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Sandwich as a triboelectric nanogenerator

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ABSTRACT

For the past few years, triboelectric nanogenerators (TENGs) have been demonstrated as an unprecedented method as self-powered, power generation and blue energy. The materials and electrodes used to fabricate TENGs are usually polymer materials and metals. The article demonstrates a new TENG that use entirely bio- and environmental degradable materials. The basic ingredients of the TENG are wheat bread and vegetable leaves for fabricating a sandwich structured TENG (S-TENG). The maximum voltage and current of this S-TENG can reach about 15 V and 3 μA, respectively, when it works in the single electrode mode under the optimal conditions. Additionally, the effects of linear motor frequency, different triboelectric layers, and the area of triboelectric layers on the output of S-TENG were investigated in this work. Several application experiments have confirmed that the S-TENG is capable of driving commercial LED and initiating an alarm apparatus. This work provides a new prospect for the extensiveness of power objects and proves the potential of natural materials applied to the aspect of environmental-friendly power sources and harvesting the green energy.

1. Introduction

Energy supply remains a challenge for sustainable operation of portable electronics [1]. The widely usage of lithium ion batteries and other chemical batteries will leave long period of negative effect to environment after the working life, because these batteries are hard to dispose and degrade [1,2]. This current situation requires a new energy supply device that is environmental friendly, self-powered and efficient to replace the old ones. As a novel-innovative, environmental-friendly, efficient electric generator, triboelectric nanogenerators (TENGs) [3–7] provide a new solution for these issues, it can transfer ambient energy around the environment into electricity by taking the advantage of light weight, low cost and high efficiency. However, the former TENGs are usually composed of triboelectric layers and electrode made of metals and polymers that are difficult to recycle and degrade [8–13]. Even some degradable TENGs' degradation products are not completely innocuous. It may become a rising problem after long term accumulation. In consequence, to develop a kind of metal-free and plastic-free TENG [14,15] will be a new trend for not only TENG research, but also the world's energy issues [16–18].

Up to now, it has been demonstrated that the natural plants such as leaves have potential as an electrode in TENGs. In 2017, a natural leaf assembled triboelectric nanogenerator (Leaf-TENG) [19] is designed by utilizing green leaves as a triboelectric layers and electrodes to effectively harvest environmental mechanical energy. Besides, the Leaf-TENG is capable of driving advertising LEDs and commercial electronic temperature sensors. Recently, a triboelectric nanogenerator that derived from all edible materials (E-TENG) [20] were developed for the first time. This E-TENG used laver coated with an edible silver leaf serves as the active layer and a rice sheet as the substrate. The E-TENG is bioresorbable that can be degrade in the PBS in 28 days. Even the materials are all edible, it still requires time to degrade because of the usage

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of polymeric materials.

In this work, wheat bread and vegetables bought from supermarket directly are the most appropriate option for TENG materials, a kind of edible, metal-free and plastic-free TENG is produced on the purpose of pure ecologic. This new TENG takes food and vegetables as the triboelectric layers and electrode to make it completely innocuous and degradable. The bread and vegetable were used to construct a sandwich structure TENG and this TENG works on a single electrode mode. Bread is one of the triboelectric layers, while the vegetable is both electrode and another triboelectric layer. Through this structure and material design, the sandwich structure triboelectric nanogenerator (S-TENG) can reach a voltage about 15 V. In addition, different kinds of vegetable triboelectric layers' effect on triboelectric nanogenerator output performance was investigated and the effect of bread's surface morphology, roughness, surface potential were analyzed. Furthermore, this experiment has proved its degradable and stable performance and found that it can basically stay the same output after 1000 times circulation when the linear motor frequency is 2 Hz with the peak speed is 0.333 m/s and a contact area of 48 cm^2. On the whole, this research has provided a new method to generate electricity by pure natural materials such as food and vegetables directly, which begins a new era that generate electricity without any non-degradable material. This S-TENG will lead an energy evolution that no more polymer and metal materials are required in the future and our human beings can generate electricity by edible and pure natural materials. This design of integrated S-TENG takes full advantages of the characteristics of natural vegetables, which have potential in environmental-friendly power sources and harvesting the green energy.

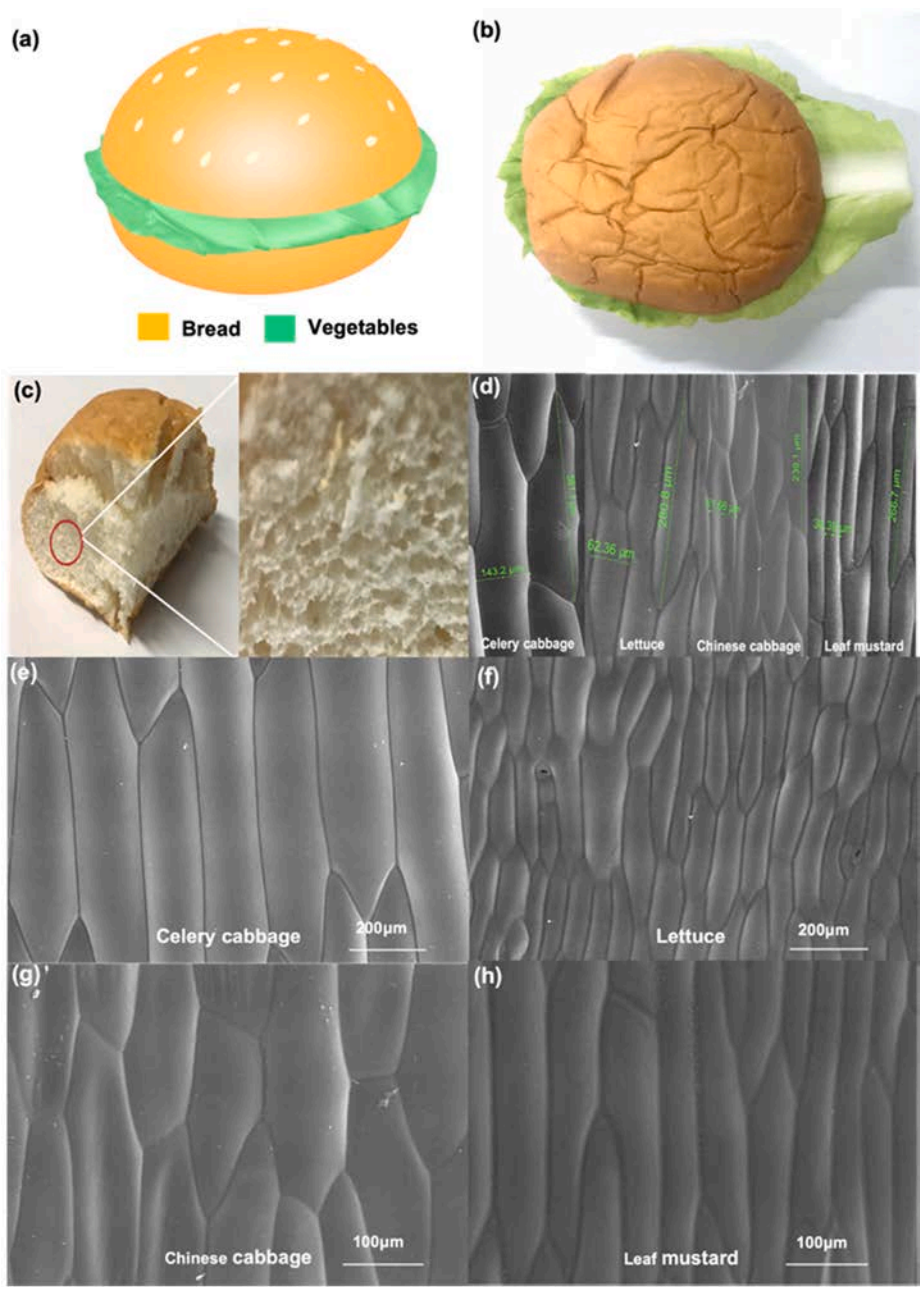

Fig. 1. The structure of S-TENG. (a) 3D model of S-TENG. (b) Photographs of S-TENG assembled with natural vegetables and bread directly. (c) The cross-section drawn of the bread. (d) SEM images of four vegetables applied as electrodes. (e–h) SEM images of celery cabbage, lettuce, Chinese cabbage, and leaf mustard, respectively.

2. Result and discussions

The common bread and vegetables were purchased from the supermarket and adopted in this research. The 3D model of the S-TENG is shown in Fig. 1a. In this S-TENG, bread and two pieces of vegetables act as a role of triboelectric layers. In the meanwhile, the vegetables were also chosen as the single electrode of this TENG due to its inner abundance conductive liquid that can transfer charges easily.

The physical map is shown in Fig. 1b, bread and vegetables are very common in our surroundings. In order to manufacture a nanogenerator with a sandwich structure, fresh vegetables were connected to an alligator clip as electrode. Fig. 1c shows the cross section of the bread, which is a loose porous structure. This structure results in a certain flexibility and recoverability of the S-TENG.

Based on previous research, TENGs' electrical performance is tightly related to triboelectric layers, thus four kinds of vegetables are chosen as TENG's triboelectric layers to optimize our TENGs, they are lettuce, leaf mustard, celery cabbage and Chinese cabbage. Therefore, the investigation based on distinguished triboelectric layers is conducted as follows. Fig. 1d shows the surface of four vegetables with different cell sizes and water content. The selected vegetables have an outer surface and an inner electrolyte, which can be used as the electrode and triboelectric layers of the S-TENG. These four kinds of vegetables have similar cell structure, which present an elongated structure composed of polygons. Thus, different vegetables have different cell sizes. Fig. 1e–h illustrate the different cell topographies and microscopic dimensions of the four vegetables in detail. By comparing and analyzing the cell morphology and size of four vegetables, it can be perceived that the cell size of celery cabbage on average is the biggest which implies that the highest electrolyte content. On the contrary, the cell of leaf mustard shows a long strip shape and the single cell electrolyte content is relatively low.

The working mechanism of S-TENG is shown in Fig. 2a, which is divided into four steps (Fig. 2a–i). shows the initial state of S-TENG, when the S-TENG is not under external pressure, no electrons are generated inside. Although electrostatic induction produces charge accumulate, flow hasn't appeared in circuit because of electrostatic equilibrium (Fig. 2a–ii). As the external force applied on the S-TENG, the device was heavily compressed, then the effective contact area is increase sharply lead to a potential appear. As a result, there will be a current developed in grounded circuit (Fig. 2a–iii).

For this S-TENG, the interval between the triboelectric layers will have a certain effect on the output performance. When the S-TENG reaches the maximum released state, the electrical potential also obtained the maximum value company with the current return to zero (Fig. 2a–iv). Since the S-TENG isn't perfect elasticity, some deformation can't return to normal and the device come into a sub-initial state which has a shorter working distance and more stable performance. As the basic structure and working mechanism hasn't change, the sub-working process is basically same to before and the device begin another circulation. Fig. 2b and c shows the performance produced by the S-TENG

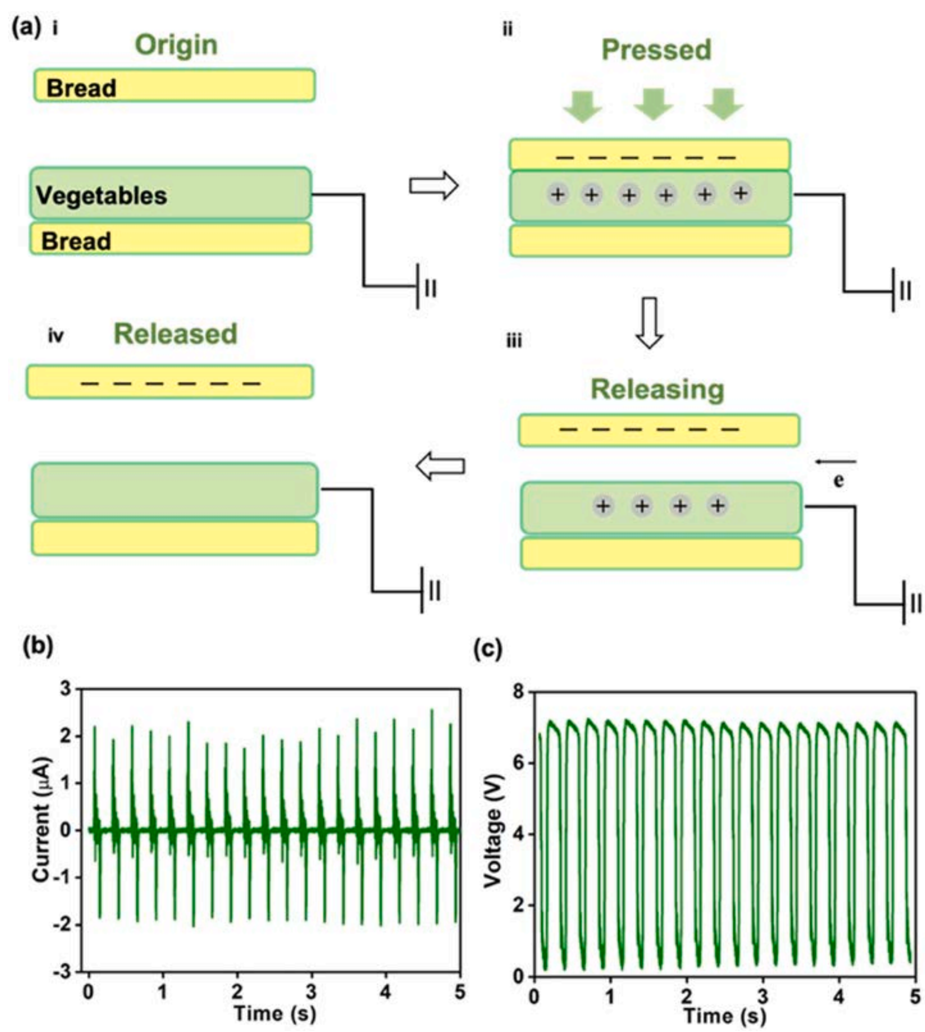

Fig. 2. The working mechanism of S-TENG. (a) Schematic illustration of working principles of S-TENG in the single electrode mode. I: Initial state; ii: pressed state; iii: releasing state; iv: released state. (b) The open-circuit voltage and (c) short-circuit current of lettuce and bread assembled S-TENG.

assembled in the above procedures. In the experiment, Chinese cabbage was selected and an optimization parameter was chosen with a contact area of 48 cm^2, the movement frequency of 2 Hz and peak velocity of 0.333 m/s. The open circuit voltage and peak current generated are about 6.5V, 2 μA.

As the effect of contact is closely related to the two disparate contact materials, different vegetables were used to investigate the performance of S-TENG. Fig. 3a and b illustrate the electrical output of S-TENG assembled with various vegetables. As a pure natural TENG, the output performance of S-TENG is influenced heavily by the inner electrolyte of vegetable leaf, which play an important role in charge transfer. The voltage and current depend on the species of vegetables, which have different electrolyte content and surface character. The output of the four S-TENGs are various owing to the disparate surface roughness and internal water content of the four vegetables. When the linear motor frequency is 2 Hz with the peak speed is 0.333 m/s, the four vegetables in the same contact area as the bread, as shown in Fig. 3a and b, the output of the celery cabbage can reach the optimal performance, 2 V, 0.29 μA.

The reason that celery cabbage's output is superior to the other three varieties of vegetables is that the cell of celery cabbage is bigger than the others which implies the higher electrolyte content and more convenient for transporting electrons. Consequently, the celery cabbage was adopted to process a series of parameter optimization experiments. After optimizing the parameters just like linear motor frequency, contact area between bread and vegetables and external resistance, as shown in Fig. 3c and d, the maximum output performance of the celery cabbage can reach 15V, 3 μA with a contact area of 48 cm^2, a movement frequency of 5 Hz and a peak velocity of 0.333 m/s.

In order to illustrate the output performance of the S-TENG, factors such as vegetable surface area, mechanical frequency and external resistance were compared. In this experiment, an optimization parameter was chosen with a contact area of 48 cm^2, the movement frequency of 5 Hz and peak velocity of 0.333 m/s. Fig. 4 characterizes the output performance of the S-TENG in detail. In the parameter optimization experiment, the method of control variable method was adopted. Fig. 4a reflects the effect of the linear motor frequency on the output performance of S-TENG. In this experiment, according to the control variable method, only the frequency of the linear motor requires to be changed, keeping other variables still. It can be seen that when the motor frequency is 5 Hz, the voltage of S-TENG is about 10 V which is supreme to the other frequencies, and the maximum peak speed is reached 0.333 m/s. As we know, the voltage of S-TENG will not always increase with the increase of frequencies, it is related to the area, charge density and separating distance. The voltage of S-TENG increases obviously with the increase of frequencies, it can be explained by structure of wheat bread, which is highly flexible and porous. When the working frequency is set in a low value, the deformation of S-TENG has enough time to recover, and the porous structure limits the contact area of two triboelectric layers. As the frequency increase gradually, the deformation has no time to recover so the S-TENG can't be recover completely in each cycle. The deformation accumulates gradually and makes the porous structure become more compact. The S-TENG has different contact-separate states with different frequencies, and the potential between two triboelectric layers is also different [21,22]. Then the voltages will increase because of the increase of effective contact areas.

Simultaneously, with the same experimental method, when the contact area between the two triboelectric layers is 48 cm^2, the maximum output can reach 4.3 V, 1.4 μA. Fig. 4b and c shows the effect of surface area on the output of the S-TENG. When the frequency of the linear motor is 5 Hz, the surface area of the vegetables is varying from 24 cm^2, 36 cm^2, 40 cm^2–48 cm^2. This figure shows the larger the surface area of the vegetables which means the larger the contact area is, the higher the output of the S-TENG. Therefore, the S-TENG's output is positively correlated with the contact area and motor frequency.

The materials adopted in this experiment are all edible materials and this device is not rigid structures instead of a loose porous structure, therefore the stability and durability of S-TENG should be consider to ensure the continuous output of S-TENG [23]. Fig. 4c shows the cyclicity of the S-TENG. Repeating the experiment 1000 times with a frequency of 2 Hz, the output of the S-TENG is not significantly reduced after 1000 recycles, which fully demonstrates the high stability and cycle characteristics of S-TENG. Owing to the characteristic of bread and vegetables,

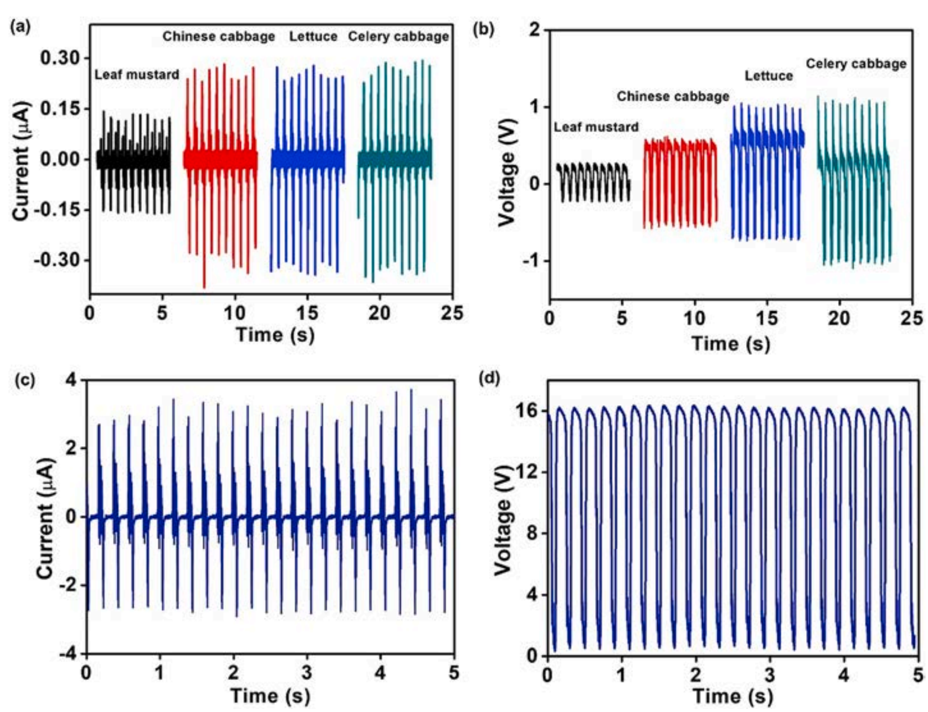

Fig. 3. A comparison of output performance of the four as-designed S-TENG. (a) The open circuit voltage and (b) short-circuit current of the four vegetables-assembled S-TENGs. (c) The maximal current and (d) voltage output performance produced by the S-TENGs.

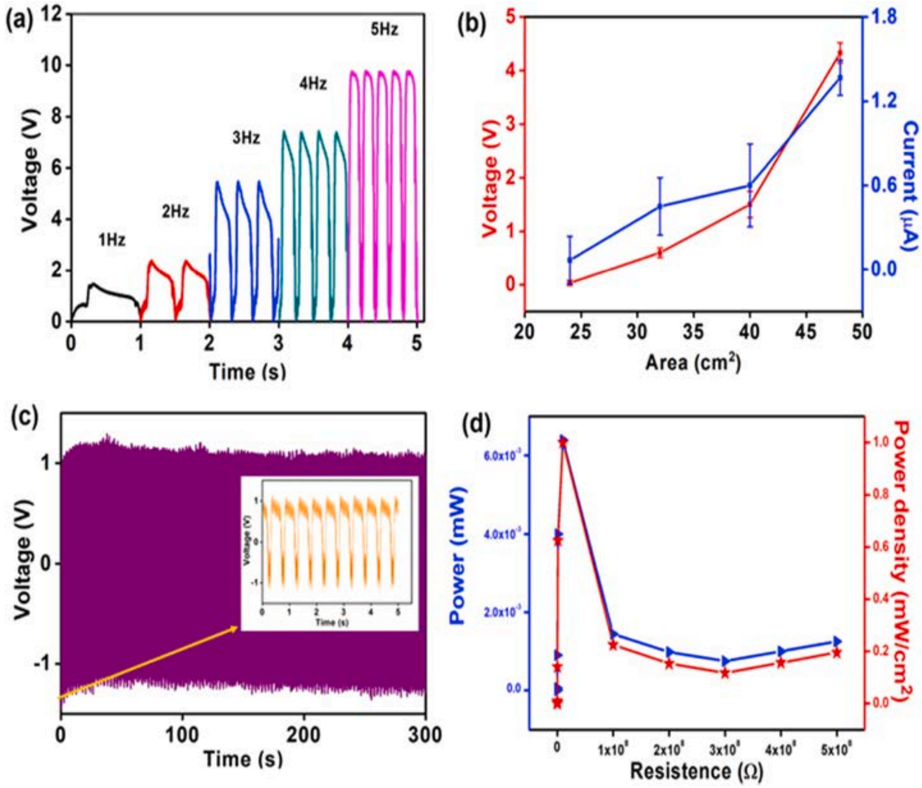

Fig. 4. The effect of linear motor frequency, contact area, external resistance, and cyclical of S-TENG. (a) The open circuit voltage of different linear motor frequency. (b) The relation between the area of S-TENG and the electrical output. (c) The circulating test of the S-TENG. (d) The power and the power density with the external loading resistance.

the mechanical strength is poor, which may lead to a large fluctuation in the output of the S-TENG.

The matching of impedance and output power is an important method to obtain better performance [24,25]. We have measured the power density with different resistance to increase the output performance of S-TENG. The external resistance increases from 50 to 3 × 10^8 Ω. As shown in Fig. 4d, the power density increased firstly and decreased at a certain value. Then we can see that the maximum power density of S-TENG is 1.0 mW/m^2 in an optimized matching state.

S-TENGs can effectively collect the mechanical energy in the environment, combine its edible characteristics, it will be able to progress many new ways to efficiently supply humans in more fields. As shown in Fig. 5a, the S-TENGs can be used for a miniature sensor. Here, a S-TENG can be used as an alarm which is "invisible" compared with the alarms in the cognitive range. When an emergency occurs, the S-TENG can be directly pressed to alarm which can greatly improve the safety performance, which is a step closer to achieving a smart-safety home. Fig. 5b illustrates the potentiality of S-TENG as a safe home. As shown in the figure, this nanogenerator can successfully initiate the alarm and play a warning role to people.

Due to the randomness and volatility of environmental mechanical energy, the output of the S-TENG is also vary and alternative, which can't be used directly to drive micro device and sensors. It is necessary to change the alternative current of S-TENG into direct current and store the energy with suitable energy storage unit to increase energy harvest efficient [26]. Fig. 5c shows charging curve of different commercial capacitors charged by S-TENG. The equivalent circuit diagram is shown in the inset. The capacitor with larger capacity has better storage capacity, but to reach the required voltage needs longer time. The charging speed under different capacitors is also different, thus it is very significant to choose the appropriate capacitor according to different equipment. Based on the characteristics that the S-TENG can be used to charge capacitors, capacitors which charged with S-TENG has been adopted to drive commercial LEDs. The S-TENG is connected to a linear motor and use a rectifier bridge to convert the alternating current to direct current. In parallel with the LED light, the linear motor squeezes S-TENG at a frequency of 5 Hz, and the S-TENG produces an output sufficient to illuminate the LED light. As shown in Fig. 5d, which successfully confirms the potential of this S-TENG as a self-powered system.

Fig. 5e implies the physical map of the working state of the S-TENG which confirms that the S-TENG possess high biocompatibility and without any metal electrodes and conventional polymer materials. On account of the material used to fabricate the S-TENG are all natural and edible, Fig. 5f shows the edible character of S-TENG. The materials are common bread and ordinary vegetables that can be seen everywhere in our surroundings. It is distinguished to sum up that the S-TENG is an unprecedented type of green energy source with integrated, completely edible and mental free.

3. Conclusions

To summarize, the purpose of this paper is to put forward a totally unprecedented idea that the TENGs can be genuinely edible with no tradition electrodes. When it worked in single electrode mode under the optimization condition, the maximum output performance can reach 15 V, 3 μA. And the as-designed S-TENG was fabricated to investigate the working mechanism of S-TENG based on contact electrification. Additionally, the pure-natural S-TENGs were demonstrated to power the commercial LEDs and charge the capacitors, which exhibits its fine quality to harvest mechanical energy. This work not only presents the possibility of food or natural plants being used for power generation, but also broadens the development and utilization of green energy.

4. Experimental section

Fabrication of sandwich structure triboelectric nanogenerator (S-

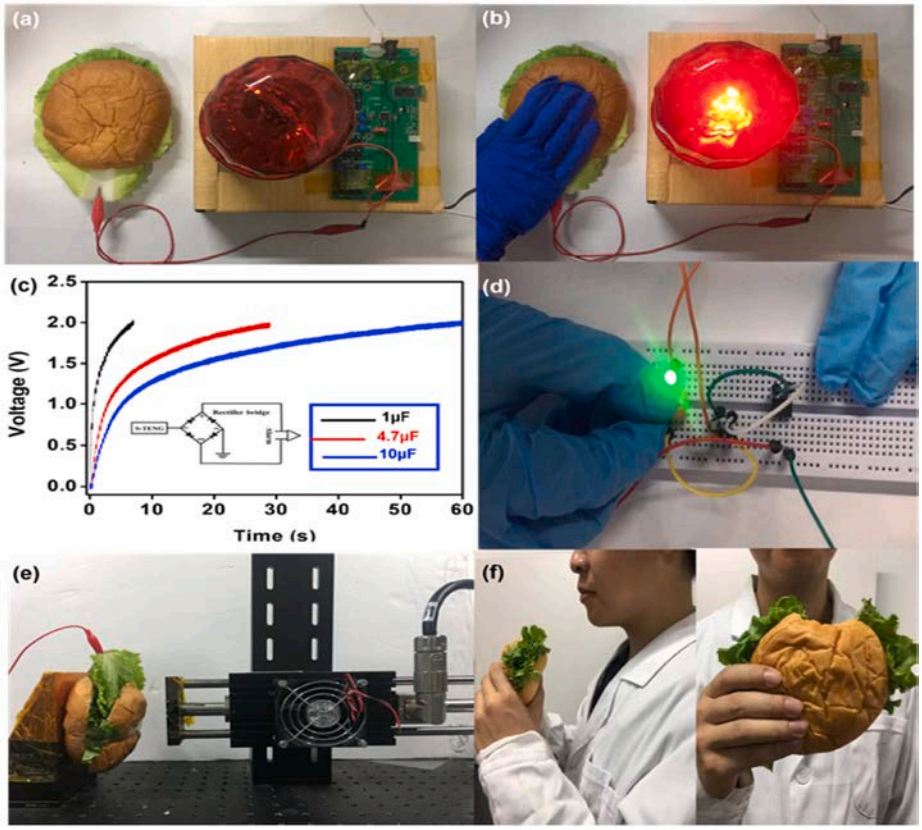

Fig. 5. The application experiment of S-TENG. (a) S-TENGs can drive alarm and its equivalent circuit. (b) S-TENGs successfully drive the alarm with its light on. (c) Voltage profile of capacitors (1, 4.7, 10 μF) charged by S-TENG, the inset shows equivalent circuit. (d) S-TENGs store current in capacitors and drive commercial LED lights. (e) The physical map of the working state of the S-TENG. (f) The edible test of the S-TENG.

TENG): Fresh vegetables (lettuce, leaf mustard, celery cabbage and Chinese cabbage) and common circle-shaped bread were bought in the nearby supermarket. And washed the four vegetables with deionized water for several times and fully dried at room temperature. Then two equal-sized bread, two pieces of vegetables were prepared, then sandwiched the vegetables between the two pieces of bread to complete the assembly of the S-TENG. The bread and vegetables were chosen as triboelectric layers. And this device was completely no metal or polymer materials.

Measurement and characterization: The surface morphology of the four vegetables (lettuce, leaf mustard, celery cabbage and Chinese cabbage) were examined by a Quanta 450 FEG Schottky field emission environment scanning electron microscope (ESEM)in the low vacuum mode. For the measurement of electrical outputs of S-TENG, a home-made motor system was used to supply the external mechanical force. The electrical outputs of S-TENG were collected by a Keithley 6514 system electrometer with computer measurement software written in LabVIEW.

CRediT authorship contribution statement

Jingyi Jiao: Data curation, Formal analysis, Writing - original draft, Investigation. **Qixin Lu:** Data curation, Formal analysis, Visualization, Investigation. **Zhonglin Wang:** Supervision, Resources, Writing - review & editing. **Yong Qin:** Supervision, Resources, Writing - review & editing. **Xia Cao:** Conceptualization, Supervision, Resources, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Y. Song, H. Wang, X. Cheng, G. Li, X. Chen, H. Chen, L. Miao, X. Zhang, H. Zhang, Nano Energy 55 (2019) 29–36.
[2] Q. Zhang, Z. Zhang, Q. Liang, F. Gao, F. Yi, M. Ma, Q. Liao, Z. Kang, Y. Zhang, Nano Energy 55 (2019) 151–163.
[3] J. Henschel, S. Wiemers-Meyer, M. Diehl, C. Luerenbaum, W. Jiang, M. Winter, S. Nowak, J. Chromatogr. A 1603 (2019) 438–441.
[4] T. Liu, A. Dai, J. Lu, Y. Yuan, Y. Xiao, L. Yu, M. Li, J. Gim, L. Ma, J. Liu, C. Zhan, L. Li, J. Zheng, Y. Ren, T. Wu, R. Shahbazian-Yassar, J. Wen, F. Pan, K. Amine, Nat. Commun. 10 (2019).
[5] D. Ouyang, J. Weng, M. Chen, J. Wang, J. Electrochem. Soc. 166 (14) (2019) A3432–A3440.
[6] V.J. Ovejas, A. Cuadras, Sci. Rep. 9 (2019) 1–9.
[7] Q. Song, A. Li, L. Shi, C. Qian, T.G. Feric, Y. Fu, H. Zhang, Z. Li, P. Wang, Z. Li, H. Zhai, X. Wang, M. Dontigny, K. Zaghib, A.-H. Park, K. Myers, X. Chuan, Y. Yang, Energy Storage Mater 22 (2019) 48–56.
[8] F.R. Fan, W. Tang, Z.L. Wang, Adv. Mater. 28 (2016) 4283–4305.
[9] Z.L. Wang, ACS Nano 7 (11) (2013) 9533–9557.
[10] Z.L. Wang, Faraday Discuss 176 (2014) 447–458.
[11] Z.L. Wang, J. Chen, L. Lin, Energy Environ. Sci. 8 (8) (2015) 2250–2282.
[12] X. Cao, Y. Jie, N. Wang, Z.L. Wang, Adv. Energy Mater. 6 (23) (2016) 1–21.
[13] K. Parida, J. Xiong, X. Zhou, P.S. Lee, Nano Energy 59 (2019) 237–257.
[14] Q. Liang, Q. Zhang, X. Yan, X. Liao, L. Han, F. Yi, M. Ma, Y. Zhang, Adv. Mater. 29 (5) (2017) 1–7.
[15] W. Wu, X. Cao, J. Zou, Y. Ma, X. Wu, C. Sun, M. Li, N. Wang, Z. Wang, L. Zhang, Adv. Funct. Mater. 29 (41) (2019) 1–9.

[16] P. Bai, G. Zhu, Z.-H. Lin, Q. Jing, J. Chen, G. Zhang, J. Ma, Z.L. Wang, ACS Nano 7 (4) (2013) 3713–3719.

[17] L. Dhakar, P. Pitchappa, F.E.H. Tay, C. Lee, Nano Energy 19 (2016) 532–540.

[18] Y. Song, X. Cheng, H. Chen, J. Huang, X. Chen, M. Han, Z. Su, B. Meng, Z. Song, H. Zhang, J. Mater. Chem. 4 (7) (2016) 14298–14306.

[19] Y. Jie, X. Jia, J. Zou, Y. Chen, N. Wang, Z.L. Wang, X. Cao, Adv. Energy Mater. 8 (12) (2018) 1–7.

[20] T.M. Gaurav Khandelwal, Sanjeev Kumar Yadav, Arunkumar Chandrasekhar, Subash Chandra Gupta, Sang Jae Kim, Nano Energy 65 (2019) 1–9.

[21] Kequan Xia, Jiangming Fu, Zhiwei Xu, Adv. Energy Mater 10 (28) (2020) 1–9.

[22] Lingxiao Gao, Shan Lu, Weibo Xie, Xin Chen, Liangke Wu, Tingting Wang, Aobo Wang, Caiqian Yue, Daqiao Tong, Wenqian Lei, Hua Yu, Xiao bin He, Xiao JING Mu, Zhong Lin Wang, Ya Yang, Nano Energy 72 (2020), 104684.

[23] Kequan Xia, Zhiyuan Zhu, Hongze Zhang, Chaolin Du, Zhiwei Xu, Rongji Wang, Nano Energy 50 (2018) 571–580.

[24] Kequan Xia, Di Wu, Jiangming Pu, Zhiwei Xu, Nano Energy 77 (2020), 105112.

[25] Lingxiao Gao, Xin Chen, Shan Lu, Hong Zhou, Weibo Xie, Junfei Chen, Mengke Qi, Hua Yu, Xiaojing Mu, Zhong Lin Wang, Ya Yang, Adv. Energy Mater. 9 (44) (2019), 1902725.

[26] Xin Chen, Lingxiao Gao, Junfei Chen, Shan Lu, Hong Zhou, Tingting Wang, Aobo Wang, Zhifei Zhang, Shifeng Guo, Xiaojing Mu, Zhong Lin Wang, Nano Energy 69 (2020), 104440.

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