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Contamination-Resilient, High-Output Triboelectric Nanogenerator With Fully-Recycled, Multi-Material Crumpled Balls

Minju Jee¹ | Kyunghwan Cha¹ | Seh-Hoon Chung¹ | Hyungseok Yong² | Youngho Jin³ | Jinkee Hong⁴ | Sangmin Lee¹ 

¹School of Mechanical Engineering, Chung-ang University, Seoul, Republic of Korea | ²Department of Mechanical Engineering, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA | ³Department of Advanced Materials Engineering, Chung-ang University, Anseong, Republic of Korea | ⁴Department of Chemical and Biomolecular Engineering, College of Engineering, Yonsei University, Seoul, Republic of Korea

Correspondence: Youngho Jin (yhjin@cau.ac.kr) | Jinkee Hong ([jinkee.hong@yonsei.ac.kr](mailto:jinkeehong@yonsei.ac.kr)) | Sangmin Lee (slee98@cau.ac.kr)

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ABSTRACT

With rapid industrialization, municipal solid waste (MSW) production has increased, necessitating effective recycling solutions. However, material sorting and chemical post-treatment processes reduce user convenience and contribute to environmental pollution. To solve this problem, this study introduces a fully recycled, multi-material crumpled-ball triboelectric nanogenerator (FRMC-TENG). This device is composed entirely of recycled materials by applying a unique and effective crumpled ball design. Among fully recycled material-based TENGs, the FRMC-TENG showed excellent electrical performance by adopting an electrostatic discharge generation mechanism and exhibited a high peak current output of 1.76 A. Output performance was improved by using a multi-ball mixing structure, and the optimal structure was determined through various experiments. The effect of kitchen contaminants on the device was assessed. Even after exposure to contaminants, its electrical performance quickly recovered with a simple wipe. The FRMC-TENG can be fabricated in less than 1 min using recycled materials, lit up 1000 LEDs, and maintained the performance for over 30 min of hand operation. Its contamination resistance and diverse applicability suggest an effective and novel strategy for waste-to-energy.

1 | Introduction

Owing to rapid global growth and increasing population density, municipal solid waste (MSW) generation is rapidly increasing. Annually, 2.01 billion tons of MSW are generated worldwide, and 33% of the generated MSW is not properly managed [1, 2]. Improper management of MSW, such as indiscreet disposal in landfills, illegal incineration, and marine pollution, poses

serious threats, including environmental pollution, resource depletion, and potential risks to public health [3, 4]. Recycling is the most eco-friendly method for handling MSW. However, it requires additional steps, such as cleaning, reclassification, and thermal treatment, which not only lower the recycling rate but also create additional pollution and waste during the process [5–7]. An efficient recycling strategy is crucial for mitigating the adverse environmental impacts of increasing waste

Minju Jee and Kyunghwan Cha contributed equally to this work.

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production. To address this issue, many studies have explored the potential of MSW as a reusable energy source, attracting global interest [8, 9].

Recently, triboelectric nanogenerator (TENG), which is an energy-harvesting method based on friction charging and electrostatic induction, has emerged as an attractive “waste-to-energy (WTE)” solution, because of its advantages such as broad material availability, low cost, and easy fabrication [10–12]. Many studies have proposed waste-based TENGs; however, most materials require post-processing because of the need for reclassification of mixed materials and the presence of contaminants [13–15]. Consequently, these TENGs share the same limitations as conventional recycling methods and exhibit significant output loss when exposed to contaminants [16]. Therefore, developing new strategies that enable easy manufacturing without additional processes while generating a high current output by utilizing MSW worldwide is essential.

This study proposes a fully recycled, multi-material crumpled-ball triboelectric nanogenerator (FRMC-TENG). This device is composed entirely of used aluminum foil, PVC wrap, and two hemispherical coffee cup dome lids. Despite their usability, these materials are representative materials that are difficult to recycle and cause environmental pollution because of their additives, contamination, and other complexities [17–23]. The advantage of the FRMC-TENG is that no post-processing is required, despite the device being made solely of recycled materials. Generally, TENGs are significantly affected by surface contamination. However, the FRMC-TENG adopts a crumpled ball structure that can hide the one-sided contaminated surface, thereby minimizing the impact of contamination that occurs during kitchen use. Even after the device has been exposed to contamination, its electrical output can be restored within 50 s of operation using a simple hand wipe.

The FRMC-TENG can achieve a high current output through the electrostatic discharge (ESD) generation mechanism. The

electrical performance is enhanced through the contact of multi-material balls. Interaction with PVC-wrap crumpled balls (WCBs) rapidly increases the surface charge of aluminum-foil crumpled balls (FCBs). In addition, FRMC-TENG is applicable to various forms—it can utilize various after-use disposal materials, such as coffee cups, food containers, and dome lids. Its ultra-light and durable structure greatly increases the user's hand operability. This study demonstrates the application of a dome-lid-based FRMC-TENG, which can be fabricated in less than 1 min. The device generated a high current output of up to 1.5 A and lit 1000 LEDs using only recycled materials. This approach presents a new strategy to enhance the usability of future WTE technologies.

2 | Results and Discussion

Figure 1a illustrates the materials used to fabricate the FRMC-TENG. This device requires a closed container, a thin polymer film, and a thin metal film, with common examples including coffee cups, PVC wraps, and aluminum foil. These materials are frequently used in kitchens owing to their convenience and high strength [24, 25]. However, they are generally discarded after a single use and are difficult to recycle because they contain contaminants. Consequently, they are usually landfilled, contributing to long-term environmental pollution [26, 27]. The FRMC-TENG provides a simple and chemical-free method to repurpose these materials into energy devices in a way that anyone can do at home. Figure 1b shows a simplified conceptual diagram of an FRMC-TENG. The device was fabricated using only disposable products. The PET hemispherical dome lids of the coffee cup were used as the substrate, and 5×5 cm aluminum foils were attached to both the top and bottom of the device as electrodes. The aluminum foil and PVC wrap were crumpled into 1.5 cm diameter balls. The final device weighs less than 50 g and has a spherical design with a diameter of 12.5 cm, making it easy to hold and operate by hand. Figure 1c shows the characteristics of the FRMC-TENG composed of repurposed materials

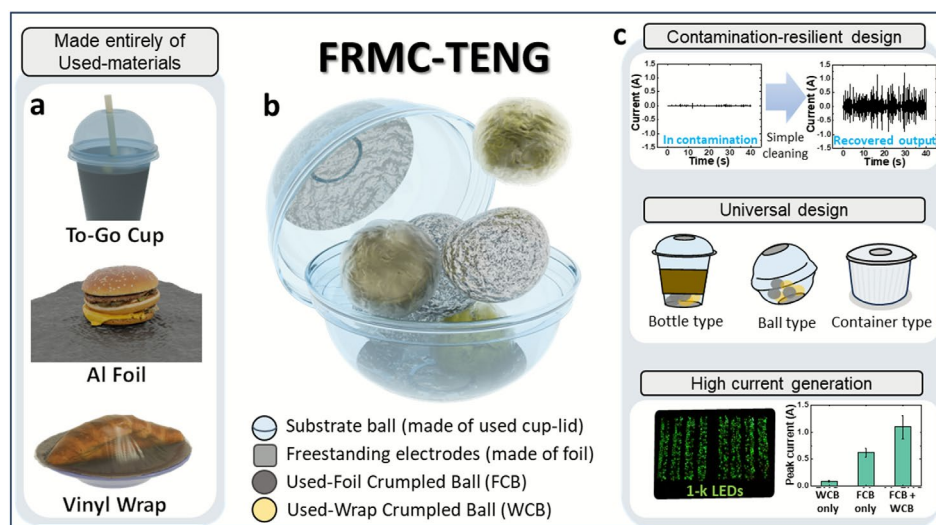


FIGURE 1 | Concept and characteristics of the fully recycled, multi-material crumpled-ball triboelectric nanogenerator (FRMC-TENG): (a) 3D structure of the FRMC-TENG, composed entirely of used materials; (b) schematic diagram of the FRMC-TENG; (c) characteristics as a hand-operable device.

as an energy-generation device. The proposed crumpled-ball design efficiently reduces the impact of contaminated materials used in food packaging because it can hide contamination on one side without exposure. Even after exposure, the FRMC-TENG can recover its electrical performance with simple hand wiping. The continuous contact separation between the WCB and FCB induces a strong surface charge on the balls, which rapidly restores the high ESD output. Surface charge density is an important factor for improving the output performance of TENG devices. This strong charge-induction effect allows the device to quickly restore electrical output even after the substrate has been exposed to contaminants. A major advantage of the FRMC-TENG is its universal design, making it not limited to specific applications. FCB and WCB can be made from most materials that can be crumpled, and an FRMC-TENG can be fabricated as long as a substrate is present that can contain them. This is an effective strategy from a WTE perspective as it can utilize various types of waste materials while greatly increasing convenient production. In addition, the performance of the device was improved by incorporating an air-breakdown mechanism to overcome the issue of low current output. While traditional TENGs relying solely on fully recycled materials typically produce low current outputs in the range of a few microamperes, this mechanism enables the FRMC-TENG to generate a high output of up to 1.6 A [28, 29]. Furthermore, by adding WCBs, a stronger surface charge was induced in the FCBs, resulting in an enhanced electrical performance compared to configurations using only FCBs. Specifically, the WCB-mixed structure showed a 215% increase in current output compared with the FCB-only design. In addition, when compared with a device consisting solely of WCBs, the FRMC-TENG achieved a 4100% increase in current output.

Figure 2a shows the working mechanism of the FRMC-TENG, comparing two different configurations: one device with two FCBs and another with one WCB and one FCB. Both devices exhibited high electrical output because of direct electron transfer facilitated by the air-breakdown phenomenon. When the aluminum FCB collides with the polymer material, a positive surface charge is induced because of the difference in electron affinity. This positive surface charge on the FCB attracts a negative charge on the electrode through electrostatic induction, and a stronger electric field is formed as the FCB and electrode move closer. According to Paschen's law, electrons accumulated on an electrode under a strong electric field are accelerated by field emission and collide with molecules in the air, causing ionization. This process generates additional positive ions and electrons, resulting in an electron avalanche [30–32]. Eventually, air breakdown occurs, and the breakdown voltage of the air is generally 3000 V/mm. As a result, direct electron transfer occurs between the electrode and the FCB, generating a high peak output [33–36]. The key difference between the two device configurations lies in the material primarily responsible for inducing surface charge on the FCB. For the device composed solely of FCBs, the positive surface charge on the FCB is mainly induced through contact with the PET substrate. During operation, rolling-type contact separation occurs, and owing to the difference in electron affinity between the two materials, negative surface charges are accumulated on the PET substrate, and positive surface charges are accumulated on the aluminum FCB. When the distance between the FCB and the

electrode becomes sufficiently small to cause air breakdown, direct electron transfer from the electrode to the FCB occurs, generating a strong negative peak output. In contrast, for the device with both FCBs and WCBs, the surface charge on the FCBs is induced by both the PET substrate and the PVC WCBs. Because PVC generally has a higher electron affinity than PET, the FCB develops a higher positive surface charge when in contact. This enhanced surface charge allows ESD to occur over longer distances, improving the electrical output performance of the device. As shown in Figures 2b and S1, the FRMC-TENG generated peak currents of 1.46, 0.68, and 0.07 A and peak voltages of 307, 166, and 26 V for devices with 3 FCBs + 3 WCBs, 6 FCBs, and 6 WCBs, respectively. Generating an ESD using only WCBs without FCBs is difficult. Therefore, the device with six WCBs produced only a small electrical output based on the electrostatic induction phenomenon, and the power generation mechanism is presented in Figure S2. Figure S3 presents the expanded electrical performance of an FRMC-TENG composed of six FCBs. The device demonstrated a significant increase in output because of the ESD generation mechanism, and further performance improvements were observed when three of the FCBs were replaced with WCBs. Figure 2c shows the maximum peak power as a function of external load resistance under different ball configuration conditions. The device with 3 FCBs + 3 WCBs achieved a peak power of 0.77 W, the device with 6 FCBs reached 0.18 W, and the device with 6 WCBs produced 3.7 mW, under external resistances of 1, 0.2, and 20 M Ω , respectively. Figure S4 shows an enlarged graph of the peak power as a function of external resistance for the device with six WCBs. Figures 2d and S5 show the average current per cycle and raw current graph for 300 cycles when the device was operated at 120 rpm. The introduction of WCBs increased the number of contacts that induced charge on the aluminum balls. This led to rapid surface charge accumulation on the aluminum balls, and as a result, the device steadily generated a saturated output of 0.85 A after 150 cycles.

To further investigate the effect of WCB on electrical output, the electrical output was measured for different WCB materials. Figure 2e presents the voltage output of the FRMC-TENG with a single electrode, operated at a low input speed of 10 rpm. The device with a nylon WCB showed a negative peak voltage of -140 V, while the device with a PVC WCB showed a positive peak voltage of 98 V. Nylon is a representative positive triboelectric material [37, 38]. When contact separation occurs between the nylon WCB and the aluminum ball, a negative surface charge is induced on the aluminum ball. As this negatively charged FCB approaches the electrode, electrons move from the electrode to the aluminum ball, resulting in negative voltage peaks. Conversely, when PVC, a negative triboelectric material, is used as the WCB, a positive surface charge is induced on the aluminum ball. As the distance between the electrode and the FCB decreases, the charge moves from the electrode to the aluminum ball. These results indicate that the WCB plays a more significant role than the PET substrate in supplying charge to the FCB. Figure 2f shows the variations in electrical performance caused by different WCB materials in the freestanding electrode structure. When nylon, PET, PVC, and PTFE films were crumpled into balls of the same size and applied as WCBs, the voltage outputs were 163.0, 98.2, 165.1, and 219.2 V, respectively, and the current outputs were 0.77, 0.69, 1.05, and 1.08 A, respectively. The raw voltage and

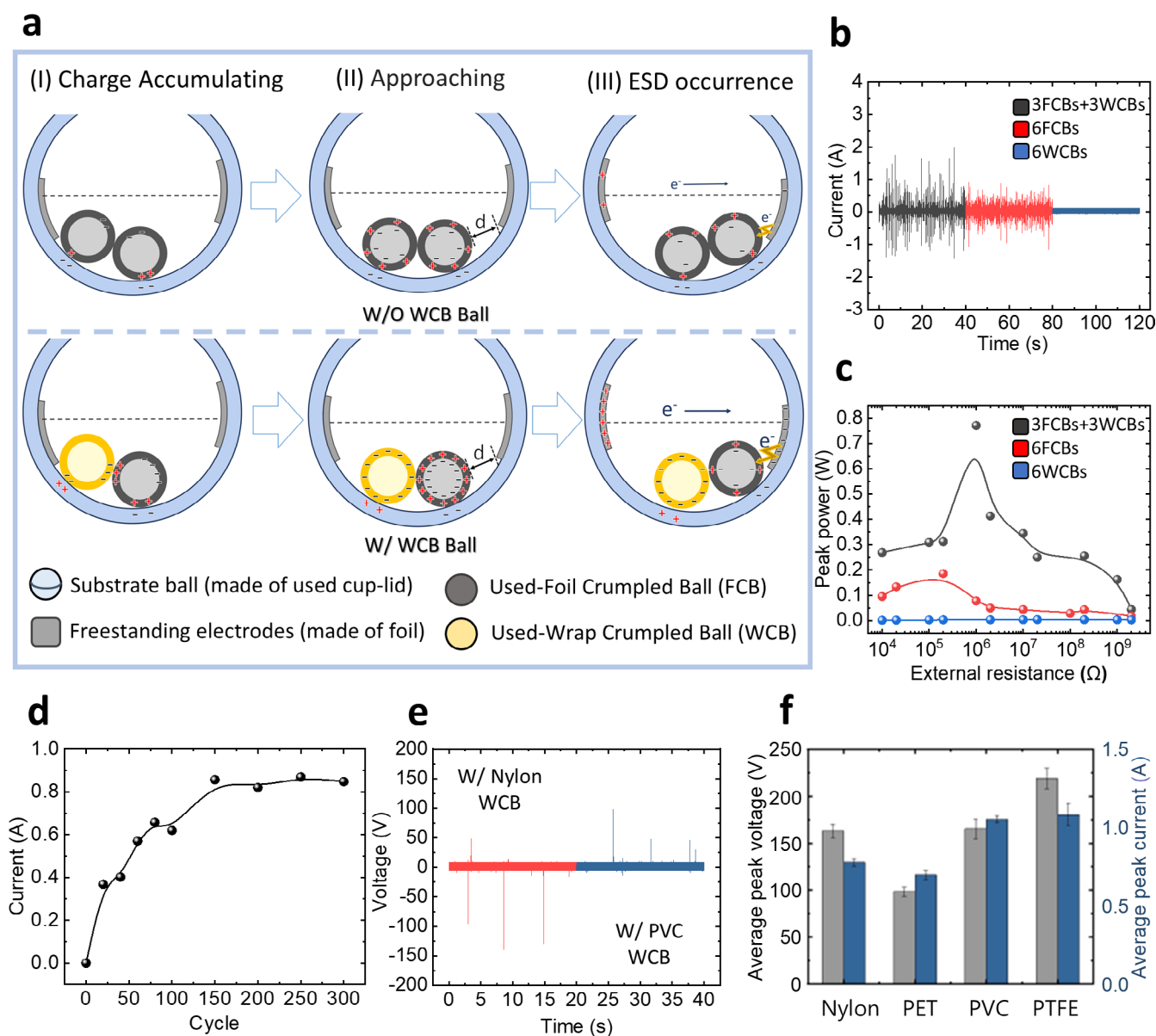


FIGURE 2 | Working mechanism and output of the FRMC-TENG: (a) schematic illustration of electrostatic discharge (ESD) generation mechanism with and without PVC-wrap crumpled balls (WCB) in the FRMC-TENG; (b) current output and (c) peak power as functions of external load resistances for FRMC-TENGs with different components; (d) peak output current for 300 working cycles; (e) peak voltage output of single electrode FRMC-TENG for different PVC-wrap crumpled balls (WCB) materials; (f) average peak voltages and currents of the FRMC-TENG with WCB materials.

current graphs for each data are shown in Figures S6 and S7. These differences in electrical output are due to differences in electronegativity between the FCB and WCB materials. These results are consistent with those of known triboelectric series [39, 40].

In a typical kitchen environment, aluminum foil and polymer wrap are commonly used as food packaging materials, with one side in direct contact with food and the other clean side that is exposed to the outside. Because TENG usually shows a sharp decrease in output when contaminants are exposed on the surface that contacts the electrode or counterpart material, these materials can be effectively utilized by concealing the contaminated side. Figure 3a shows the effect of the folding direction on the output performance. One group folded

all materials inward to minimize contamination exposure, whereas the other group folded them outward to assess the effect of contamination on the output. The crumpled design was folded inward by the user to minimize the impact of contamination on the exposed surface. The experiment was conducted using six balls—three FCBs and three WCBs. Figure 3b,c show the average peak voltages and currents for the inward and outward folding of the contaminated FCBs and WCBs. The FRMC-TENG with inward crumpled balls generated output currents of 1.26, 1.34, 1.35, and 1.33 A and output voltages of 172, 190, 184, and 186 V for honey, ketchup, mayo, and oil, respectively. For comparison, the device without contaminants generated an output of 1.44 A and 204 V (dotted line in the figures). The raw voltage and current graphs for each data set are shown in Figures S8 and S9.

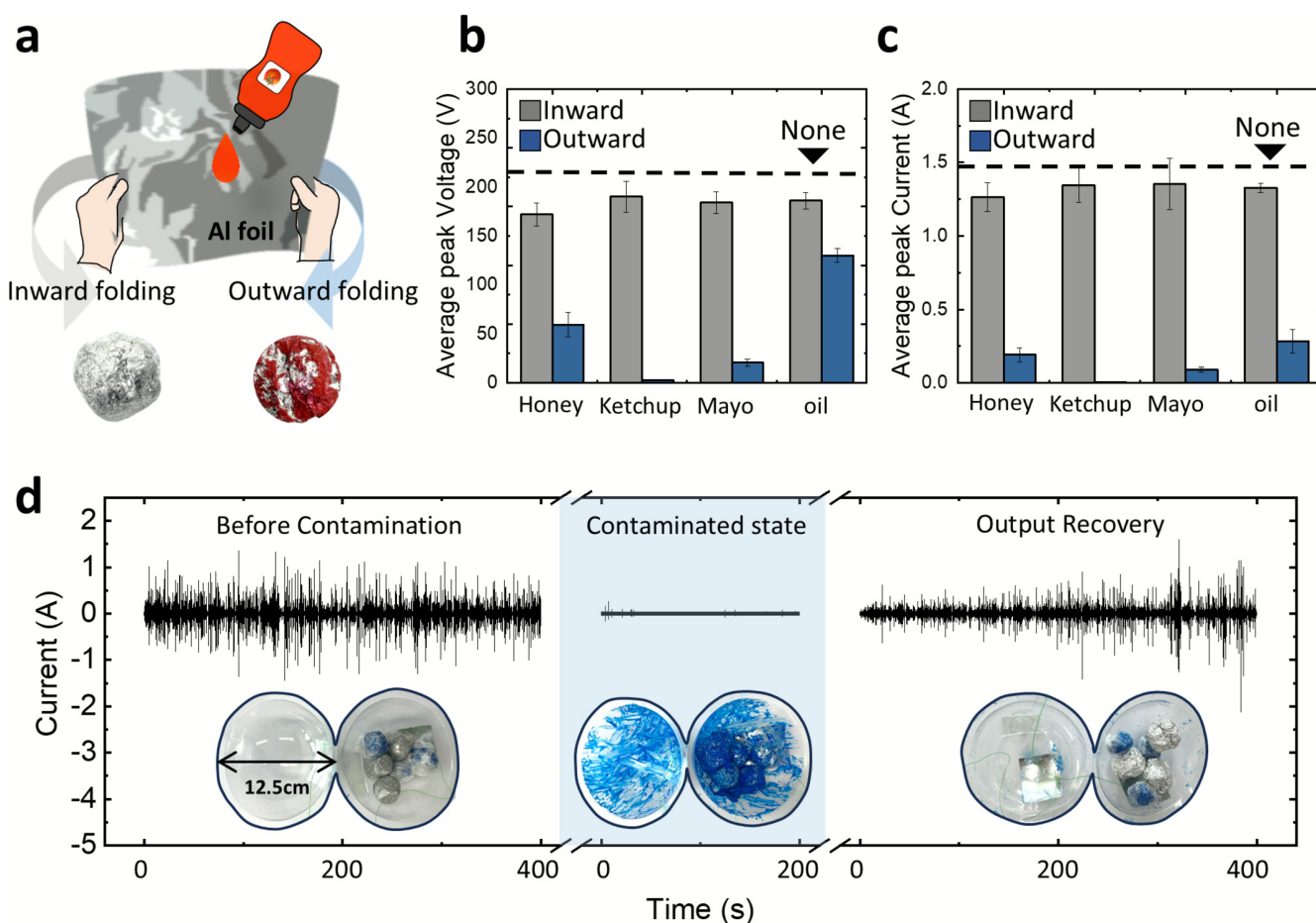


FIGURE 3 | Effect of contaminants on the FRMC-TENG: (a) schematic of the folding used in FRMC-TENG to determine the effect of contaminant exposure; (b) average peak current and (c) voltage of the FRMC-TENG under exposure to different kitchen contaminants; (d) output current of the FRMC-TENG (device diameter: 12.5 cm) before contamination, after contamination, and after simple hand wiping.

On the other hand, the device with outward crumpled balls, where contaminants were exposed, generated output currents of 0.2, 0.003, 0.09, and 0.28 A and output voltages of 49.4, 2.24, 17.3, and 108.4 V with honey, ketchup, mayo, and oil, respectively. The raw voltage and current graphs for each data set are shown in Figures S10 and S11. These results indicate that when the device is exposed to contaminants, the output is significantly reduced. Because TENGs are greatly influenced by surface charge, contaminated devices are affected during operation because of a reduction in the surface charge density [41]. When a device becomes contaminated, foreign particles can hinder effective contact between materials, reducing the surface charge density. This reduction in charge density can severely affect the ability of the device to generate sufficient electrical output. Additionally, contaminants may physically block or interfere with the interactions between the triboelectric materials, further impairing the ability of the device to generate electricity. These results demonstrate that crumpled balls with contaminants folded inward can minimize output reduction, confirming their suitability as materials for high-power TENG devices.

Furthermore, contamination of the substrate causes a decline in electrical performance, which is difficult to recover. To address this problem, some studies have proposed additional chemical

cleaning processes or the use of self-cleaning materials [42, 43]. Although these methods are effective, chemical processes are impractical for household use, and self-cleaning materials are rarely available in kitchen environments. Therefore, these approaches are unsuitable for recycled material-based devices. However, the FRMC-TENG showed high output recovery even after simply wiping off the contaminants from the substrate ball, without the need for chemical post-processing, owing to the strong surface charge induction effect between the WCB and FCB. Figure 3d shows the electrical output under different contaminated conditions of the substrate ball.

The “before contamination” case shows the output of the device without any contaminants. In this case, an average peak current of 1.1 A was steadily produced. Thereafter, all the FCBs and WCBs were folded in a way that the contaminants were exposed. In the “contaminated state” case, the substrate ball quickly became polluted, causing an initial low peak output of 0.26 A, followed by a large decrease in performance. This is because the contaminants screen the surfaces of the substrate, FCBs, and WCBs, disrupting the induction of surface charges. Moreover, the thin film of contaminants between the FCB and the electrode prevents the already reduced surface charges from approaching sufficiently close to trigger air breakdown, further diminishing the performance of the device. However, with a

simple cleaning process, such as wiping with tissue, the device can recover its electrical performance.

The device, which consists of a substrate ball wiped with tissue and crumpled balls with contaminants folded inward, quickly recovers its surface charge through interaction. After 300s, it generated a peak output of 1.1 A, closely matching its performance before contamination. These results indicate that a simple cleaning process can restore the output, even when contaminants are present on the substrate. This is because, as shown in Figures S12 and 2e,f, the contact separation between the crumpled balls has a more significant effect on the surface charge than the influence of the substrate ball. As a result, even if the substrate ball is not completely removed contaminated, the surface charge of the crumpled balls is restored, thus restoring the device's electrical output. By simply wiping the substrate to remove contaminants, the output can be restored to its original level. These results demonstrate that the device can be easily fabricated and maintained through a simple process, even after all the materials have been contaminated.

Additional experiments on crumpled balls were conducted to optimize the output of the FRMC-TENG. Figures 4a and S13 show the current and voltage output, respectively, as the number of WCBs varies (1, 2, 3, 6, and 9 units), while the number of FCBs remains fixed at one, to analyze the effect of the FCB-WCB ratio on the output. As shown in Figure 4b, the average peak voltages of 36, 67.1, 60.9, 56.6, and 43.2 V and the currents of 0.32, 1.2, 1.08, 0.64, and 0.52 A were generated when the numbers of WCBs were 1, 2, 3, 6, and 9, respectively. According to the ESD generation mechanism, the air breakdown effect usually results in an immediate discharging of the surface charge [44]. When the number of WCBs increases from one to two, the contact separation between the FCB and charge-inducing WCBs becomes more frequent, which increases the surface charge on the FCB, thereby improving the output when the FCB contacts the electrode. However, the increased number of WCBs not only impedes the movement of the balls but also impedes the contact between the FCB and the electrodes. The number of peaks generated per second was up to 10, 11, 8, 5, and 5 units for 1, 2, 3, 6, and 9 WCBs, respectively (Figure 4c). The enlarged current

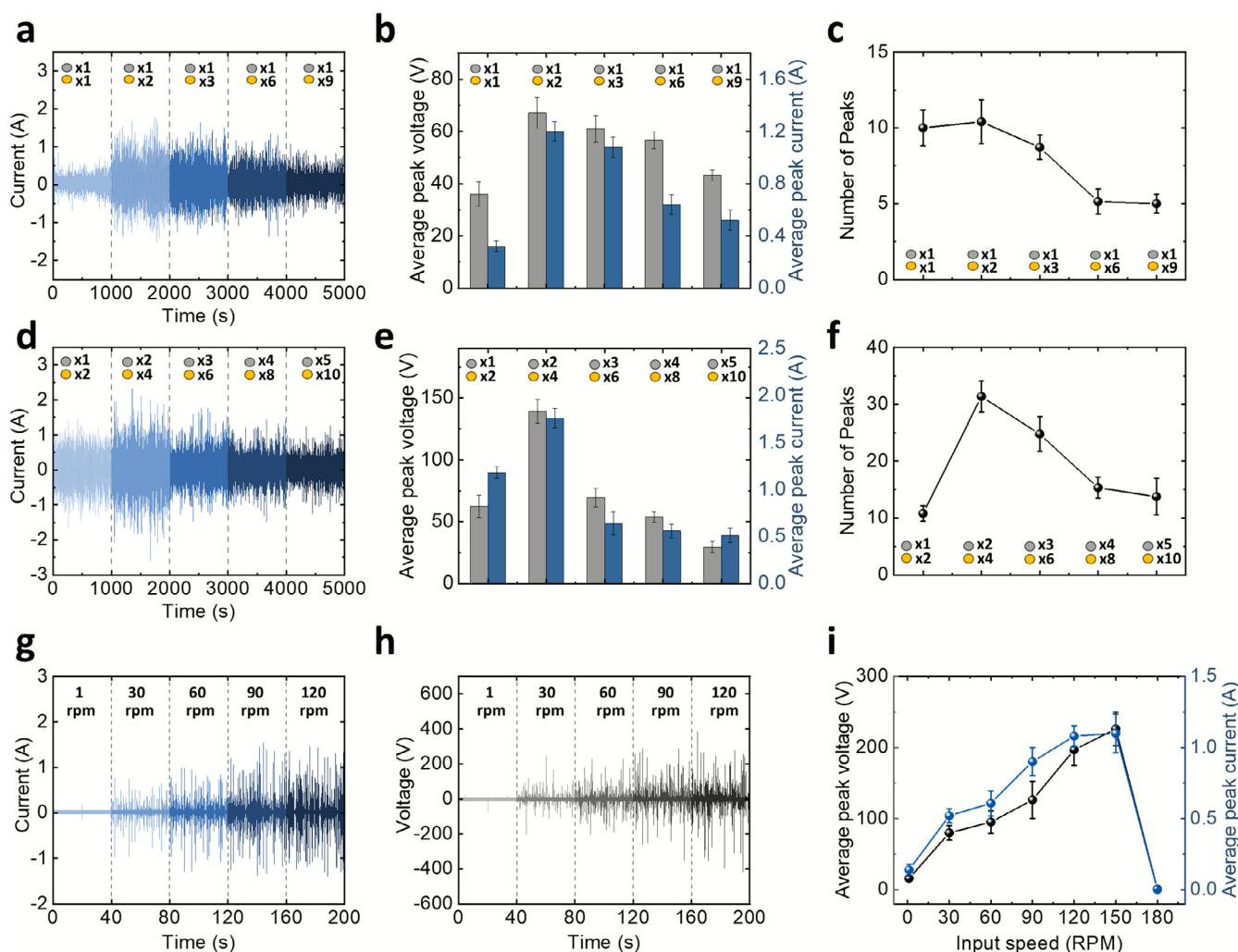


FIGURE 4 | Structure variables and optimization of the FRMC-TENG: (a) current output of FRMC-TENG depending on the number of PVC-wrap crumpled balls (WCBs); (b) average peak voltage and current and (c) number of peaks of the FRMC-TENG with varying number of WCBs; (d) current output of FRMC-TENG with different number of balls with the same composition ratio; (e) average peak voltage and current and (f) number of peaks of FRMC-TENG with different number of balls; (g) peak current, (h) voltage, and (i) average peak voltage and current of the FRMC-TENG under various rotational inputs.

graphs for the confirmed frequency are shown in Figure S14. A higher number of peaks was obtained when two WCBs were used. However, after that, the number of peaks gradually decreased. As the number of WCBs increases, the overall density of the substrate rises, which interrupts the direct contact between the FCB and the electrode, leading to a decrease in frequency. Therefore, the maximum electrical output was generated when the FCB-to-WCB ratio was 1:2.

Figures 4d and S15 show the current and voltage output as the number of FCBs and WCBs increases while maintaining a 1:2 ratio. The average peak voltages of 62.5, 139.2, 69.5, 53.8, and 29.4 V and the currents of 1.18, 1.76, 0.64, 0.56, and 0.51 A were measured when the number of FCBs and WCBs was in a 1:2 ratio, specifically with 1, 2, 3, 4, or 5 FCBs and 2, 4, 6, 8, or 10 WCBs, respectively (Figure 4e). The electrical output increased as the number of FCBs increased from 1 to 2, whereas it decreased when the number increased from 3 to 5. The initial improvement in electrical performance with the increasing number of FCBs is because of the increased number of free electrons. However, as the number of balls further increases, the free movement of the balls is hindered owing to friction between them. The balls remain attached to each other as a bulk mass, which prevents the contact-separation process and reduces the surface charge induction effect for the FCBs. Additionally, an increased number of WCBs interferes with the contact between the electrodes and FCBs. As shown in Figures 4f and S16, when the number of FCBs increased from 1 to 2, the number of peaks increased from 10 to 31. However, after the FCB count reached 3, the number of peaks decreased to 24, and with 4 and 5 FCBs, the number of peaks further decreased to 15 and 13, respectively. Consequently, as shown in Figure S17 optimal electrical performance was achieved with two FCBs and four WCBs, which occupied approximately 20% of the substrate space, various ball ratios (1:1, 1:2, 1:3 and 2:1).

Moreover, the influence of external force on the electrical output was examined based on the input revolutions per minute (RPM). Figure 4g,h shows the electrical performance of the FRMC-TENG at different rpms. The measured current and voltage outputs were 0.14, 0.52, 0.6, 0.9, 1.08, and 1.1 A and 16, 80, 95.2, 196.8, and 226 V at rotation speeds of 1, 30, 60, 90, and 120 rpm, respectively. The maximum electrical output increased as the rotation speed increased from 1 to 120 rpm because the increased contact separation rate between the FCBs and WCBs induced greater surface charge simultaneously. Figure 4i shows the average peak voltage and current for different input speeds, showing a decrease at 180 rpm. As the speed increases, the centrifugal force acting on the internal balls also increases. Up to 120 rpm, the centrifugal force remains relatively low, allowing the balls to move freely and make effective contact with the electrodes. However, when the speed exceeds 180 rpm, the voltage and current output rapidly decrease (Figure S18). This is because excessive centrifugal force causes the balls to stick to the substrate wall, preventing them from moving to the electrode. This irregular contact with the electrodes results in a prolonged period without contact, leading to a rapid decrease in output. However, as shown in Figure S19, our device can be operated in any direction by hand (unlike a motor that moves along a single axis); therefore, electrical output can still be generated efficiently by simply operating the device at a rapid pace.

Figure 5a illustrates the fabrication process of the FRMC-TENG using kitchen waste materials. Common daily-use items, such as aluminum foil, vinyl wrap, and coffee cup dome lids are typically contaminated when discarded after use, making it difficult to recycle them in their original form. These materials usually require post-treatment to enable recycling. In this study, we proposed a strategy to eliminate the need for this additional post-treatment process. The optimal configuration was determined to be two FCBs and four WCBs based on experiments. The

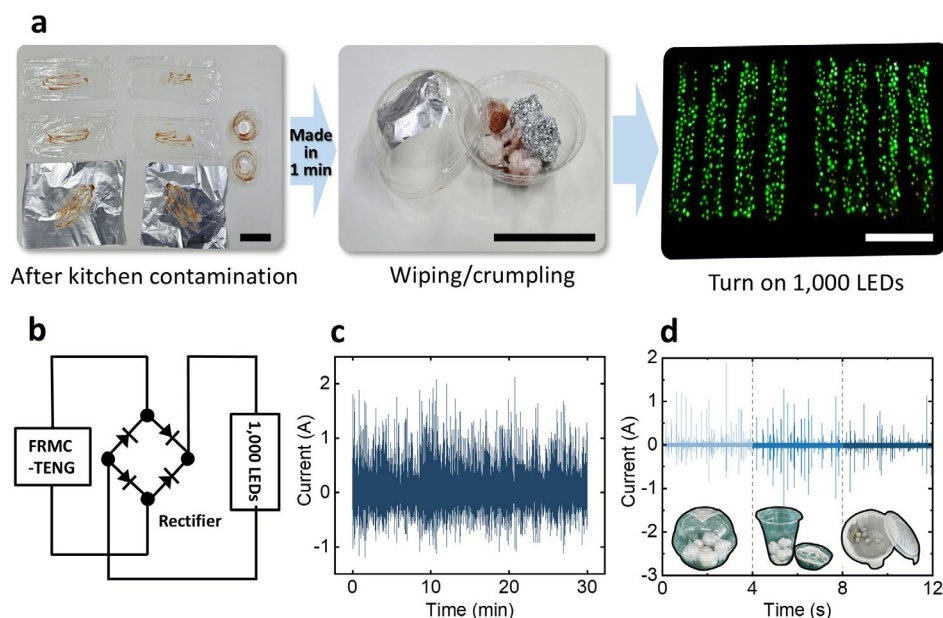


FIGURE 5 | Electrical performance and application of FRMC: (a) photograph demonstrating the fabrication of the FRMC-TENG in 1 min (scale bar: 13 cm); (b) electrical circuit used to power 1000 LEDs; (c) peak output current of a hand-driven FRMC-TENG; (d) peak output current for various real-use substrates.

FRMC-TENG can be fabricated in less than 1 min by crumpling aluminum foil and vinyl wrap, with contaminants inside to prevent exposure, and placing the balls inside a coffee cup dome lid (Video S1). In addition, this easily and quickly fabricated under 1-min FRMC-TENG can power 1000 LEDs with simple hand operation (Video S2). Remarkably, despite being entirely composed of waste materials, the device can generate sufficient power for practical use in daily life. Figure 5b shows a single-full-bridge rectifying electrical circuit used to illuminate the LEDs.

Furthermore, a long-term electrical sustainability test of the FRMC-TENG was conducted by hand-operating the device for 30 min (Figure 5c). Throughout the period, the device maintained a stable output, demonstrating its durability and reliability under extended mechanical stress. Owing to its lightweight design, it can be operated with hand without significant effort, and no mechanical damage was observed to the device. In addition, the crumpled structure prevents the contaminants inside the ball from being exposed, ensuring consistent output performance. As shown in Figure S20, a stable electrical performance was maintained over 1000 s even under hand operation, which imposes much harsher mechanical stress in the actual use environment. The device has a universal design, and because the shape of the substrate is not specified, the device can be used in various applications. Figures 5d and S21 show the current and voltage outputs for different substrate shapes. The device generated currents of up to 1.08, 0.86, and 0.78 A and voltages of 128, 124, and 72 V for dome-lid-based, to-go-cup-based, and container-based substrates, respectively. Its ability to generate a high output regardless of the shape or form of the substrate further highlights its utility. This result, along with that shown in Figure 2b, indicates that although slight variations in electrical performance may arise depending on the materials used, the FRMC-TENG can be fabricated using various kitchen wastes without imposing significant restrictions on material selection. To check the environmental resistance of the device, Figure S22 shows the current output of the FRMC-TENG measured over 2000 s while being exposed to environmental resistance. As a result, we confirmed that the FRMC-TENG can achieve high output power based on air breakdown in environments with relative humidity of 35%–60% [45]. This demonstrates that high output can be achieved over the long term in everyday home environments. Consequently, the potential application spectrum of the FRMC-TENG is significantly expanded. The high output performance of the FRMC-TENGs was demonstrated in various experiments. Therefore, the FRMC-TENG, which utilizes fully recycled materials, can play an important role as a sustainable energy-harvesting technology that enhances the efficiency of recycling systems and minimizes the environmental impact.

3 | Conclusion

In this study, we demonstrate the successful conversion of “waste to energy” using only fully recycled materials. The FRMC-TENG introduces an innovative charge supply mechanism based on waste materials to enhance the surface charge and achieve a high output through air breakdown. When multiple materials were used as charge supply materials instead of a single material, the peak power increased by 4.3 and 257 times compared to using only six WCBs and six FCBs, respectively. Additionally, a

crumpled design was introduced to minimize exposure to contamination. Even if contaminants are exposed inside because of substrate contamination, the output can be recovered to its original state in 300 s with a simple wiping with a tissue. The design variables of the FRMC-TENG were quantitatively optimized, with the optimal number of balls determined as two FCBs and four WCBs. With the optimized design, the FRMC-TENG can generate a voltage of 139.2 V and a current of 1.76 A. With this high electrical output, the FRMC-TENG can power 1000 LEDs through hand operation. Its universal design and exclusive use of fully recycled waste materials position the FRMC-TENG as an attractive solution for WTE applications across various domains.

4 | Methods

4.1 | Fabrication of the FRMC-TENG

The FRMC-TENG comprises three major parts: a PET substrate, freestanding aluminum electrodes, and crumpled foil/wrap balls. The substrate (Woosin Sea & Air Co., China) is made of PET material with a surface diameter of 12.5 cm and a height of 5.5 cm, and it is connected to a slip ring. To fabricate a crumpled ball, aluminum foil with dimensions of 25 cm (height) × 30 cm (width) with a thickness of 14 μm (SINWOO Co., South Korea) and PVC wrap film with dimensions of 15 cm (height) × 80 cm (width) with a thickness of 10 μm (SAMYOUNG Chemical Co., South Korea) were cut and subsequently crumpled into structure. To ensure reproducibility and minimize inter-operator variation, the fabrication procedure was standardized by cutting aluminum foil and PVC wrap according to the proposed dimensions, thereby maintaining the final crumpled ball size at approximately 1.5 cm. For the electrodes, two aluminum foils (5 × 5 cm each) were attached to the top and bottom sides of the substrate. To study the design parameters, WCB ball materials and commercial polymer film tapes were used, such as PTFE (ASF-110, Chukoh Chemical Industries Co., Japan), PVC wrap (SAMYOUNG Chemical Co., South Korea), PET (DUCKSUNG HITECH Co., South Korea), and nylon (GFM Co., South Korea).

4.2 | Electrical Measurement and Characterization

The mechanical input was applied using a DC motor (BXSD120-C, Oriental Motor Co.) operating at 120 rpm. The voltage and current were measured using a mixed-domain oscilloscope (MDO 34, Tektronix Co., United States). A high-voltage differential probe (THDP0100, internal resistance: 10 MΩ, Tektronix Co., United States) and a current probe (TCP0030A, Tektronix Co., United States) were used for these measurements.

Author Contributions

Minju Jee: conceptualization, data curation, formal analysis, visualization, writing – original draft and writing – review and editing. **Kyunghwan Cha:** conceptualization, data curation, formal analysis, visualization, writing – original draft and writing – review and editing. **Seh-Hoon Chung:** data curation, formal analysis and visualization. **Hyungseok Yong:** methodology and visualization. **Youngho Jin:** conceptualization and supervision. **Jinkee Hong:** formal analysis,

supervision and writing – review and editing. **Sangmin Lee:** conceptualization, formal analysis, supervision and writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information. **Video S1:** Making Video of FRMC-TENG, including kitchen contaminants. **Video S2:** FRMC-TENG Turn on 1000 LEDs with hand operation.