk Waste: A Focused Review on Material Design and Energy Performance

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Abstract

The increasing demand for sustainable energy solutions and environmentally responsible waste management has encouraged the exploration of agricultural residues as functional materials for energy harvesting technologies. Among these residues, agricultural husks represent an abundant and underutilized lignocellulosic resource with intrinsic structural and chemical characteristics that are advantageous for triboelectric nanogenerators (TENGs). This review provides a focused and systematic analysis of agricultural husk–derived materials for TENG applications, with particular emphasis on material design strategies and energy performance. The unique natural architecture of husks, including their fibrous morphology, inherent surface roughness, abundant hydroxyl functional groups, and, in some cases, silica-rich composition, plays a decisive role in charge generation and retention. Various processing approaches such as mechanical grinding, nanoporous silica conversion, chemical functionalization, and composite integration are critically discussed in relation to their influence on electrical output parameters, including open-circuit voltage, short-circuit current, and power density. Reported studies demonstrate that rational material engineering significantly enhances triboelectric performance and enables practical applications such as wearable sensors, smart agriculture monitoring, portable electronics, and low-power IoT systems. Despite promising progress, challenges remain in terms of biomass variability, moisture sensitivity, long-term durability, and large-scale fabrication. Future development should focus on standardized processing, environmentally compatible modification strategies, and fully biomass-derived device architectures to improve reliability and sustainability. Overall, this review establishes a comprehensive framework for transforming agricultural husk waste into high-performance triboelectric materials and highlights their potential as a viable platform for next-generation self-powered energy systems.

INTRODUCTION

Agriculture plays a crucial role in the global economy and food supply, but it also generates large amounts of biomass residues each year, including husks, shells, and other lignocellulosic by-products (Babu et al., 2022; Gupta et al., 2022; Troncoso et al., 2023). Much of this waste is underutilized or improperly managed through practices such as open burning, contributing to air pollution and greenhouse gas emissions, making sustainable valorization increasingly important in the transition toward renewable and low-carbon energy technologies. While conventional biomass conversion methods such as biogas production, gasification, pyrolysis, and bioethanol synthesis have been widely explored, substantial untapped potential remains in

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utilizing agricultural residues for emerging energy harvesting technologies. In particular, agricultural husks possess natural fiber structures, intrinsic surface roughness, and, in some cases, silica-rich compositions that make them promising candidates for advanced functional materials (Ufitikirezi et al., 2024). One innovative and underexplored approach is their application in triboelectric nanogenerators (TENGs), offering a novel pathway to convert low-value agricultural waste into sustainable, self-powered energy systems beyond traditional fuel and chemical production routes (Troncoso et al., 2023).

TENGs have attracted significant attention due to their ability to convert low-frequency mechanical energy, such as contact, friction, vibration, wind, and human motion, into electrical energy through the combined effects of contact electrification and electrostatic induction (Kim et al., 2021). When two materials with different electronegativities undergo periodic contact and separation, electrons or ions are transferred from one surface to the other, creating a surface charge imbalance and an electric potential difference that drives electron flow through an external circuit. Conventionally, materials used in TENGs are dominated by synthetic polymers, including polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), and polydimethylsiloxane (PDMS), owing to their favorable triboelectric properties and ease of processing (Bindhu et al., 2024; Ma et al., 2024; Yang et al., 2023). However, these polymers are primarily derived from fossil-based resources and raise concerns regarding sustainability, environmental persistence, and end-of-life disposal. As a result, increasing attention has been directed toward the development of TENG materials based on renewable resources, particularly biomass-derived materials and biowaste.

Several review studies have examined the utilization of biomass and waste materials as triboelectric materials for TENG applications. A wide range of waste streams, including plant- and animal-based biowaste, medical waste, household waste, and electronic waste, have been reviewed with respect to material design, processing and fabrication strategies, energy-harvesting performance, and potential applications (Basith et al., 2024; Bhaduri & Ha, 2024; Du et al., 2024; Kumar et al., 2024). Beyond waste-derived materials, naturally harvested biomass extracted directly from plants has also demonstrated strong potential as triboelectric materials, largely due to the abundance of hydroxyl functional groups in cellulose that facilitate charge transfer during contact electrification (Troncoso et al., 2023; Zhou et al., 2022). Furthermore, several review articles have focused on the conversion of biomass into carbon-based materials prior to TENG integration, highlighting advantages such as enhanced electrical conductivity, mechanical flexibility, and improved resistance to humidity (Li et al., 2023; Park & Kim, 2024; Wu et al., 2025).

In addition to material development, recent reviews have explored the application of TENGs in smart agriculture, particularly as self-powered sensors, enabling circular utilization pathways that link agricultural activities with energy harvesting technologies (Silva et al., 2025). Despite these advances, there remains a notable lack of reviews specifically addressing triboelectric nanogenerators derived from agricultural husk waste. Agricultural husks represent a unique subclass of biomass characterized by inherent mechanical robustness, intrinsic surface roughness, fibrous architecture, and wide availability, all of which make them highly promising for sustainable triboelectric technologies. These features distinguish agricultural husks from general biomass, as husks function as protective outer layers of seeds and therefore exhibit superior structural strength compared with softer plant residues. In addition, certain agricultural husks possess silica-rich compositions that can further enhance triboelectric performance, collectively justifying a dedicated review of their unique potential in TENG applications. The agricultural husk wastes considered in this review include rice husk, coconut husk, corn husk, flax seed husk, peanut shell, and sunflower husk.

To address this gap, the present review focuses exclusively on agricultural husk waste–derived materials for triboelectric nanogenerators, with an emphasis on material design and energy-harvesting performance. This review systematically discusses (i) the types of agricultural husk waste suitable for TENG applications, (ii) their chemical composition and physical properties relevant to triboelectric behavior, (iii) processing and material design strategies, (iv) reported energy performance, and (v) current challenges and future research opportunities associated with the use of agricultural husk waste in TENG technologies. This work supports the United Nations Sustainable

Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production), by advancing the conversion of agricultural husk waste into functional materials for self-powered energy systems.

AGRICULTURAL HUSK-DERIVED MATERIALS FOR TRIBOELECTRIC NANOGENERATOR APPLICATION

Agricultural husk wastes, including rice husk, coconut husk, corn husk, flax seed husk, peanut shell, and sunflower husk, represent a distinct class of lignocellulosic biomass (Mujtaba et al., 2023); with physicochemical properties that are highly relevant for TENG applications. Unlike soft plant tissues or highly processed biopolymers, husks function as protective outer layers of seeds or grains and are therefore naturally engineered to withstand mechanical stress, abrasion, and environmental exposure (Iwuozor et al., 2024). These characteristics, combined with their chemical composition, make agricultural husks particularly attractive as triboelectric materials. The summary of the chemical composition and physical properties of agricultural husk waste used for TENG applications is illustrated in Figure 1 (a).

Chemical composition of agricultural husks

Agricultural husks are primarily composed of carbon-based organic polymers and, in some cases, inorganic mineral components, both of which play important roles in triboelectric charge generation and retention. The organic fraction of

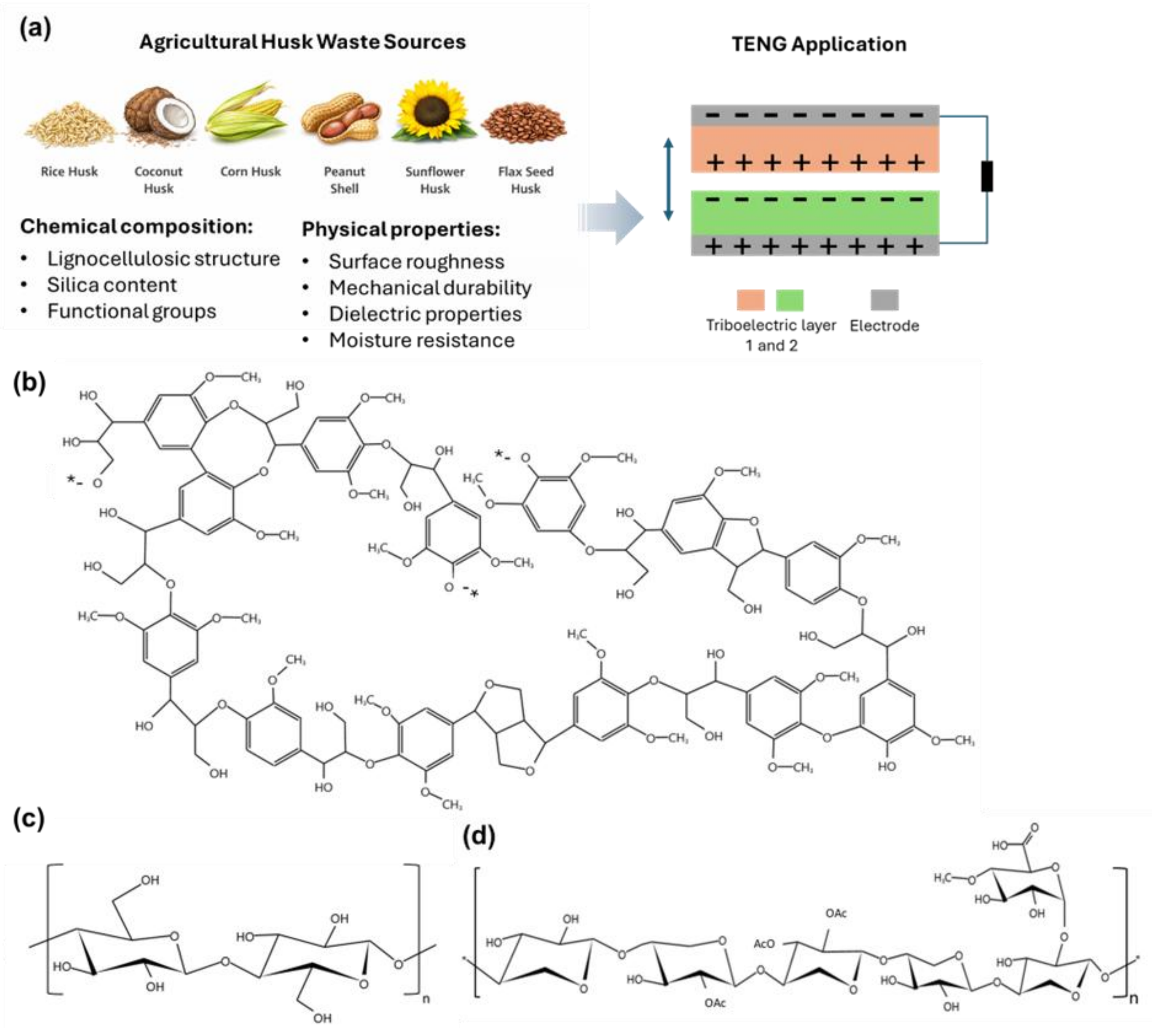

Figure 1. (a) Chemical composition and physical properties of agricultural husk waste used for TENG applications and chemical structure of (b) lignin, (c) cellulose, as well as (d) hemicellulose. (Illustration of agricultural husk waste sources was generated using ChatGPT image generator).

agricultural husks is primarily composed of cellulose, hemicellulose, and lignin, forming a lignocellulosic matrix that governs both their chemical reactivity and mechanical behavior. Typical lignocellulosic biomass consists of approximately 40–45 wt% cellulose, 30–35 wt% hemicellulose, and 20–30 wt% lignin, although the exact composition varies depending on crop type and growth conditions (Verma et al., 2026). The chemical structures of cellulose, hemicellulose, and lignin constituting the lignocellulosic matrix are illustrated in Figure 1(b)–(d). Cellulose provides abundant hydroxyl (–OH) functional groups, which act as active sites for charge transfer during contact electrification (Zhou et al., 2022). Hemicellulose contributes additional polar functional groups, while lignin enhances mechanical strength and hydrophobicity (Troncoso et al., 2023). A high lignin content, as observed in coconut husk (up to ~50 wt%) and peanut shell (~25 wt%), significantly improves wear resistance and structural stability under repeated contact–separation cycles (Anuchi et al., 2022; Lu et al., 2023). Beyond their direct use as triboelectric surfaces, the carbon-rich nature of agricultural husks enables their conversion into carbonized derivatives through thermal treatments such as pyrolysis or carbonization. These processes yield functional carbon materials, including biochar, carbon black–like structures, and, in some cases, graphitic carbon, depending on processing conditions (Li et al., 2023). Carbonized husk materials can serve as conductive components or electrodes in TENG devices, reducing reliance on metal-based electrodes and improving device sustainability.

Among agricultural husks, rice husk is particularly distinguished by its high silica content, typically ranging from 15 to 28 wt% (Chen et al., 2013). Silica exhibits strong electron affinity and contributes to enhanced surface charge density and dielectric properties when incorporated into triboelectric layers or polymer composites (Wu et al., 2016). Other husks, such as sunflower husk and corn husk, contain lower but non-negligible mineral fractions (Ca, Mg, K) that can still influence dielectric behavior and surface charge accumulation (Quaranta et al., 2011; Zakrzewska et al., 2023). The coexistence of organic polymers and inorganic silica within agricultural husks creates a naturally hybrid material system, combining the flexibility and functionality of biomass with the charge-enhancing characteristics of inorganic fillers (Lai et al., 2019). This intrinsic hybrid nature reduces the need for synthetic additives in TENG material design. Functional groups such as hydroxyl (–OH), carboxyl (–COOH), and ether (–C–O–C–) groups are widely present in agricultural husks due to their polysaccharide-based structure (Troncoso et al., 2023). These polar groups facilitate electron or ion transfer at the contact interface and play a central role in determining the triboelectric polarity of the material.

Physical properties relevant to triboelectric behavior

Several physical properties of agricultural husks strongly influence their suitability for triboelectric applications. Agricultural husks naturally exhibit micro- to nanoscale surface roughness, arising from their fibrous structure and hierarchical morphology. Increased surface roughness enhances the effective contact area during mechanical interaction, leading to higher triboelectric charge density (Liang et al., 2024; Wu et al., 2016). Unlike smooth synthetic films that often require artificial surface patterning, husks provide intrinsic surface texturing that can significantly improve triboelectric output with minimal processing (Brăileanu & Pascu, 2025). As protective biological structures, husks possess high mechanical strength and resistance to abrasion. Materials such as coconut husk and peanut shell demonstrate excellent durability under repeated mechanical stress, making them suitable for TENGs operating under cyclic contact or sliding modes (Liang et al., 2024; Saparin et al., 2024, 2025; Saqib et al., 2020). This mechanical robustness contributes to stable electrical output over extended operating cycles and is a key advantage over softer biomass materials such as fruit peels or leaves (Basith et al., 2024).

The dielectric constant of triboelectric materials directly affects charge storage and electrostatic induction. Agricultural husks exhibit moderate dielectric constants due to their organic polymer matrix, while silica-rich husks, particularly rice husk, can achieve enhanced dielectric behavior (Lai et al., 2019; Wu et al., 2016). When used as fillers in polymer composites, husk-derived materials can increase the overall dielectric constant of the triboelectric layer, thereby improving energy-harvesting efficiency. In addition, moisture sensitivity is a critical concern for TENG performance, especially in outdoor or agricultural

Table 1. Representative physicochemical properties of selected agricultural husk wastes relevant to TENG applications.

Husk Type	Lignocellulose Content (%)			Mineral Content (%)	Dielectric Constant	Ref
	Lignin	Cellulose	Hemicellulose			
Rice husk	20 – 25	35 – 40	15 – 20	Silica: 15 – 28	3.87	Chen et al., 2013; Gao et al., 2018; Pereira et al., 2023
Coconut husk	50	20 – 30	15 – 30	Mineral ash: 0.5	1.35	Anuchi et al., 2022; Yan et al., 2023
Corn husk	13.92	46.50	33.79	Silica: 0.33	3.9 – 7.2	Ratna et al., 2022
Peanut shell	28	48	3	Calcium: 0.20, Phosphorus: 0.06, Magnesium: 0.07, Potassium: 0.57	2.44 – 17.38	Lei et al., 2024; Zhang et al., 2025
Sunflower husk	20.30	40.10	32.40	Mineral ash: 1.8	1.30 – 2.84	Cui et al., 2019; Hernández-Nava et al., 2025

environments (Du et al., 2023; Manojkumar et al., 2025; Zhang et al., 2024). Compared with soft biomass, agricultural husks generally show lower moisture uptake due to their dense fiber structure and higher lignin content (Manojkumar et al., 2025; Troncoso et al., 2023). Nevertheless, moisture can still influence surface charge retention, particularly for cellulose-rich husks such as corn husk and flax seed husk (Gu et al., 2022; Veerabhadraswamy et al., 2024). The combination of carbon-rich lignocellulosic structure, mineral content (notably silica), abundant functional groups, intrinsic surface roughness, and mechanical durability positions agricultural husk waste as a highly promising class of materials for triboelectric nanogenerators. These properties enable agricultural husks to function as triboelectric layers, dielectric fillers, or carbon-based components within TENG devices, supporting both performance optimization and sustainable material sourcing. A quantitative comparison of the key physicochemical properties of representative agricultural husk wastes is summarized in Table 1 to facilitate cross-material evaluation for TENG applications.

PROCESSING AND MATERIALS DESIGN STRATEGIES

Agricultural husk biomass must undergo careful physical and chemical processing before it can be effectively used in triboelectric nanogenerators. Material design strategies are essential for controlling surface chemistry, micro- and nanostructure, mechanical flexibility, and interfacial charge transfer, all of which directly influence the electrical output and long-term stability of triboelectric nanogenerators (Li et al., 2024; Shang et al., 2022). Therefore, a clear understanding of these processing pathways is crucial for transforming husk waste into efficient and reliable triboelectric materials.

Biomass Pretreatment and Material Preparation

The conversion of agricultural husks from raw waste into high-performance triboelectric materials requires a multi-stage pretreatment process. This stage is critical to standardize material properties, as agricultural biomass naturally varies in moisture content, fiber density, and surface purity (Awogbemi & Kallon, 2022). An initial washing step with deionized water is used to remove surface dust and loosely adhered impurities from raw husk (Shaukat et al., 2021; Veerabhadraswamy et al., 2024). However, raw husks also contain non-conductive waxes, lipids, and other environmental contaminants that shield active cellulose surfaces and hinder charge transfer. Therefore, solvent washing is further employed, often involving sequential cleaning with deionized water followed by ethanol or acetone, as demonstrated for rice husk (Kar et al., 2024; Wu et al., 2016) and corn husks (Kheirabadi et al., 2023). Moisture removal is equally critical, as residual water facilitates charge leakage and degrades triboelectric performance. Pretreated husks are therefore oven-dried at 60–80 °C for at least 24 h (Gu et al., 2022; Wu et al., 2016).

Beyond cleaning and drying, mechanical grinding is commonly employed to reduce macroscopic husk structures into micro-scale particles, to maximize the effective surface area, which directly governs surface charge density in TENGs (Saqib et al., 2020; Shaukat et al., 2021; R. Zhang et al., 2022). As shown in Figure 2a, dried peanut shells (Saqib et al., 2020) are mechanically ground using an electric mixer to obtain peanut shell powder (PSP). The resulting powder is then deposited onto adhesive-coated aluminum substrates and compressed to form uniform and compact triboelectric films. A similar fabrication procedure has also been reported for sunflower husk–based triboelectric layers (Shaukat et al., 2021), demonstrating the adaptability of this simple and scalable processing approach for biomass-derived TENG materials. In these systems, mechanical grinding plays a dual role: it increases the effective surface area while simultaneously introducing irregular micro- and nanoscale surface roughness (Saqib et al., 2020; Shaukat et al., 2021; Zhang et al., 2022). This intrinsic rough morphology enhances interfacial contact intimacy and promotes stronger mechanical interlocking during the contact–separation cycle. Consequently, frictional interactions are intensified, leading to improved charge generation and more efficient charge transfer at the triboelectric interface (Saqib et al., 2020; Shaukat et al., 2021)

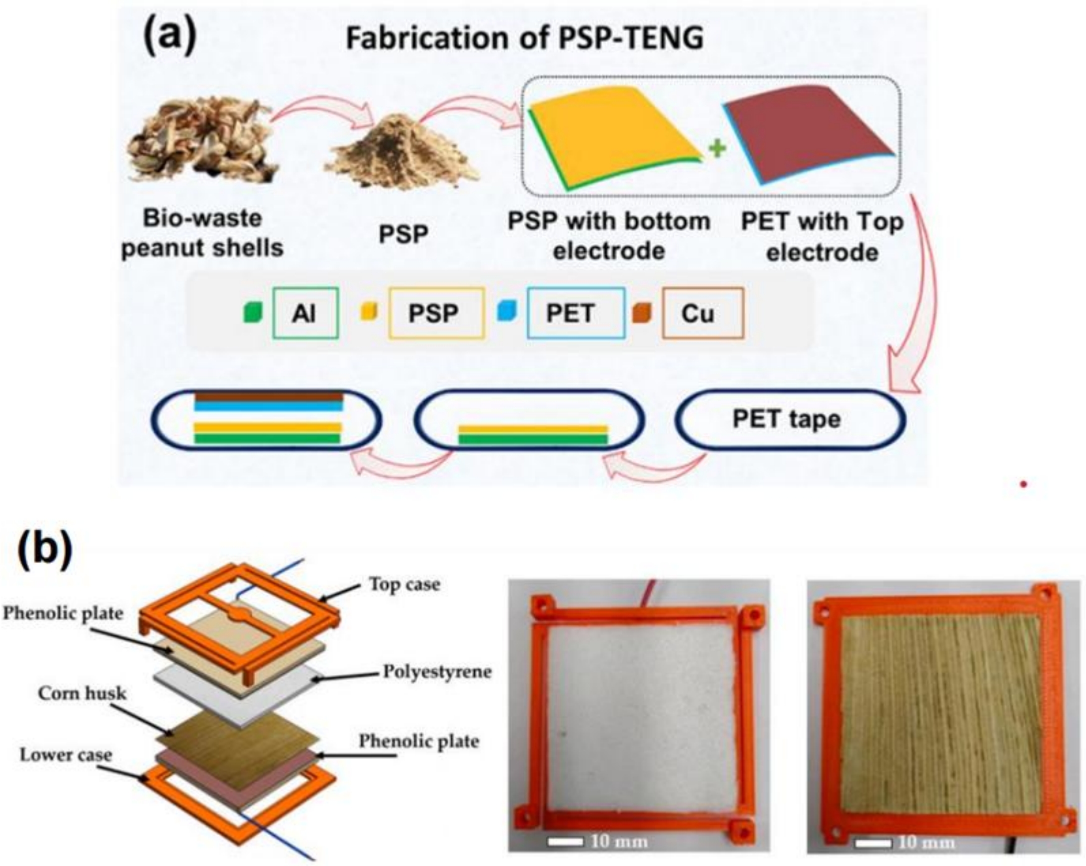

Figure 2. (a) Schematic illustration of the fabrication process of peanut shell powder (PSP)–based TENG. Reprinted with permission from Saqib et al. (2020). (b) Corn husk–based TENG device architecture and assembled structure. Reprinted with permission from Elvira-Hernandez et al. (2024).

A similar method was applied to dried corn husks, which were crushed using a pulverizer (Gu et al., 2022). In this case, pulverization facilitates material processability and enables the formation of thin, uniform, and functional films. When combined with methylcellulose as a thickener, the resulting powder shows improved film-forming behavior and enhanced triboelectric performance. In contrast, the processing of corn husks and coconut coir in fiber-based TENGs emphasizes fiber isolation rather than pulverization, thereby preserving the intrinsic lignocellulosic hierarchy and native fibrous morphology (Kheirabadi et al., 2023). As illustrated in Figure 2b (Elvira-Hernández et al., 2024), dried corn husks can also be directly integrated into layered TENG architectures without prior pulverization, where the intact fibrous structure is sandwiched between structural plates to serve as an active triboelectric layer. Another study similarly employed corn husks in their native form without mechanical size reduction (Singh et al., 2025). These bio-inspired surface morphology provides inherent roughness and increases the density of contact electrification sites without requiring complex lithographic patterning (Elvira-Hernández et al., 2024; Kheirabadi et al., 2023; Singh et al., 2025).

Chemical Modification and Functionalization

Chemical modification and functionalization of husk biomass are essential for tailoring surface chemistry and interfacial properties to maximize triboelectric charge transfer. By selectively targeting lignocellulosic components such as cellulose, hemicellulose, and lignin, researchers can systematically tune dielectric constant, surface potential, moisture resistance, and long-term stability, all of which directly influence device output and durability (Troncoso et al., 2023; Zhou et al., 2022). One of the most widely used strategies is alkali and acid treatment, which selectively removes non-cellulosic components, particularly lignin and hemicellulose (Lorenci Woiciechowski et al., 2020). In husk-based TENG materials, acid treatment using HCl has been applied to rice husk, often following high-temperature thermal annealing (Lai et al., 2019; Wu et al., 2016). For example, silica extraction from rice husk via acid hydrolysis and subsequent calcination at 700 °C for 3 h has been reported, producing nanoporous silica powder ($RHSiO_2$) with pore sizes of 20–40 nm, high surface area, and favorable surface polarity. This results in a highly positive surface dominated by dense Si–O–Si, Si–OH, and OH groups, which promotes strong triboelectric charge generation (Wu et al., 2016). This process involves hydrochloric acid treatment to remove metal impurities (K^+, Na^+, Ca^{2+}) and controlled thermal decomposition of organic components, enabling precise tuning of pore size, surface chemistry, and crystallinity for integration into dielectric-to-dielectric TENG configurations (Wu et al., 2016).

In a separate study, $RHSiO_2$ was further subjected to post-synthesis purification and surface functionalization to modulate surface potential and triboelectric behavior (Lai et al., 2019). After acid hydrolysis and thermal treatment, the particles were repeatedly washed and collected to remove residual impurities, followed by surface modification using organosilane agents with different terminal groups, including amine (NH_2), chlorine (Cl), and fluorine (F) functionalities. This material design strategy exploited the intrinsic three-dimensional nanoporous structure of $RHSiO_2$ to maximize surface area and contact efficiency, while chemical functionalization significantly enhanced charge density, hydrophobicity, and environmental robustness, resulting in substantial improvements in power density compared with untreated materials (Lai et al., 2019). Chemical modification is also closely integrated with composite film fabrication and matrix engineering. In this study, embedding husk-derived fillers into polymer matrices allows simultaneous control over surface chemistry, dielectric properties, and mechanical robustness. In rice husk ash polyvinylidene fluoride systems, the silica-rich biomass acts as a nucleating agent that promotes the transition from the non-polar α phase to the electroactive β phase, thereby enhancing dielectric constant and output power density (Kar et al., 2024; Lai et al., 2019). In more sustainable designs, polyvinyl alcohol serves as a biodegradable binder for flax seed husk, enabling flexible and bio-inspired composite films (Veerabhadraswamy et al., 2024).

Structural Design and Morphology Control

Structural design and morphology control strategies are employed to increase the effective surface-to-volume ratio, enhance interfacial contact efficiency, and introduce additional functional properties through controlled micro- and nanostructuring. By converting natural architectures into engineered morphologies, researchers can substantially improve charge generation, retention, and transport in biomass-based triboelectric systems (Troncoso et al., 2023). One of the most effective approaches is the transformation of biomass into nanoporous dielectric structures (Kar et al., 2024; Lai et al., 2019; Wu et al., 2016). In the case of rice husks, a combination of thermal annealing and acid hydrolysis enables full phase transformation into amorphous, nanoporous silica structures known as $RHSiO_2$ (Kar et al., 2024; Lai et al., 2019; Wu et al., 2016). This process removes organic components while preserving a rigid inorganic skeleton with pore sizes typically ranging from 20 to 40 nm (Wu et al., 2016). These nanoporous frameworks contain abundant surface hydroxyl groups and Si-O-Si bonds that act as efficient charge trapping sites. As a result, current density is significantly enhanced because the internal pore network provides a large hidden surface area for charge induction that far exceeds the geometric footprint of the device (Kar et al., 2024; Lai et al., 2019; Wu et al., 2016).

Rather than relying on costly lithographic techniques, many studies leverage the intrinsic hierarchical morphology of corn husks to enhance interfacial contact efficiency (Elvira-Hernández et al., 2024; Gu et al., 2022; Singh et al., 2025). Unlike lithography, which produces predefined and often two-dimensional patterns, corn husks possess an inherent fibrous architecture that creates random, multi-scale surface roughness. This natural hierarchy increases mechanical friction and enlarges the effective contact area between triboelectric layers through three-dimensional interlocking, leading to improved charge generation. In parallel, incorporating flax seed husks powder into polymer matrices (e.g., PVA) yields bio-inspired composites that replicate the roughness-on-roughness hierarchy observed in natural materials (Veerabhadraswamy et al., 2024). This interlocking surface architecture promotes deeper mechanical engagement during contact-separation cycles, thereby facilitating more effective charge transfer and resulting in enhanced electrical output.

Device Fabrication and Integration

Device fabrication strategies in agricultural husk–based TENGs generally adopt simple yet effective configurations, with the vertical contact–separation mode being the most widely implemented due to its high voltage output and structural simplicity. In powder-based systems, such as peanut shell (Saqib et al., 2020) and sunflower husk (Shaukat et al., 2021), fine bio-powders are deposited onto adhesive-coated aluminum foils and paired with polymeric counter layers to form compact dielectric–metal interfaces deposited onto adhesive-coated aluminum foils and paired with polymeric counter layers to form compact dielectric–metal interfaces. Similarly, rice husk–derived nanoporous silica ($RHSiO_2$) has been integrated into dielectric–dielectric configurations using PTFE as the counter layer, improving chemical stability and corrosion resistance (Wu et al., 2016). These configurations emphasize controlled separation distance, uniform compression, and stable electrode attachment to maximize charge induction and current density.

Composite-based integration strategies have become an important integration pathway for enhancing mechanical robustness and flexibility. For instance, rice husk ash (RHA) incorporated into PVDF matrices enables the fabrication of flexible triboelectric energy harvesters capable of powering IoT-based systems, while also benefiting from enhanced electroactive phase content (Kar et al., 2024). In bio-inspired designs, flax seed husk powders have been embedded into polyvinyl alcohol (PVA) matrices to form flexible composite films assembled in arch-shaped structures, improving repeatability and mechanical durability (Veerabhadraswamy et al., 2024). These composite strategies not only enhance dielectric constant and mechanical durability but also enable wearable and deformable device architectures. Such composite-based strategies allow improved interfacial adhesion between biomass fillers and electrodes while maintaining surface roughness necessary for efficient charge transfer.

Integration strategies further extend to encapsulation, power management, and application-level deployment. Surface-functionalized $RHSiO_2$ particles have been encapsulated within quartz housings to enable stable underwater wireless sensing, demonstrating the feasibility of biomass-based TENGs in harsh environments (Lai et al., 2019). In practical demonstrations, husk-based devices have been connected to rectifier circuits and capacitors to power LEDs, calculators, and small electronic devices, validating their real-world energy

Table 2. Overview of processing and material design approaches in agricultural husk–based TENGs

Strategy	Method	Design Purpose	Ref
Biomass Pretreatment			
Cleaning and drying	Washing, solvent cleaning, oven drying (60–80 °C)	Remove impurities and moisture	Gu et al., 2022; Wu et al., 2016
Size reduction / fiber isolation	Grinding or native fiber use	Increase surface area or preserve roughness	Saqib et al., 2020; Singh et al., 2025
Chemical Modification			
Acid treatment	HCl hydrolysis (rice husk)	Silica extraction and dielectric tuning	Wu et al., 2016
Surface functionalization	Silane modification (NH_2/F)	Improve hydrophobicity and charge retention	Lai et al., 2019
Structural Design			
Nanoporous formation	Thermal calcination (~700 °C)	Introduce charge trapping sites	Lai et al., 2019
Composite morphology	Husk–polymer hybrid films	Improve interfacial contact	Kar et al., 2024
Device Integration			
Powder-based device	Husk powder on Al electrode	Form dielectric–metal interface	Saqib et al., 2020
Flexible composite device	RHA/PVDF, husk/PVA	Enhance mechanical flexibility	Veerabhadraswamy et al., 2024

harvesting capability (Saqib et al., 2020; Shaukat et al., 2021). To facilitate a clearer understanding of the experimental framework described in this section, the key fabrication processes and material design strategies employed in agricultural husk–based triboelectric nanogenerators are summarized in Table 2. The reported approaches generally involve sequential stages of biomass pretreatment, chemical modification, structural morphology control, and device-level integration, each of which contributes to tailoring dielectric properties, surface charge generation, interfacial contact efficiency, and mechanical stability (Wu et al., 2016; Lai et al., 2019; Gu et al., 2022; Kar et al., 2024).

ENERGY PERFORMANCE

TENGs operate based on the coupling of contact electrification and electrostatic induction, enabling the conversion of mechanical energy into electrical energy. When two materials with different triboelectric polarities come into contact, electrons transfer from one surface to the other according to their relative electron affinity (Biutty et al., 2020; C. Wu et al., 2019). Upon separation, opposite charges remain bound on the surfaces, generating a potential difference that drives electron flow through an external circuit. This cyclic contact–separation process produces alternating current output, which can be rectified and stored for practical use. In most agricultural husk–based systems, the vertical contact–separation mode is adopted due to its structural simplicity and high voltage output (Saqib et al., 2020; Shaukat et al., 2021). The basic working principle of this mode is illustrated in Figure 3, where agricultural husk acts as the tribopositive layer. The energy conversion cycle involves four key stages: (i) in the initial state, the two surfaces are apart, and no current flows; (ii) during contact, electrons transfer from the husk to the more electronegative layer (e.g., PTFE or PDMS), resulting in opposite charge accumulation; (iii) once fully compressed, electrostatic equilibrium is established; and (iv) during release, separation of the layers generates a potential difference that drives current through the external circuit (Fan et al., 2012). The tribopositive behavior of agricultural husks originates from their lignocellulosic composition, which is rich in hydroxyl (–OH) and carboxyl (–COOH) functional groups. These polar sites facilitate charge donation, making husks ideal for coupling with strongly electronegative materials to achieve high surface potential differences and optimized electrical output (Dahlström et al., 2021).

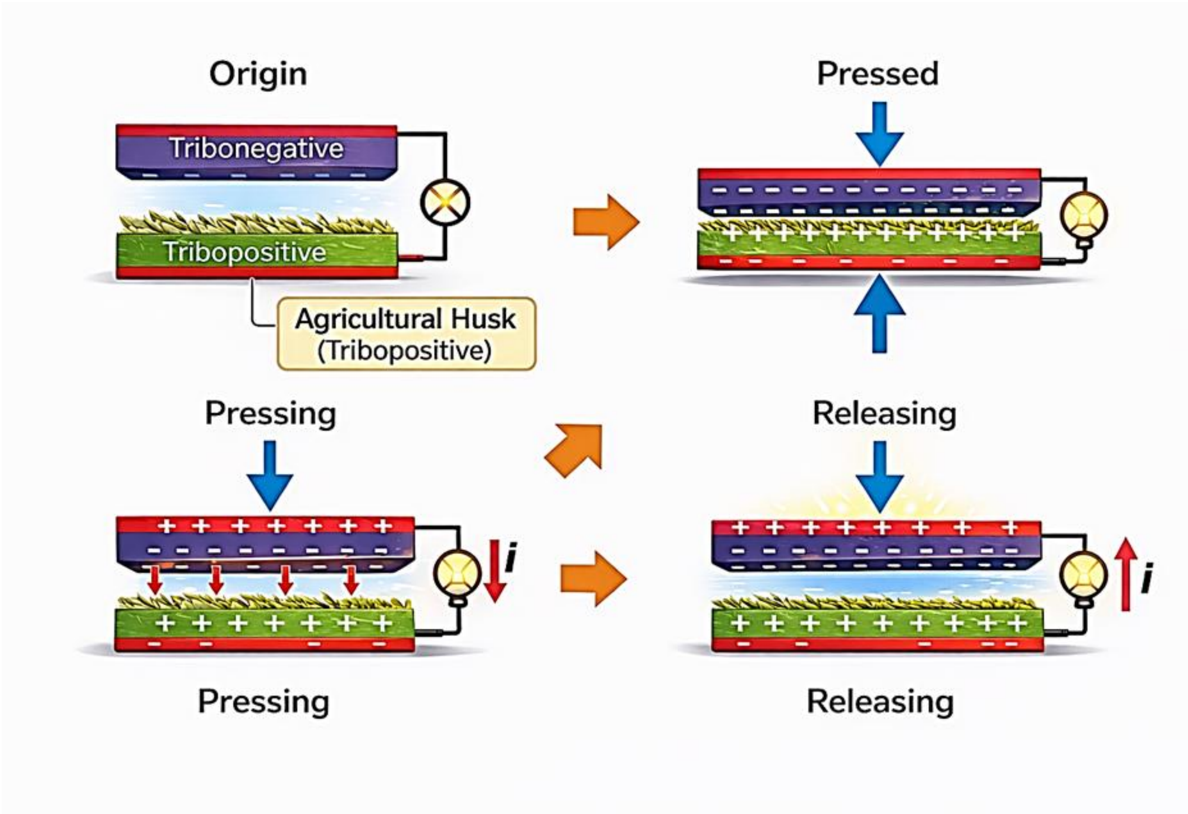

Figure 3. Schematic working mechanism of a vertical contact–separation TENG.

Electrical Output Performance

Peak open-circuit voltage (V_{oc}) is primarily determined by the triboelectric potential difference between the active layer and its counter surface, most commonly PTFE or PDMS (Biutty et al., 2020; Biutty & Yoo, 2021). The highest voltage reported among all studies is achieved by the corn husk/g-C_3N_4 hybrid system, which reaches an ultra-high V_{oc} of 630 V (Kheirabadi et al., 2023). This performance far exceeds that of non-hybridized corn husk devices, which typically operate in the range of 100–215 V (Gu et al., 2022; Singh et al., 2025). The incorporation of two-dimensional g-C_3N_4 nanosheets creates a highly engineered interface that enhances charge trapping, surface potential, and interfacial polarization. A second tier of high performance is observed in rice husk ash (RHA)/PVDF composites, which generate voltages up to 463 V (Kar et al., 2024). In this case, the synergy between silica-rich RHA and the PVDF matrix promotes the formation of the electroactive β-phase, introducing a combined triboelectric–piezoelectric contribution to the output. In contrast, powder based-system such as peanut shell powder (PSP) and sunflower husk powder (SFP) also exhibit high open-circuit voltages, reaching approximately 910 V and 488 V, respectively (Saqib et al., 2020; Shaukat et al., 2021), demonstrating that even untreated agricultural waste can deliver competitive voltage outputs.

Short-circuit current (I_{sc}) and current density are governed not only by surface potential but also by the effective contact area, charge transport pathways, and the rate of charge transfer during mechanical excitation. The highest current output is reported for nanoporous rice husk–derived silica (RH_{SiO_2}), which reaches 12.0 μA (Wu et al., 2016). The removal of organic components produces an amorphous silica network with a highly developed internal surface area, enabling a large density of induced charges to participate in conduction through the external circuit. Corn husk–based devices configured as wireless sensors exhibit a comparatively high current of 3.5 μA (Gu et al., 2022), attributed to the hierarchical fibrous morphology that enhances mechanical interlocking and accelerates charge transfer during contact. By comparison, devices based on PSP embedded in soft elastomeric matrices such as Ecoflex or PDMS typically show current peaks in the range of 0.9–1.5 μA (Zhang et al., 2022). Although these polymers provide mechanical compliance and flexibility,

Table 3. Electrical performance of different agricultural husk–based TENG materials reported in the literature.

Husk Source	Material Systems	V_{oc} (V)	I_{sc} (μA)	Peak Power Density	Ref
Corn husk	Native husk, composite, hybrid systems	100–630	up to 3.5	up to 0.5 W cm^{-2}	Gu et al., 2022; Singh et al., 2025; Kheirabadi et al., 2023
Rice husk	$RHSiO_2$, RHA/polymer composites	up to 463	up to 12.0	–	Wu et al., 2016; Kar et al., 2024
Peanut shell	PSP powder-based devices	~910	0.9–1.5	115 mW cm^{-2}	Saqib et al., 2020
Sunflower husk	SFP powder-based devices	~488	–	–	Shaukat et al., 2021

their insulating nature limits charge mobility and thus constrains current output.

The practical utility of these devices is ultimately reflected in their peak power density, which depends on both voltage and current as well as optimal impedance matching. The corn husk/g-C_3N_4 hybrid system demonstrates a peak power density of approximately 0.5 W/cm^2 (Kheirabadi et al., 2023), sufficient to directly power high-demand components such as large LED arrays. Most bio-based TENGs exhibit optimal load resistances in the range of 10 MΩ to 100 MΩ. For instance, PSP-based composites reach their maximum power density of 115 mW/cm^2 at around 50 MΩ (Saqib et al., 2020). Proper impedance matching is therefore essential for efficient energy extraction and reliable integration of husk-based TENGs with energy storage units and low-power electronic systems such as IoT sensors. A comparative summary of the electrical output performance of different agricultural husk–based TENG materials reported in the literature is presented in Table 2. Since the electrical outputs may vary depending on material treatment, device configuration, and testing conditions, the values in Table 3 are presented as performance ranges to represent the minimum and maximum outputs reported for each husk source.

Operational and Environmental Stability

The operational stability and output reliability of biomass-based triboelectric nanogenerators are strongly influenced by external mechanical stimuli and ambient environmental conditions. Across the reviewed studies, electrical output generally increases with both the rate and intensity of mechanical deformation, although the response varies depending on whether the triboelectric layer is composed of fibrous structures or powder-based composites. For example, as shown in Figure 4a, in corn husk/recycled polystyrene composites, resonance characterization and frequency-dependent testing revealed that stable and optimal electrical output was achieved at low-frequency operation, particularly around 14 Hz, which is representative of realistic environmental vibrations (Elvira-Hernández et al., 2024). Because most environmental vibrations occur at low frequencies, the TENG performance was further tested at 8–14 Hz under varying separation distances. In this regime, increasing the contact–separation frequency produces a nearly linear rise in short-circuit current due to the increased charge transfer rate (Elvira-Hernández et al., 2024). Similarly, coconut coir sliding-mode devices exhibit enhanced output at higher frequencies, although excessive speeds may accelerate mechanical wear of natural fibers (Saparin et al., 2024). Furthermore, impact force also plays a critical role, as depicted in Figure 4b. The devices based on peanut shell powder (PSP) and sunflower husk fillers show increased voltage and current when the applied force rises, as compression of the porous bio-fillers enlarges the real contact area and promotes deeper interfacial interlocking (Saqib et al., 2020).

Due to the intrinsic hydrophilic nature of lignocellulosic biomass, which contains abundant hydroxyl (–OH) groups, humidity is one of the most significant environmental factors influencing device performance. Moisture adsorption increases surface conductivity and accelerates charge dissipation, leading to reduced voltage and current output.

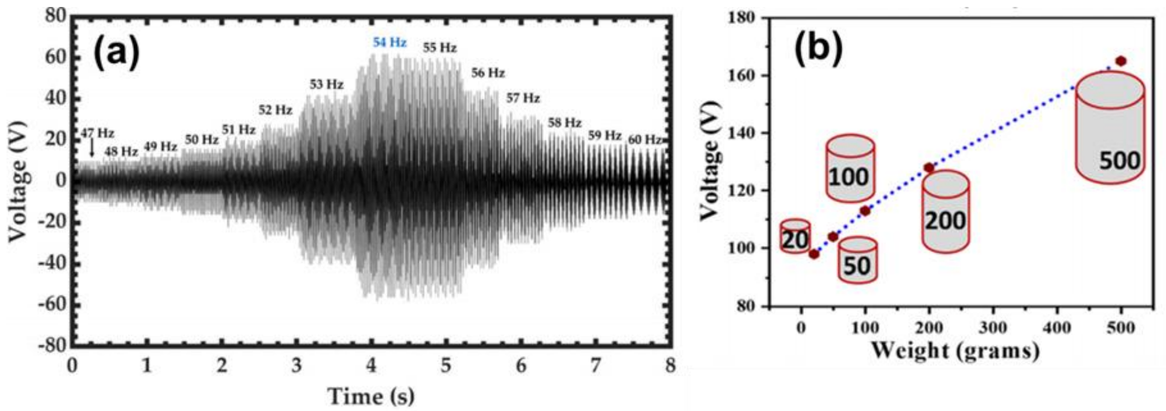

Figure 4. (a) Output voltage of corn husk-based TENG at different frequency. Reprinted with permission from Elvira-Hernandez et al. (2024). (b) Output voltage at of PSP-based TENG different gram forces. Reprinted with permission from Saqib et al. (2020).

Sunflower husk–based TENGs were systematically evaluated under relative humidity levels ranging from 38% to 89%, where a gradual performance degradation was observed at higher humidity conditions (Shaukat et al., 2021). Similar moisture sensitivity has been discussed in rice husk–derived systems, where careful drying and surface modification were emphasized to prevent charge leakage (Wu et al., 2016).

In addition, surface engineering and encapsulation strategies have been demonstrated to significantly improve environmental robustness. In $RHSiO_2$-based devices, fluorinated silane functionalization enhanced hydrophobicity and stabilized surface charge retention, leading to improved operational durability (Lai et al., 2019; Wu et al., 2016). Furthermore, encapsulation of functionalized $RHSiO_2$ within a quartz housing enabled stable underwater operation and wireless vibration sensing, demonstrating that biomass-derived materials can function reliably in liquid environments when appropriately protected (Lai et al., 2019). Mechanical durability under repeated contact–separation cycles is another key performance criterion. Arch-structured flax husk/PVA composite TENGs exhibited stable cyclic behavior due to their flexible architecture and controlled separation distance (Veerabhadraswamy et al., 2024), while powder-based peanut and sunflower husk systems also demonstrated stable repeated output under continuous mechanical excitation (Saqib et al., 2020; Shaukat et al., 2021).

Practical Application

The practical value of husk-based triboelectric nanogenerators lies in their ability to convert intermittent, high-voltage and low-current electrical pulses into stable power outputs capable of driving real-world electronic systems. The practical applications of agricultural husk-based TENGs were depicted in Figure 5. Since TENGs intrinsically produce alternating current characterized by high internal impedance, they are typically combined with rectification circuits and energy storage units to achieve stable direct current operation. Capacitor charging efficiency is strongly correlated with the short-circuit current I_{sc} of the device, as higher charge transfer rates enable faster energy accumulation. The nanoporous rice husk–derived silica system demonstrates superior charging capability compared with other biomass-based configurations, owing to its enhanced current generation and effective charge transport (Wu et al., 2016). In contrast, devices fabricated from conventional bio-powders such as peanut shell and sunflower husk generally exhibit slower charging behavior due to comparatively lower current output (Saqib et al., 2020; Shaukat et al., 2021). Furthermore, the incorporation of corn husk fillers into a recycled polymer matrix improves dielectric properties and accelerates energy storage performance, underscoring the critical role of matrix engineering in optimizing charging efficiency (Elvira-Hernández et al., 2024).

Beyond energy storage, several studies demonstrate the feasibility of directly powering portable electronics using agricultural waste–based TENGs. Peanut shell powder–based devices have successfully powered digital thermometers and scientific calculators by charging a 22 μF capacitor to the required operating voltage (Saqib et al., 2020). Similarly, sunflower husk and corn husk/recycled polystyrene systems have been shown to drive electronic watches and small liquid

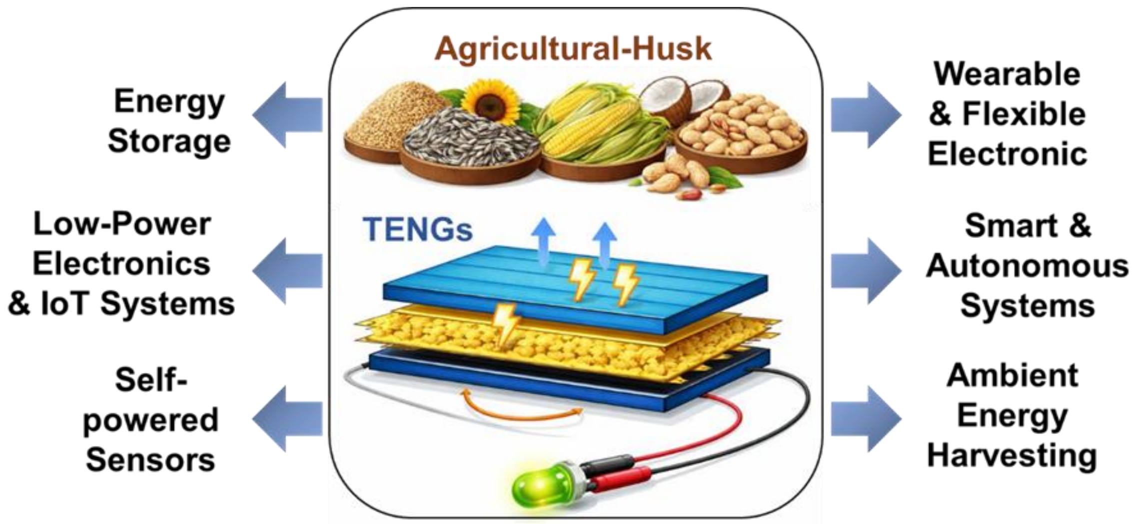

Figure 5. Practical applications of agricultural husk–based TENGs. (Illustration of agricultural husk and TENGs were generated using ChatGPT image generator)

crystal displays (Saqib et al., 2020; Shaukat et al., 2021). In one notable example, a corn husk–based TENG maintained continuous operation of a digital watch using only mechanical energy from finger tapping, underscoring its potential for self-powered wearable and portable electronics (Elvira-Hernández et al., 2024). In applications where high-voltage output is sufficient, the energy storage stage can be bypassed entirely to enable direct electrical actuation. The corn husk-hybrid device, which achieves an ultra-high open-circuit voltage of 630 V, exhibits exceptional direct-drive capability (Kheirabadi et al., 2023). Under simple mechanical excitation such as manual tapping or vibration, this device can instantaneously illuminate more than 100 commercial light-emitting diodes connected in series. This level of performance enables biomechanical energy sources, including walking on rice husk/PVDF floor mats (Kar et al., 2024) or hand pressing flax-seed husk patches (Veerabhadraswamy et al., 2024), to provide immediate lighting or signal transmission without the need for batteries, demonstrating the readiness of husk-based TENGs for emergency and off-grid power applications.

CHALLENGES AND FUTURE PERSPECTIVE

Although significant progress has been achieved in engineering agricultural husks for triboelectric nanogenerators, including exceptionally high outputs such as the 630 V reported for hybridized corn husk systems (Kheirabadi et al., 2023), several fundamental challenges must be addressed before these technologies can achieve large-scale deployment. A major limitation arises from the inherent heterogeneity of biomass. Unlike synthetic polymers such as FEP or Kapton, agricultural husks exhibit substantial variability in chemical composition, cellulose-to-lignin ratio, and surface morphology due to differences in soil conditions, climate, and harvesting practices (Singh et al., 2025). This natural variability complicates performance standardization and hinders reproducibility across large manufacturing batches. In addition, a critical trade-off exists between biodegradability and long-term durability. While bio-composites such as peanut shell/PDMS systems demonstrate mechanical robustness and stable electrical output (Saqib et al., 2020), the incorporation of synthetic matrices compromises the environmental sustainability of the device. Furthermore, despite advances in moisture-resistant designs, including superhydrophobic coconut-derived foams (Liang et al., 2024), most husk-based TENGs remain vulnerable to humidity-induced charge leakage. The hygroscopic nature of cellulose continues to pose a fundamental barrier to reliable outdoor operation, particularly in agricultural sensing environments (Gu et al., 2022).

In addition, the development of agricultural husk–based TENGs is expected to follow several strategic directions. Advanced hybridization is likely to play a central role, enabling multi-source energy harvesting through the integration of husk materials with two-dimensional nanomaterials such as g-C_3N_4 and MXenes, or semiconductor oxides such as TiO_2.

These photo-triboelectric systems can simultaneously harvest mechanical and solar energy, potentially achieving power densities suitable for smart agriculture and distributed infrastructure (Kheirabadi et al., 2023; Saparin et al., 2025). In parallel, the functional role of bio-TENGs is expanding beyond power generation toward intelligent sensing. Recent demonstrations of corn husk–based activity monitoring systems illustrate a shift toward extracting diagnostic information from electrical signal patterns, paving the way for machine learning–assisted health and agricultural monitoring (Singh et al., 2025). Finally, future research should emphasize circular manufacturing strategies, aiming to fabricate fully biomass-derived devices in which both triboelectric layers and structural components are sourced from the same agricultural waste stream, such as lignin-based binders or starch-derived matrices. Such "all-biomass" TENGs would enable a closed-loop lifecycle and represent a critical step toward truly sustainable energy harvesting systems.

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LIST OF NOTATION

C	Capacitance (F)
F	Applied mechanical force (N)
f	Operating frequency (Hz)
Isc	Short-circuit current (A)
P	Output power (W)
R	Load resistance (Ω)
V	Voltage (V)
Voc	Open-circuit voltage (V)

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