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Review

Triboelectric Nanogenerator-Based Electronic Sensor System for Food Applications

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Abstract: Triboelectric nanogenerators (TENGs) have garnered significant attention due to their ability to efficiently harvest energy from the surrounding environment and from living organisms, as well as to enable the efficient utilization of various materials, such as organic polymers, metals, and inorganic compounds. As a result, TENGs represent an emerging class of self-powered devices that can power small sensors or serve as multifunctional sensors themselves to detect a variety of physical and chemical stimuli. In this context, TENGs are expected to play a pivotal role in the entire process of food manufacturing. The rapid development of the Internet of Things and sensor technology has built a huge platform for sensor systems for food testing. TENG-based sensor data provide novel judgment and classification features, offering a fast and convenient means of food safety detection. This review comprehensively summarizes the latest progress in the application of TENGs in the food field, mainly involving food quality testing, food monitoring, food safety, and agricultural production. We also introduce different TENG-based, self-powered devices for food detection and improvement from the perspective of material strategies and manufacturing solutions. Finally, we discuss the current challenges and potential opportunities for future development of TENGs in the food field. We hope that this work can provide new insights into the structural and electronic design of TENGs, thereby benefiting environmental protection and food health.

Keywords: triboelectric nanogenerator; self-powered sensing; food; energy harvester

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1. Introduction

According to the Food and Agriculture Organization of the United Nations, one-third of the food produced (1.3 billion tons per year) is lost or wasted in the food supply chain [1]. One of the main reasons for this outcome is that food spoils during storage and transportation. The World Health Organization reports that there are 600 million cases of foodborne diseases worldwide each year, resulting in 420,000 deaths [2]. One of the main reasons for these deaths is the presence of harmful substances or microorganisms in food. Unsafe food costs low- and middle-income countries US $110 billion in lost productivity and health-care costs every year [3]. Ensuring the availability and sufficient quantities of good-quality food is a critical issue for governments and food industry bodies. Food safety and quality are important guarantees for human health, quality of life, social development, and economic growth. In all aspects of food production, processing, storage, transportation, and consumption, any substances or factors that endanger human health can cause significant losses [4]. As population growth, resource shortages, environmental pollution, and other problems intensify, food safety is facing increasingly severe challenges. Effectively detecting, sterilizing, tracing, and preserving food are controversial and difficult issues in the field of food science and technology.

Methods commonly used for ensuring food safety and quality often require external power sources, complex instruments, and manual intervention [5–7]. However, these methods can be energy consuming, costly, inefficient, and inaccurate. Triboelectric nanogenerator (TENG) technology, which emerged rapidly in 2012, can flexibly collect various mechanical energy from the environment and convert it into electrical energy. TENGs have been applied in different fields, such as medical treatment [8–10], self-powered sensing [11,12], wearable devices [13–15], and maritime applications [16–18]. The working principle of TENGs is based on the triboelectric effect and electric field effect. When two different materials contact or separate from each other, charge transfer and distribution occur, forming surface charges and induced charges that generate potential differences and currents. As a new power-generation device that can convert mechanical energy into electrical energy, TENGs have the advantages of a high output voltage (510 V for sterilization [19] and 4.07 kV for driving UV-C lamps [20]), low cost, light weight, and wide material selectivity [21–23]. In recent years, the application of TENGs in the food industry has gradually attracted attention for food safety, quality testing, and production.

As a new method to improve food safety and quality, TENGs have demonstrated a broad range of applications. In addition to driving various biosensors [24], chemical sensors [25], electric field generators [26], and electrochemical reactors [27] using mechanical energy, TENGs can also enable self-powered, wireless, and intelligent processing of food testing and preservation. For example, TENGs, using food materials, can realize the detection of food ingredients through its voltage output performance [28]. TENGs can be used as power sources to drive sensors or preservation equipment. Through appropriate material selection and structural design, it can also be used as an instrument for food detection and food preservation [29,30]. The application of TENGs in food safety and quality can be simple and cost-effective.

This review covers the application status and development trends of TENGs in the food industry, aiming to provide references and inspiration for research in this field. The first part introduces the four working forms of TENGs, which can be divided into four basic types based on their structures and working modes. In the following sections, we discuss three potential applications of TENG-based, self-powered equipment in the food industry, as depicted in Figure 1. First, TENG is utilized as a self-powered device for food quality inspection and monitoring. Second, TENG-based, self-powered sterilizers are employed for food sterilization. Third, TENG-based self-powered systems are utilized to enhance food harvesting. TENGs can electrically stimulate crop growth or power agricultural sensors. The review introduces different types of TENG-based, self-powered equipment for food improvement from the perspective of material strategies and manufacturing solutions. Finally, the review summarizes the current application status and development trends of TENGs in the food field and considers the future direction, prospects, and challenges of TENG application in the food field.

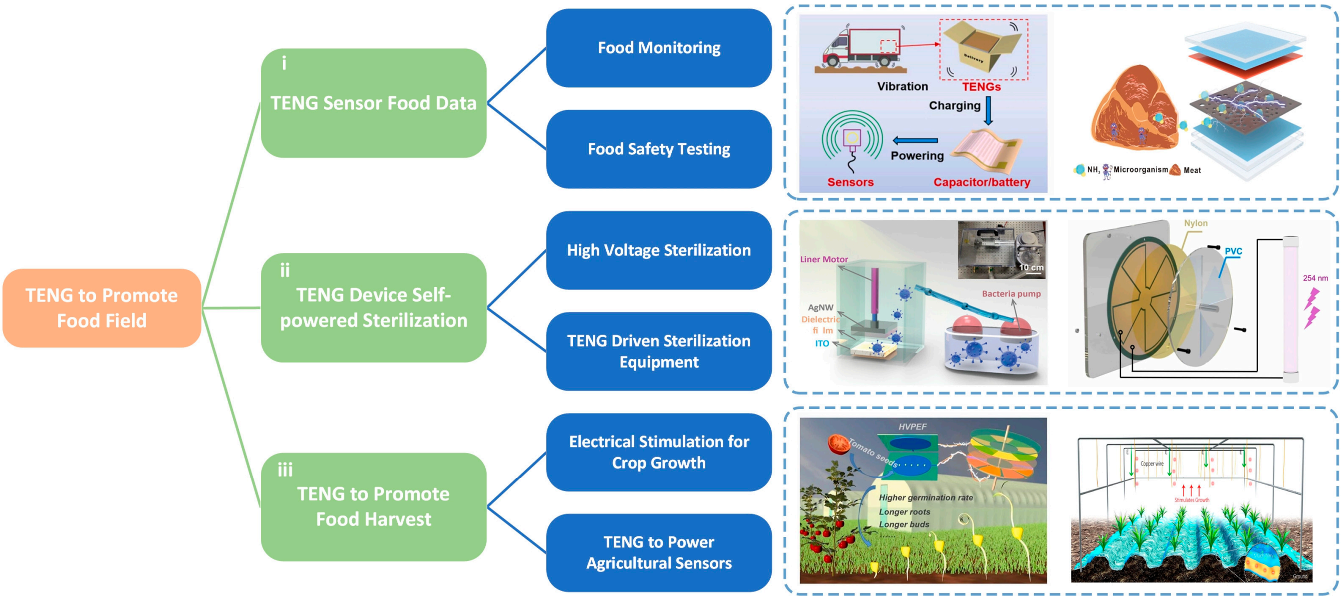

Figure 1. Schematic diagram of three ways in which TENG equipment can be used in the food field. i. TENG-based, self-powered sensor for food quality sensing. ii. TENG-based, self-powered sterilization equipment for food sterilization. iii. TENG-based, self-powered system to promote crop growth.

2. Principles and Working Principle of TENG for Food Application

The triboelectric nanogenerator (TENG) was invented to harvest mechanical energy by coupling triboelectricity and electrostatic induction [31,32]. When two dissimilar materials come into contact, a chemical bond charge is formed on their surface to balance their electrochemical potentials. Upon separation, some bonded atoms tend to retain extra electrons, while others tend to release them, creating triboelectric charges on the surface [33]. The presence of triboelectric charges on the surface of a dielectric material can drive the flow of electrons in the electrodes to balance the resulting potential dr510op. Based on this principle, TENGs have been studied under four different working modes.

2.1. Vertical Contact-Separation Mode

The vertical contact-separation mode is a type of TENG that involves coating electrodes on the top and bottom surfaces of a stacked structure. When two different dielectric film surfaces come into physical contact, oppositely charged surfaces are created. Upon separation, a potential drop in electrical potential occurs due to the small gap between the two surfaces under the action of an external force. If two electrodes are electrically connected by a load, free electrons in one electrode will flow to the other electrode, forming an opposite potential to balance the electrostatic field [33,34]. Once the gap is closed, the frictional charge generated will disappear, and the electrons will flow back to balance the potential difference between the two electrodes [35,36].

Vertical contact–separation mode has a simple structure, easy design, and high output performance [37,38]. Cai et al. proposed an ammonia-sensing TENG based on this working mode, which can maintain good performance and stability in the food cold chain within a specific range of temperatures and humidities (Figure 2a) [29].

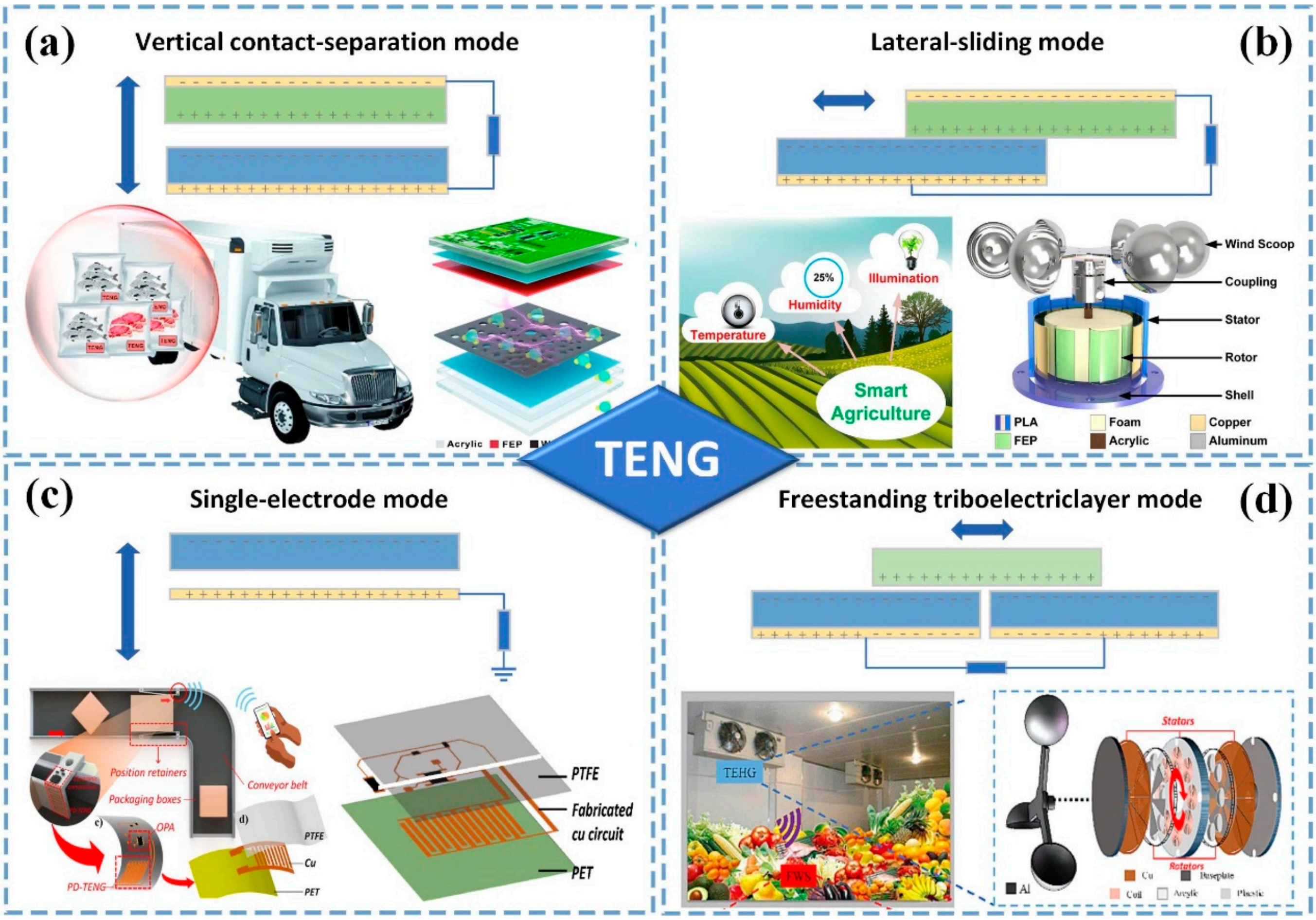

Figure 2. Schematic diagram of the four working modes of TENG applied in the food field. (**a**) Schematic diagram of TENG based on vertical contact separation mode; a vertical separation mode TENG for ammonia sensing. (**b**) Schematic diagram of lateral sliding mode; a lateral sliding mode TENG for wind energy harvesting. (**c**) Schematic diagram of single-electrode mode TENG; a single-electrode mode TENG for food location determination. (**d**) Schematic diagram of independent triboelectric layer mode TENG; a freestanding triboelectric layer mode TENG for powering food monitoring systems.

2.2. Lateral Sliding Mode

When two dielectric films come into contact in the lateral sliding mode, the relative film sliding parallel to the surfaces generates triboelectric charges on the two surfaces. This process introduces transverse polarization along the sliding direction, driving the flow of electrons on the top and bottom electrodes to balance the electric field generated by the triboelectric charge. A periodic slide apart and off produces AC output. Sliding can consist of planar motion, cylindrical rotation, or disk rotation. The first two modes have two electrodes connected to each other by a load so that the TENG can move freely [39,40].

TENGs in transverse sliding mode generally have good sealing properties and can effectively cope with variable humidity in food production [38]. Li et al. proposed a cylindrical TENG based on the lateral sliding mode to drive an electrical stimulation system, and they experimentally demonstrated that it could be used to drive various agricultural sensors to promote food growth (Figure 2b) [41].

2.3. Single-Electrode Mode

In some cases, the object that is part of the TENG cannot be connected to the load electrode. To obtain energy in this situation, a single-electrode TENG was introduced, in which the electrode at the bottom of the TENG was grounded. This mode is called the single-electrode mode. The approach or departure of the top object from the bottom will change the local electric field distribution so that there is electron exchange between the bottom electrode and the ground to maintain the potential change of the electrode [42]. This energy-harvesting strategy can be used in contact separation mode and contact sliding mode simultaneously.

The single-electrode mode has a simple design and wiring, facilitating energy collection while reducing the interference of complex designs in food monitoring [43]. Yang et al. used the friction characteristics of the friction belt itself to propose a TENG position sensor (PD-TENG) for food-delivery systems that is small and easy to manufacture. (Figure 2c) [44].

2.4. Freestanding Triboelectric-Layer Mode

The freestanding triboelectric layer mode is a type of TENG that involves plating two equal-sized and disconnected symmetrical electrodes on the back side of the same dielectric material. For example, if a charged object reciprocates between two electrodes, electrostatic induction will continuously produce potential difference changes between the two back electrodes, driving the free electrons on the back electrode between the two electrodes through an external load. The charged objects moving in this working mode do not necessarily need to be in direct contact with the dielectric layer, significantly reducing surface wear. This way is a good one for extending the durability of TENGs [45,46].

Taking advantage of this mode, Wang et al. reported a self-powered, flexible, wireless sensor based on a triboelectric electromagnetic hybrid generator (TEHG) for monitoring food quality (Figure 2d) [47]. The rotating TENG in the TEHG can harvest energy from the airflow when the cooling fan is running.

3. Triboelectric Nanogenerator Applications in Food Quality

3.1. Triboelectric Nanogenerators for Food Quality Testing

Food testing refers to the process of qualitative or quantitative analysis of harmful substances, microorganisms, or nutritional components in food [48]. Traditional food testing methods usually require the use of instruments, such as microscopes, chromatographs, and mass spectrometers [49,50]. Although these methods are accurate and reliable, they require professional operations and are time consuming and labor intensive. With the development of science and technology, new detection methods have also emerged. In recent years, detection methods based on nanotechnology have gradually become a popular research topic [51,52]. TENGs can be used to realize self-powered detection of food using mechanical energy to drive various biosensors and chemical sensors to achieve simple, fast, and sensitive detection of food. These new detection methods provide more choices for food safety and bring new opportunities to the development of the food industry.

Melamine (Mel) is sometimes used as an additive by unscrupulous businesses to improve the protein content index in food testing [53]. Long-term intake can cause damage to the human body, including the reproductive and urinary systems [54]. Zhu et al. developed a TENG-based, self-powered Mel-detection method by taking advantage of the strong electronegative characteristics of Mel [55], as shown in Figure 3a. The authors found that the addition of Mel could change the surface morphology and relative dielectric constant of the PTFE material, thereby increasing the triboelectric charge density. The current signal generated when the TENG was compressed or released increased as the Mel content increased. According to the linear relationship between the current change value and the Mel content, the Mel concentration could be calculated. Based on this phenomenon, the authors designed a highly sensitive Mel sensor based on a polytetrafluoroethylene TENG, which could achieve fast, simple, and low-cost detection of Mel. The sensor can be used not only to detect Mel in food but also to detect other biomolecules with strong electronegative properties.

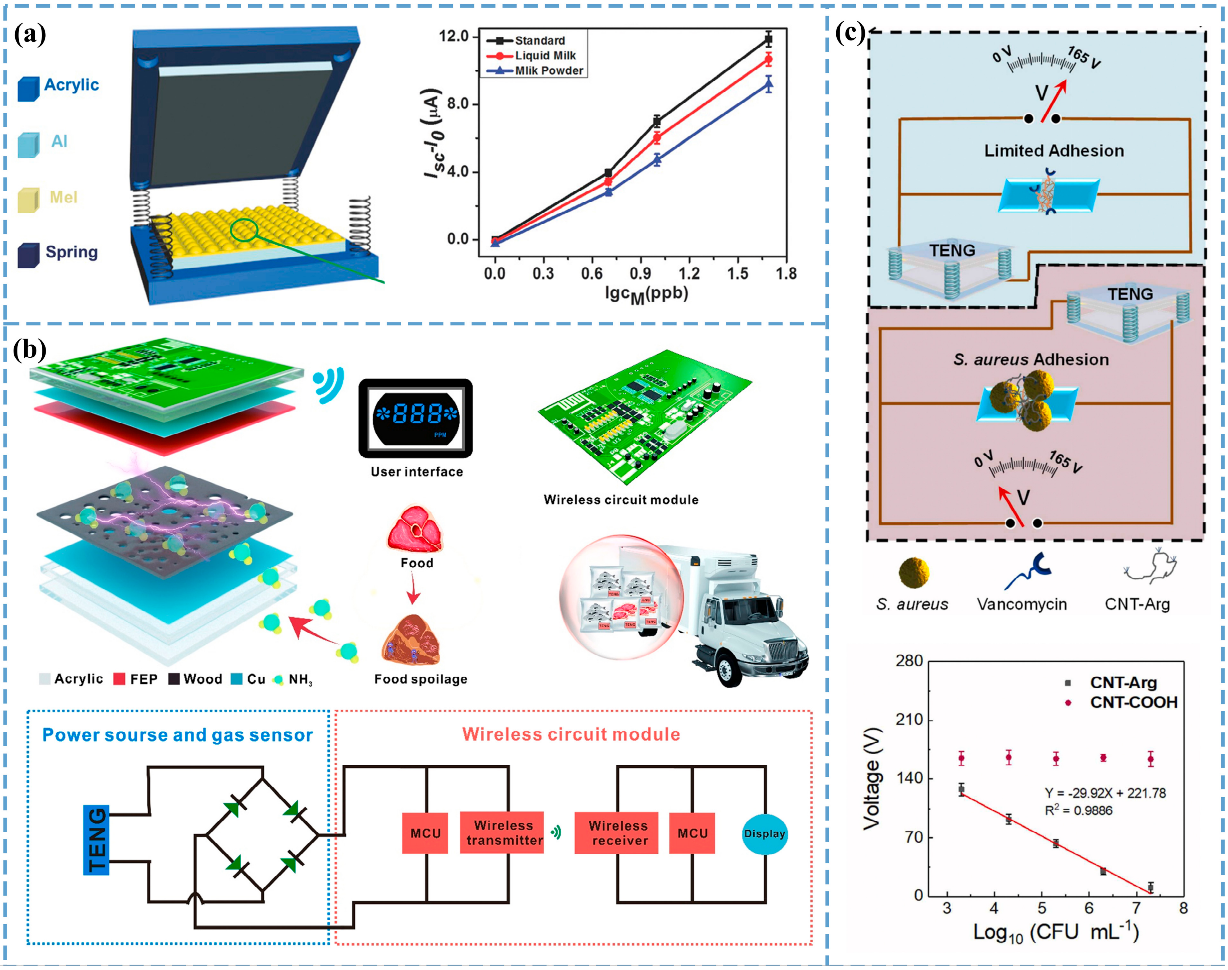

Figure 3. TENG used for food−quality testing. (**a**) Schematic diagram of Mel−based TENG; sensitivity of TENG in detecting Mel in standard samples, liquid milk, and milk powder samples. (**b**) TWGSS for food quality monitoring; equivalent circuit of TWGSS. (**c**) TENG−based, self-powered biosensing system detection; linear fitting of *Staphylococcus aureus* suspension response.

Ammonia is a marker of food spoilage [56,57]. Cai et al. proposed a wireless gas sensor system (TWGSS) based on a self-powered TENG to achieve selective, sensitive, and real-time wireless food quality assessment in cold supply chains (Figure 3b) [29]. Taking advantage of the three-dimensional porous structure of wood and the sensitivity of carbon nanotube materials to ammonia, they designed a porous wood TENG. When ammonia gas enters the porous wood TENG, ammonia will be adsorbed on the surface of the carbon nanotubes and undergo an oxidation reaction with oxygen ions, thereby releasing electrons and reducing the resistance of the conductive wood. Therefore, the surface charge density and resistance of the TENG change. The authors found that the output voltage of TENG decreased as the ammonia concentration increased, and it had high selectivity and sensitivity for ammonia. Leveraging system integration and power management, they implemented a self-powered triboelectric drive system that doubles as a gas sensor and wirelessly transmits data to the user interface. Under conditions of high humidity (75%) and low temperature (−18 °C), the selectivity, sensitivity, and stability of the TWGSS toward ammonia were verified, as well as its application in perishable foods, such as frozen chicken, fish, and beef.

Gram-positive bacteria can cause food spoilage and contamination [58,59]. Some common pathogenic bacteria may appear in liquid foods, such as milk, dairy products, juice, etc. [60]. Wang et al. developed a TENG-based, self-powered biosensing system for the specific detection of Gram-positive bacteria in solution (Figure 3c) [61]. This system utilizes vancomycin to identify and capture Gram-positive bacterial cells through specific vancomycin–bacterial wall interactions, utilizing guanidine-functionalized, multi-walled carbon nanotubes (CNT-Arg) as the signal amplification material. The resistance of the sensor changes according to the concentration of bacteria, thus affecting the output voltage. The vertical contact separation mode TENG uses aluminum foil and fluorinated ethylene acrylic copolymer (FEP) films as materials to power the system. It can convert mechanical energy into electrical energy with an initial output voltage of approximately 165 V. When there are bacteria on the sensor, the voltage of the TENG decreases as the bacterial concentration increases, reflecting the presence and number of Gram-positive bacteria.

Acetone is a common solvent used in food-processing plants [62,63]. However, the toxicity of acetone may pose a threat to food safety [64]. Therefore, it is necessary to detect the concentration of acetone gas in food testing. Liu et al. developed a TENG based on a chitosan (CTS)/zinc oxide (ZnO) double-layer film that can detect acetone gas at different concentrations of 1–10 ppm at room temperature [65]. The TENG uses triboelectric charges generated by the interaction between acetone molecules and ZnO in CTS/ZnO-TAS to detect acetone. It has high sensitivity (1.9545%/ppm), a low detection limit (1 ppm), and good selectivity and stability.

3.2. Triboelectric Nanogenerators for Food Monitoring

Food monitoring and management typically involve recording and querying information on all aspects of food from production to consumption, as well as tracking and monitoring the status and flow of food. Building flexible food monitoring systems generally requires an external power source, such as a supercapacitor or lithium battery. However, traditional battery power supplies face problems, such as limited life, messy wiring, and safety hazards, that must still be solved [66–68]. Overly complex systems may also bring inconveniences to the food industry in terms of space configuration and cost allocation [69]. Relying on the rapid development of the Internet of Things, TENG technology can be used to realize self-powered monitoring of food. TENGs use mechanical energy to drive various sensors and communicators, providing a guarantee for the safety, reliability, and intelligent traceability of food.

In food-delivery systems, methods to achieve food location detection may rely on independent external power systems and utilize various devices or sensors, such as photoelectric sensors [70]. To achieve miniaturized and flexible position detection, Yang et al. proposed a low-cost triboelectric nanogenerator position sensor (PD-TENG) for conveyor systems, which utilizes the friction characteristics of the conveyor belt itself to detect position (Figure 4a) [44]. The generator uses a contact-separation mode and includes a cardboard-based honeycomb frame, two PTFE/Cu friction layers, and food samples stored in the honeycomb holes. When the food sample comes into contact with or separates from the PTFE/Cu friction layer, a current signal is generated to monitor the position of the food. After the signal is amplified by the in-phase proportional amplifier circuit, it is converted into a digital signal through an analog-to-digital converter (ADC) and then carries out two-way wireless communication with the Bluetooth device through the serial port of the microcontroller unit (MCU) to achieve real-time food location information.

Wang et al. developed a self-powered flexible wireless sensor (FWS) based on a triboelectromagnetic hybrid generator (TEHG) for monitoring food quality [47], as shown in Figure 4b. The TEHG consists of two rotating TENGs and a rotating electromagnetic generator (EMG). It is driven by the air flow of the refrigeration fan and can achieve high-voltage, high-speed, and low-frequency energy harvesting. The rotary TENG uses PTFE and Cu electrodes as the rotor and stator, respectively, and generates frictional charges through relative rotation. The FWS includes multiple spectral sensors, microcontrollers, Wi-Fi modules, and flexible electronic paper, which can collect light reflection data on the food surface and evaluate the maturity parameters of the food through algorithms. Taking Philippine bananas as an example, these authors showed that the TEHG provides continuous power to the FWS, and the FWS uploads data to the cloud platform and flexible electronic paper to achieve real-time visual monitoring of food quality.

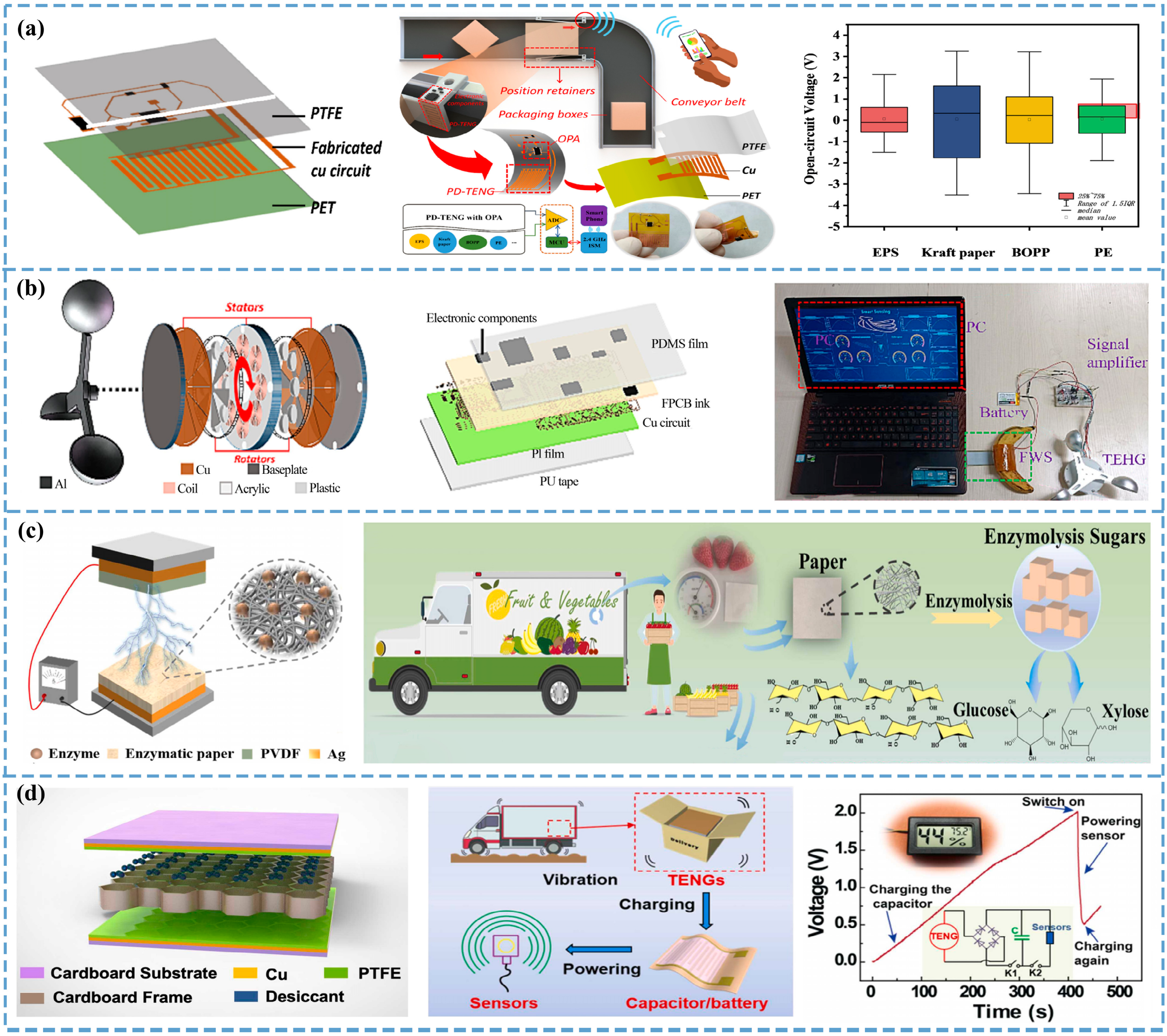

Figure 4. TENG for food monitoring. (**a**) Structure of PD−TENG; design layout of wireless sensing for food positioning on conveyor belt; voltage range of four common packaging materials. (**b**) Schematic structural diagram of TEHG; schematic structural diagram of FWS; food monitoring scenario, taking a banana as an example. (**c**) Schematic diagram of the TENG structure based on moisture-sensitive cellulose; schematic diagram of the TENG based on enzyme paper for monitoring fruit freshness. (**d**) Schematic diagram of D−TENG structure, and desiccant serves as a free-standing triboelectric material that can contact and separate from the top and bottom PTFE films; schematic diagram of an intelligent packaging system based on D−TENG; voltage changes of capacitors in the intelligent packaging system during the charge and discharge process.

Testing fruit freshness during storage is crucial to reduce fruit waste and foodborne contamination [71]. Du et al. utilized a new type of moisture-sensitive triboelectric cathode cellulose material to produce a TENG combined with fruit packaging (Figure 4c) [72]. Through biological enzymatic hydrolysis, the surface morphology and dielectric properties of cellulose fibers were changed, and a moisture-sensitive, positively charged cellulose material was prepared for the construction of an environmentally friendly TENG. When the enzymatic hydrolysis time is 72 h, the maximum output power density of the TENG is 80.3 mW/m^2. During storage, surface fibers are digested into xylose and glucose, thereby changing the roughness and contact area of the enzyme paper. The output signal of the TENG gradually decreases, as the humidity of the packaging environment changes, consistent with the changes in weight loss, hardness, decay rate, sweetness, and pH of the fruit, and the freshness of the fruit can be monitored.

Pang et al. proposed a desiccant-based triboelectric nanogenerator (D-TENG) driven a self-powered intelligent packaging system for monitoring the environmental conditions and deterioration of perishable food during transportation (Figure 4d) [73]. The D-TENG comprises a cardboard honeycomb frame, a PTFE/Cu triboelectric layer, and a desiccant filling the honeycomb holes. At a load resistance of 500 MΩ, the D-TENG can generate a maximum peak power of 0.7 mW. When the transport vehicle vibrates, the desiccant moves within the honeycomb frame, coming into contact with and separating from the friction layer to generate an electric charge, thus charging the energy storage unit and powering the digital thermometer/hygrometer. Therefore, the D-TENG can drive sensors to monitor the temperature and humidity inside the packaging. This self-powered integrated intelligent packaging system could serve as a model for future food packaging systems to achieve intelligent management and monitoring of food.

4. Application of Triboelectric Nanogenerator in Food Improvement

4.1. Triboelectric Nanogenerators for Food Sterilization

Food sterilization is the process of killing or inhibiting microorganisms in food through physical or chemical methods to delay food spoilage and deterioration [74]. Bacteria are closely related to changes in the freshness and quality of food, and sterilization is a process that can extend the shelf life of food. As consumers have higher requirements for delicious taste and nutrition, more food sterilization technologies are used in the food industry [75–77]. These methods usually require high temperatures, high pressure, ultraviolet light, ozone, and other technologies, which may require additional energy supply systems, greatly increasing the cost of food production. Triboelectric nanogenerators (TENGs) can use mechanical energy to drive various electric field generators and small sterilization equipment to achieve self-powered sterilization of food.

TENGs can be used to drive ultraviolet light sources for sterilization [78,79]. Jin et al. reported a self-generating ultraviolet disinfection device named Tribo-sanitizer, which can eliminate pathogenic bacteria, such as *Escherichia coli* O157:H7 and *Listeria* monocytogenes, from food (Figure 5a) [20]. With the optimized rotor design and charge saturation principle, the TENG in the Tribo-sanitizer can generate high-voltage output of up to 4000 V, driving a UV-C lamp to emit ultraviolet light at 254 nm. The disinfection effectiveness of two common foodborne pathogens (*E. coli* O157:H7 and *Listeria* monocytogenes) with liquid buffers, plastic films, and fresh produce was evaluated. The results showed that Tribo-sanitizer could achieve colony reductions of 5.95 log and 5.03 log, respectively, as well as significant cell membrane and DNA damage. This outcome demonstrates the potential properties of TENG to improve food safety.

Chen et al. designed and produced a self-powered sterilizer utilizing the high output voltage and breakdown discharge phenomenon based on a soft-contact, free-rotating TENG (soft-contact FR-TENG) (Figure 5b) [30]. The breakdown discharge not only increases the open circuit voltage of the TENG to 7.6 kV but also enables multi-mode sterilization based on high-voltage electric fields. Under closed conditions, self-powered sterilizers can effectively inactivate representative bacteria and mixed bacteria. This work provides an effective strategy for developing self-powered food sterilization systems.

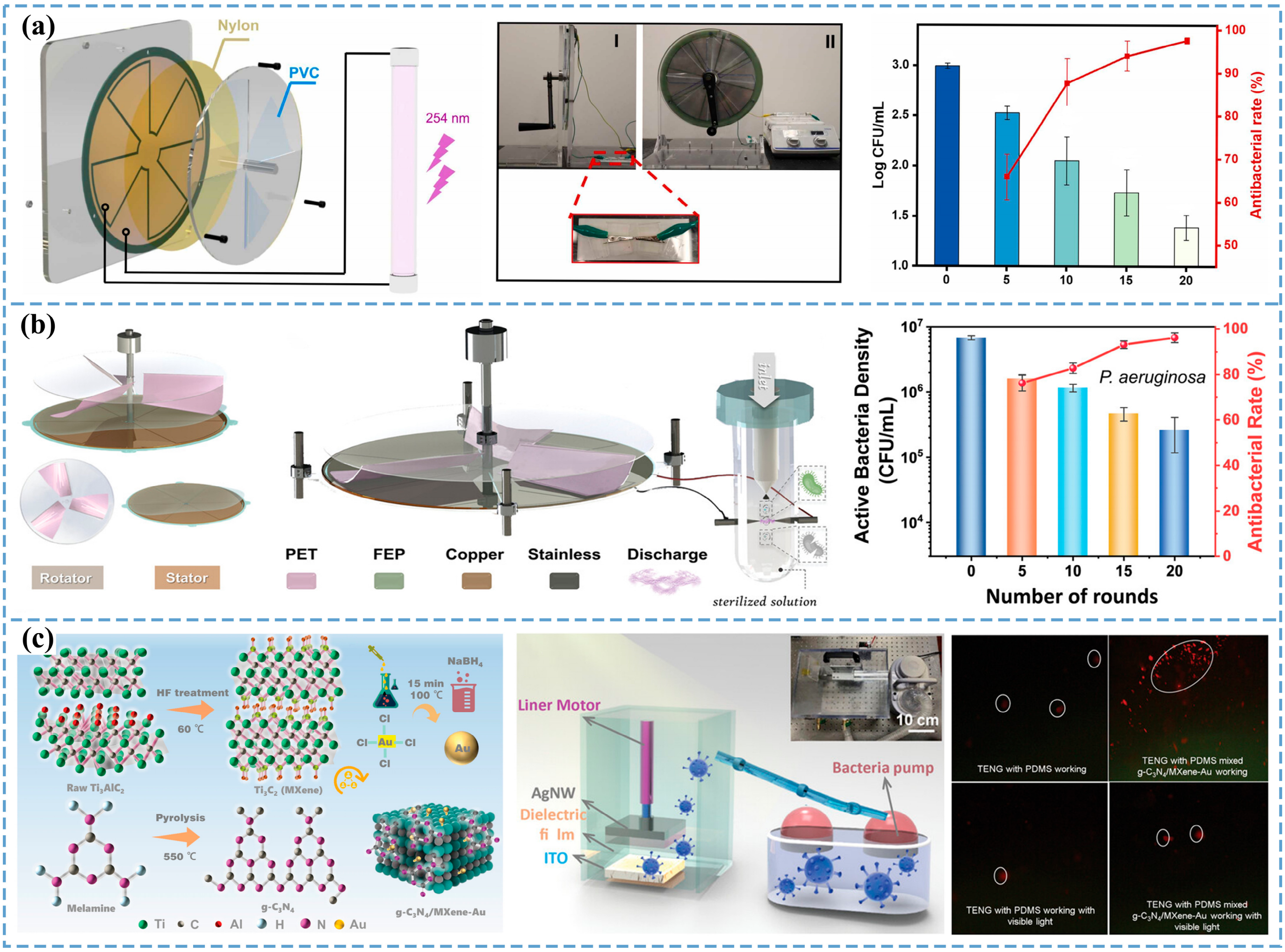

Figure 5. TENG for food sterilization. (**a**) The structure of a free-standing rotating TENG (FSR-TENG). Its stator consists of two electrodes; each electrode has four sectors. The FSR-TENG can power a 254-nm ultraviolet C (UVC) lamp. Middle panel shows the manual Tribo-sanitizer device I. from the side; and II. inactivating bacteria suspended in buffer saline. Right panel shows the changes in bacterial concentration and inactivation rate of *E. coli* O157:H7 over time. (**b**) Schematic diagram of the FR-TENG structure and the structural design of the self-powered sterilizer; the sterilization effect of the self-powered sterilizer on *Pseudomonas aeruginosa*. (**c**) Preparation process of $g-C_3N_4$/MXene-Au composite; system diagram and image of the sterilization system based on composite materials; comparison of the sterilization effect of TENG using composite materials and using PDMS.

Salmonella is a common pathogen that causes food poisoning, particularly in meat, dairy, and egg products, which are highly susceptible to contamination [80,81]. Chen et al. demonstrated a portable and effective Salmonella sterilization method using a TENG (Figure 5c) [19]. They proposed a strategy to improve the output performance of the TENG utilizing charge traps generated by the mutual coupling of photogenerated carriers and surface plasmons. The TENG adopts a vertical contact-separation mode and consists of two layers. The first layer is a silver nanowire electrode attached to PMMA, and the other layer is a mixture of PDMS and $g-C_3N_4$/MXene-Au composite material that is then spin-coated on ITO glass. Experimental results showed that the $g-C_3N_4$/MXene-Au composite had the best output performance under visible light irradiation, with a maximum open circuit voltage of 510 V and an output power of 20 mW. Taking advantage of the self-cleaning properties of this composite, the authors designed a TENG-based disinfection system and experimentally verified its effective killing effect on Salmonella.

4.2. Triboelectric Nanogenerators to Boost Food Production

In the process of food production activities, increasing grain yield and ensuring that producers obtain ideal economic benefits through planting are urgent problems that must be solved [82,83]. To promote continuous breakthroughs and development in agriculture, innovative agricultural production technologies are needed to improve the production efficiency and quality of crops [84,85]. In recent years, researchers have been exploring the application of TENGs in promoting crop growth. For example, TENGs can generate a weak electric field or current through mechanical vibration or acoustic wave excitation, which can in turn promote seed germination and seedling growth [86,87]. Relevant studies have found that external electric fields not only can shorten the germination period of seeds but also can enhance the stress resistance and yield of seedlings.

Li et al. demonstrated the application of TENGs in promoting tomato seed germination (Figure 6a) [86]. They proposed a rotary TENG (PFR-TENG) based on ternary medium friction charging, partial using soft contact and non-contact methods. Using the soft polyester fur layer as a charge pump and charge transmitter, wear and heat are reduced while maintaining 100% power output. The circuit generated DC voltage of 15 kV and AC voltage of 10 kV, as well as a maximum power of 201.83 mW. Using the high-voltage pulsed electric field generated by the PFR-TENG, tomato seeds were treated in different modes and times. The results showed that the seeds treated with a DC high-voltage pulsed electric field had the highest germination rate, shoot length, root length, germination index, and vitality index. The PFR-TENG provides a new solution for high-tech agriculture as a safe, portable, and low-cost high-voltage power supply.

Jiang et al. combined plant protein film with polylactic acid (PLA) film to prepare a bio-TENG with complete biodegradability, good mechanical properties, and excellent stability, and it is used as a new type of agricultural covering film [88] (Figure 6b). They constructed a space electric field to promote food harvesting. They then conducted a planting experiment on bean sprouts and vegetables. The electric field was generated by the prepared bio-TENG through the exciter system to simulate the process of collecting mechanical energy by the mulch film. The experimental results showed that the average length growth rate and average weight growth rate of bean sprouts covered with bio-TENG within 48 h were 132.4% and 19.1% higher than those of the control group, respectively. Using bio-TENG, the average height growth rate, average crown width growth rate, and average leaf number growth rate of covered vegetables within 11 days were 38.5%, 36.7%, and 18.2% higher than those of the control group, respectively.

Li et al. proposed a TENG driven by breeze energy (BD-TENG) for energy collection and sensor power supply in smart agriculture [41], as shown in Figure 6c. BD-TENG uses a blower to collect natural wind energy and drive sliding friction between the FEP film and the copper electrode to convert wind energy into electrical energy. With lightweight materials used to make the rotor and the designing of a suitable bailer structure, the energy conversion efficiency of BD-TENG can reach 12.06% at a wind speed of 4 m/s. It collects breeze energy in the natural environment to light up 300 red and blue light-emitting diodes connected in series to supplement lighting for crops at night. In addition, BD-TENG can also provide power for soil thermometers to monitor crop growth environments. This ability reflects the widespread application of BD-TENG in promoting crop yields.

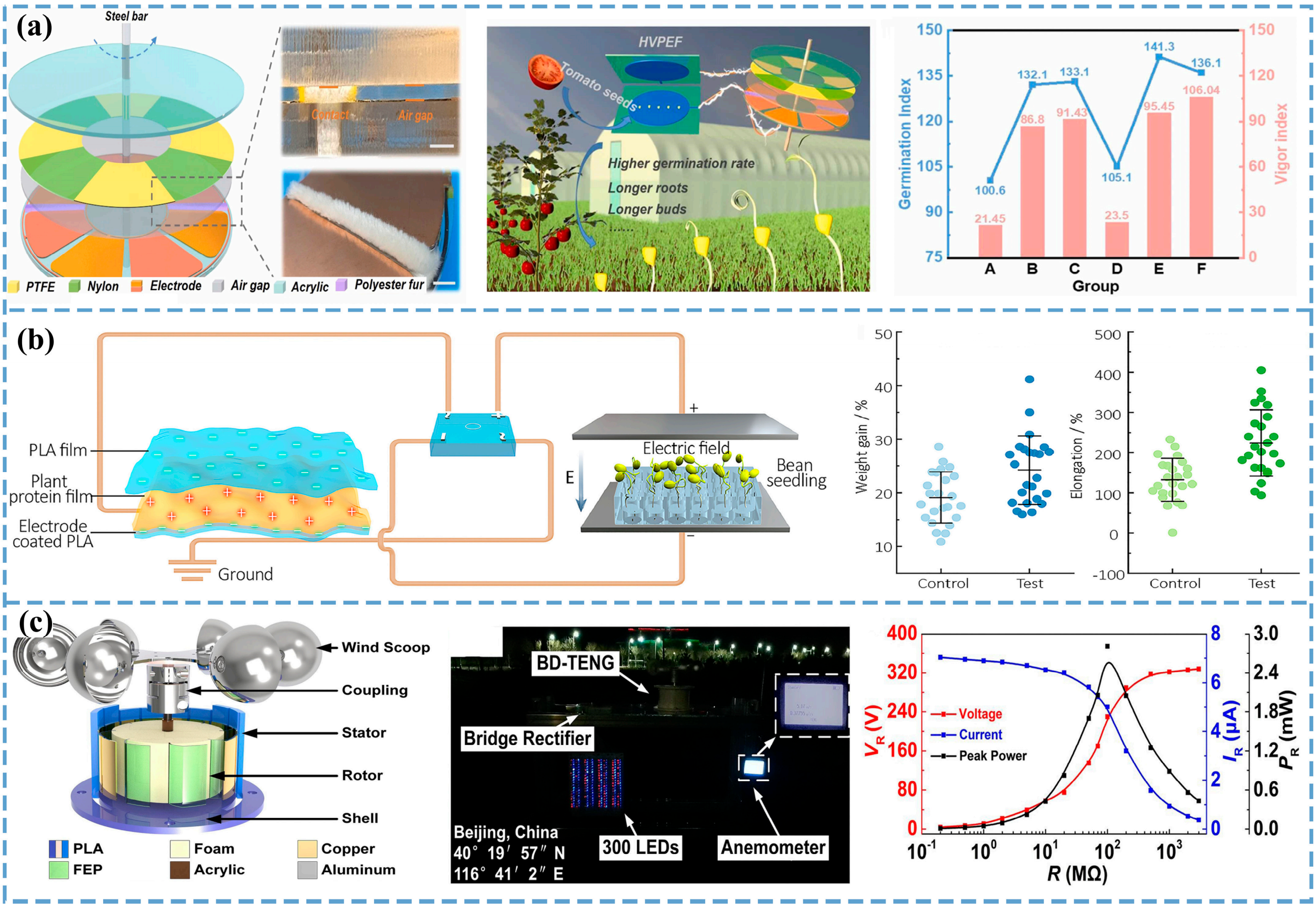

Figure 6. TENG to promote food production. (**a**) Hierarchical structure diagram of PFR−TENG, with a 2−mm air gap between the rotor and electrode; schematic diagram of PFR−TENG promoting tomato seed germination; germination and vitality indices of six groups of tomato seeds after 7 days. (**b**) Schematic diagram of the electric field experiment based on Bio−TENG; the weight gain percentage and elongation rate of the control group and the test group (with electric field). (**c**) Schematic diagram of the BD−TENG structure; the BD−TENG supplies power to 300 series−connected light-emitting diodes; the load current, load voltage, and peak power of the BD−TENG.

5. Conclusions

This review covers the application status and development trends of TENGs in food quality and food improvement, and it provides a detailed introduction and analysis from four aspects: food-quality testing, food monitoring, self-powered sterilization, and promotion of grain production. The application of TENGs in food safety and food quality has the advantages of not requiring an external power supply, no need for complex instruments, and no need to destroy food. TENGs can improve the safety and hygiene of food, as well as the quality and value of food.

By performing reasonable structural transformations and performance optimizations of existing research for TENG applications, it is possible to invest TENG technology into more food technologies. For instance, TENGs have currently been used for sterilization and disinfection of wearable devices [89,90], pipelines [78], tap water [91,92], and air [79]. These applications are not only related to environmental cleaning and protection but also closely linked to food safety. TENGs and food monitoring sensors should be compact and lightweight. These sensing systems can be implemented through integrated circuit designs and modular devices. For instance, integrating TENGs with circuit modules can enable the sensing system to collect energy efficiently and transmit data without affecting food storage.

Looking to the future, TENGs have broad prospects for food applications and are expected to realize self-powered, wireless, and intelligent detection, sterilization, antisepsis, evaluation, traceability, and monitoring of all aspects of food from production to consumption to maintain freshness. The new generation of TENG applications is expected to be more integrated with smart packaging technology and to use advanced preparation processes, such as soft photolithography, laser etching, etc., to make important contributions to the food industry.

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