

Article

An Investigation of the Output Performances of a Triboelectric Nanogenerator Lubricated with TiO₂-Doped Oleic Acid

Jiaqi Shao ¹, Guoyan Yu ^{1,2}, Yixing He ¹, Jun Li ¹, Mingxing Hou ¹ , Xianmin Wang ³, Ping Zhang ¹  and Xianzhang Wang ^{1,*} 

¹ School of Mechanical Engineering, Guangdong Ocean University, Zhanjiang 524088, China; 2112205005@stu.gdou.edu.cn (J.S.); yugy@gdou.edu.cn (G.Y.); 13415769301@163.com (Y.H.); uu337@163.com (J.L.); houmx@gdou.edu.cn (M.H.); 18661660729@163.com (P.Z.)

² Guangdong Provincial Marine Equipment and Manufacturing Engineering Technology Research Center, Zhanjiang 524088, China

³ School of Chemistry and Environment Engineering, Guangdong Ocean University, Zhanjiang 524088, China; xianmin_wang@gdou.edu.cn

* Correspondence: wangxianzhang@gdou.edu.cn

Abstract: In the past decade, triboelectric nanogenerators (TENGs) have attracted significant attention across various fields due to their compact size, light weight, high output voltage, versatile shapes, and strong compatibility. However, substantial wear at solid–solid contact interfaces presents a major obstacle to the electrical output stability of TENGs. The objective of this study is to investigate the output performances of TENGs lubricated with TiO₂-doped oleic acid. The results suggest that the triboelectrical performances of the polyimide (PI) film sliding against a steel ball under 0.1 wt% TiO₂-doped oleic acid are significantly improved compared to those under dry conditions; the growth rates are 35.2%, 103.6, and 85.6%, respectively. Moreover, the coefficient of friction dropped from 0.31 to 0.066. The wear and performance enhancement mechanism are also analyzed. This study provides an effective approach to improve both the electrical performances and tribological behaviors.

Keywords: triboelectric nanogenerators; TiO₂ nanoparticles; oleic acid lubricant; tribological characteristics; PI film



Citation: Shao, J.; Yu, G.; He, Y.; Li, J.; Hou, M.; Wang, X.; Zhang, P.; Wang, X. An Investigation of the Output Performances of a Triboelectric Nanogenerator Lubricated with TiO₂-Doped Oleic Acid. *Lubricants* **2024**, *12*, 269. <https://doi.org/10.3390/lubricants12080269>

Received: 17 June 2024

Revised: 15 July 2024

Accepted: 25 July 2024

Published: 29 July 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In the past decade, the widespread application of triboelectric nanogenerators (TENGs) in fields such as healthcare, electronics, sensors, and artificial intelligence has garnered significant attention [1,2]. TENG devices are distinguished by their compact size, lightweight nature, high output voltage, diverse shapes, and strong compatibility. They have the potential to harness wave energy from the ocean and supply power for small measuring instruments. In marine environments, numerous TENGs have been engineered to capture and store energy produced by wave motion, providing power for distributed sensors utilized in ocean monitoring [3,4]. TENGs effectively exploit random wave energy by converting it into electrical energy or signals with broad applications in blue energy collection and monitoring various water quality parameters [5–8] as well as self-powered sensor fields. Data are transmitted via Bluetooth to remote receivers and mobile communication systems [9]. TENGs integrated with signal processing circuits have been developed to establish self-powered temperature sensors and wireless self-powered waveform alarm systems, including wireless water temperature alarm systems [10] and water level alarm systems [11].

Over the years, numerous researchers have dedicated their efforts to enhancing the structure and efficacy of TENGs, delving into avenues such as optimizing the selection of materials, refining preparation methodologies, and pioneering innovative structural

designs [12–16]. The recent advances in and technologies, affecting factors, and applications of liquid–solid triboelectric nanogenerators (L-S TENGs) were summarized in [17–21].

However, TENGs have considerable problems during actual operation. Especially in the solid–solid contact mode, the material surface is subjected to serious wear, which seriously affects the enduring stability of the electrical output performance of the TENGs. The inherent limitation poses a significant obstacle to their widespread application in long-term power supply and the deployment of precision-oriented, self-sufficient sensor networks. In order to enhance the wear resistance of TENGs and optimize their electrical output performance, researchers conducted a series of studies to explore additional lubrication strategies. By introducing an appropriate liquid lubricant at the frictional interface, the wear resistance of TENGs can be significantly enhanced. Additionally, the incorporation of lubricating oil not only enhances the wear resistance of TENGs, but also improves the electrical output performance of TENGs under certain lubricants.

Many studies have demonstrated the effectiveness of lubrication in improving the electrical output performance of TENGs. For example, Wu et al. [22] observed a significant improvement in frictional performance and electrical output performance after long sliding cycles by adopting liquid lubrication. Similarly, Wang et al. [23] also found that the addition of specific lubricants to the friction surface can lead to a significant reduction in the coefficient of friction (COF) and an improvement in the electrical energy conversion efficiency. Additionally, Liu et al. [24] studied the effect of different polarity liquid lubricants on the frictional electricity of friction pairs composed of steel balls and polytetrafluoroethylene blocks. It was found that appropriate lubricants (alkanes and alkenes) and the quantity of liquid can increase the triboelectric signal, achieving a long-term stable output, while the COF is significantly reduced. Qiao et al. [25] used an MXene solution as a lubricant to increase the output current density of TENG to a high value of 754 mA/m^2 , and achieved a durability of 90,000 cycles at the same time. Yang et al. [26] achieved a decrease in the COF from 0.76 to 0.16 by adding polyalphaolefin PAO4 as a lubricant at the metal–semiconductor heterojunction interface of the planar structure while maintaining the DC output voltage almost constant.

Additionally, nanoparticles exhibit unique properties, such as a small size effect, surface effect, and interface effect [27]. As lubricant additives, they demonstrate enhanced load-bearing capacity. The incorporation of a small quantity of mono- [28,29] or multielement [30] nano-additives into lubricating oil can significantly enhance the wear resistance performance of the friction pair. Guo et al. [31] added a mixture of hexadecane and onion-like carbon (OLC) lubricants at the interface between a polytetrafluoroethylene (PTFE) film and steel. The introduction of hexadecane reduced the transfer of the PTFE material, and some OLC particles rolled between the interfaces, further improving the wear resistance performance and electrical output performance of TENGs, reducing the COF by about 75.3%. The short-circuit current I_{sc} doped with OLC hexadecane is about five times the output current of dry friction. Chen et al. [32] successfully achieved a super lubrication friction nanogenerator (SL-TENG) at the microscale. Under the condition of graphene silicone oil lubrication, the optimized high load was 10N and the high sliding speed was 1000 mm/s, resulting in an ultra-low COF of 0.008. The corresponding wear rate of the PTFE film was significantly reduced to mm^3/Nm , achieving an ultra-low wear rate and ultra-low COF. At the same time, the short-circuit current and open-circuit voltage were increased by 6.8 times and 3.0 times, respectively, compared to those observed under dry friction conditions.

In this study, an investigation was conducted on the friction pairs of a polyimide (PI) film and 304 stainless steel ball as TENG friction pairs. PI films, a PI-based polymer, have attracted more attention and research in the field of TENGs due to their excellent thermal resistance, good breakdown resistance, and dielectric properties [33,34]. While the PI film demonstrates impressive frictional electrical properties, positioning it as a main candidate for integration into the friction pairs of TENGs, its widespread application faces a challenge due to the limited electron absorption capacity of the most commonly used commercial

films, resulting in restricted charge density generation that fails to fully meet the development requirements of high-performance TENGs. This shortfall impedes meeting the stringent demands of high-performance TENGs. Consequently, enhancing the triboelectrical capabilities of PI films is a key way to propel the development of high-performance TENG systems. Furthermore, 304 stainless steel, renowned for its exceptional corrosion resistance, mechanical strength, and ease of processing, serves as a prevalent material in diverse industrial sectors. In a series of experiments, the impact of oleic acid lubrication with varying mass fractions on the wear resistance and electrical output performance of TENG friction pairs was investigated. In addition, the surface characterization of PI after wear and the analysis of the chemical composition of wear trace were also performed. Ultimately, it was determined that, under appropriate lubrication conditions, the addition of TiO_2 nanoparticles with a specific mass fraction in relation to oleic acid can enhance both the wear resistance and electrical output performance of PI films in TENGs. These results may provide important references for the promotion and in-depth research of TENGs in practical applications and provide new ideas and methods for further optimizing the design and improving the performance of TENGs.

2. Materials and Methods

2.1. Materials

The PI material used in this study was procured from Guangzhou Baike Electronics Co., Ltd. (Guangzhou, China). The 3D topography is shown in Figure S2. The thermoplastic polyurethane (TPU) material was sourced from the Dongguan Changan Belin Plastic Products Business Department, while the polydimethylsiloxane (PDMS) material was obtained from Shanghai Dibo Biotechnology Co., Ltd. (Shanghai, China), a department of Dongguan Changan Belin Plastic Products. The polytetrafluoroethylene (PTFE) material was acquired from Dongguan Hongfu E-commerce Company. The thicknesses of these four types of polymer films were 200 μm . The TiO_2 (titanium dioxide) material with a purity of 99% and particle size in the range of 20–40 μm was purchased from Jiangsu Xianfeng Nanomaterials Technology Co., Ltd. (Nanjing, China). Oleic acid and dimethylsilicone oil were obtained from Shanghai Aladdin Biochemical Technology Co., Ltd. (Shanghai, China). The quartz plate was sourced from Donghai Yibo Quartz Products Co., Ltd. (Lianyungang, China). Additionally, 6.35 mm diameter ball-shaped 304 stainless steel was acquired from a local supplier. Furthermore, TiO_2 and oleic acid were blended in accordance with the specified ratios outlined in Table 1, and the precise measurements of TiO_2 nanoparticles and appropriate quantities of oleic acid were obtained using a precision balance. The measured oleic acid and TiO_2 nanoparticles were added to a centrifuge tube and mixed to prepare oleic acid solutions with different mass fractions of TiO_2 . The mixture was subjected to ultrasonic oscillation at 30 $^\circ\text{C}$ for 15 min to promote particle dispersion and mixing. Subsequently, the mixture was transferred to a rotary mixer and stirred at 2000 rpm for 10 min to further ensure uniform mixing. The completed oleic acid-based lubricant was transferred to suitable containers for storage, ensuring its seal to prevent contamination from external impurities.

Table 1. Experimental lubrication condition.

Designation	Lubrication Condition
Dry friction	No lubrication
0.00 wt%	Pure oleic acid
0.01 wt%	Oleic acid Gew. 0.01 wt% TiO_2
0.05 wt%	Oleic acid Gew. 0.05 wt% TiO_2
0.1 wt%	Oleic acid Gew. 0.1 wt% TiO_2
0.5 wt%	Oleic acid Gew. 0.5 wt% TiO_2
1 wt%	Oleic acid Gew. 1 wt% TiO_2
2 wt%	Oleic acid Gew. 2 wt% TiO_2

Table 1 presents a comprehensive overview of the experimental lubrication conditions implemented in the study. The “Designation” column enumerates the specific designations assigned to each lubrication condition, facilitating easy reference throughout the analysis. In the “Lubrication Condition” column, detailed information regarding the composition or concentration of the lubricants utilized in each condition is provided. These lubrication conditions encompass a wide spectrum, ranging from instances of dry friction with no applied lubricant to various concentrations of oleic acid combined with TiO₂ nanoparticles, spanning from 0.01 wt% to 2 wt%. This comprehensive range allows for a thorough exploration of the effects of different lubrication conditions on the experimental outcomes.

2.2. Preparation of the TENGs

The TENGs were composed of 304 stainless steel and four polymeric components (PDMS, PTFE, TPU, and PI) in this study. The schematic of the experimental setup is shown in Figure 1, which is designed to simultaneously measure the COF and triboelectrical performances (voltage, current, and charge) in a ball-on-flat configuration. The actual experimental device is shown in Figure S1A. The 6.35 mm diameter ball-shaped 304 stainless steel served as the upper friction pair, while the PI film as a representative measuring 35 mm × 35 mm × 0.2 mm acted as the lower friction pair. The 304 stainless steel ball was securely mounted in copper foil, clamped by a polyether ether ketone rod, and attached to the friction testing machine. A copper wire connected the 304 stainless steel ball to a programmable electrometer (Keithley 6514 Electrostatic Meter, Tektronix, Shanghai, China), with the electrometer grounded. The PI film was adhered to a glass sheet measuring 35 mm × 35 mm × 3 mm using 3M double-sided adhesive tape as the lower friction pair of the TENG. Subsequently, the glass sheet was secured within a poly-ether-ether-ketone (PEEK) box. A pipette gun was utilized to apply lubricant (50 µL) onto the PI surface before initiating the sliding motion between the steel ball and PI film.

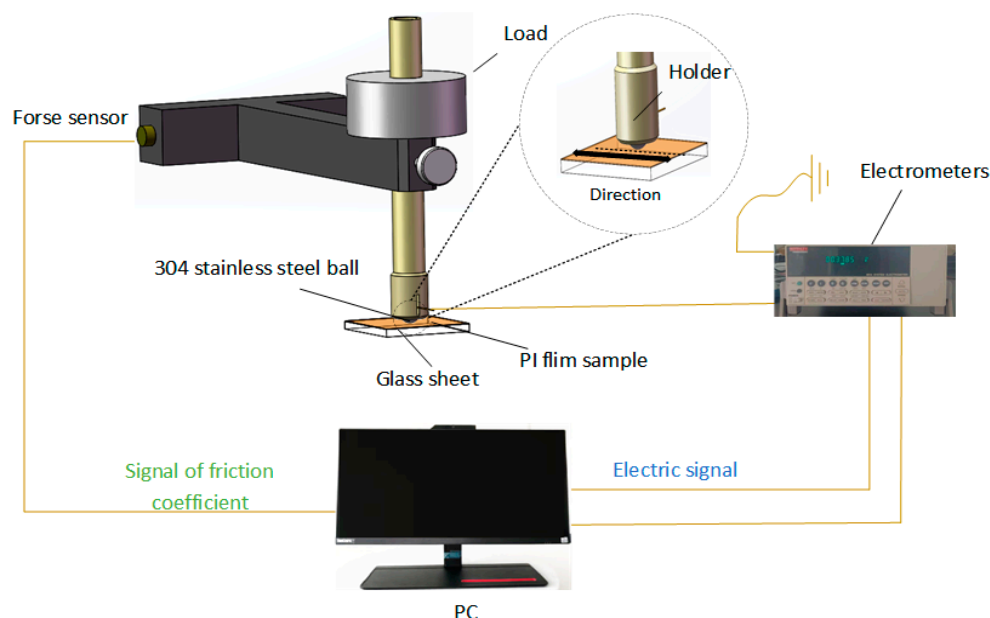


Figure 1. Schematic of the experimental apparatus.

2.3. Characterization of Triboelectric and Tribological Behaviors

The reciprocating module of the tribological tester was employed for conducting friction experiments. To prevent electron loss, the polymeric films were adhered to the glass plate using 3M tape, and subsequently, the glass plate was fixed onto the PEEK box of the friction tester. The speed of the reciprocating platform was adjusted using the computer software of the tribological tester. During the experiment, the voltage, current, charge and COF were measured for the solid–solid mode TENGs and TENGs with oleic

acid lubrication and with TiO₂-doped oleic acid lubrication. The data of voltage (V_{oc}), current (I_{sc}), and transferred charge (Q) were measured by a programmable electrometer and collected by a data acquisition card. The software platform was developed based on LabView, enabling the real-time display and storage of data on a computer. The COF was calculated using the software of the tribological tester. The surface morphology of the samples, including the depth and width of the wear traces, was measured using a 3D white-light interference surface topography instrument. Additionally, a scanning electron microscope (SEM, TESCAN MIRA LM, Brno, Czech Republic) equipped with an energy-dispersive spectrometer (EDS, Brno, Czech Republic) was employed to observe the microstructural surface features and the element distribution of the wear traces. Fourier transform infrared spectroscopy (FTIR, Thermo Fisher Scientific Nicolet iN10, Waltham, MA, USA) was utilized to analyze the molecular structure and chemical bond information of the sample surfaces.

3. Results

3.1. Effect of Materials of Friction Pairs on the Triboelectrical Performances

The selection of the materials of the friction pairs in TENGs is important for enhancing the output electrical performances, such as the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}). Four materials were chosen to investigate the effect of the materials of friction pairs on triboelectrical performances. The process of triboelectric charge accumulation on the steel ball in the dry friction state is displayed in Figure 2. When the steel ball and the PI film came in contact, the steel ball became positively charged and the PI became negatively charged. Equal positive and negative charges accumulated in the contact area (Figure 2a). The electrons were transferred from the earth to the PVDF through the ground wire and the steel ball during sliding (Figure 2b,c). When the steel ball slid in the opposite direction, electrons flowed into the ground, which generated a negative current (Figure 2d), then began the next cycle. This is in accordance with the work presented in [24].

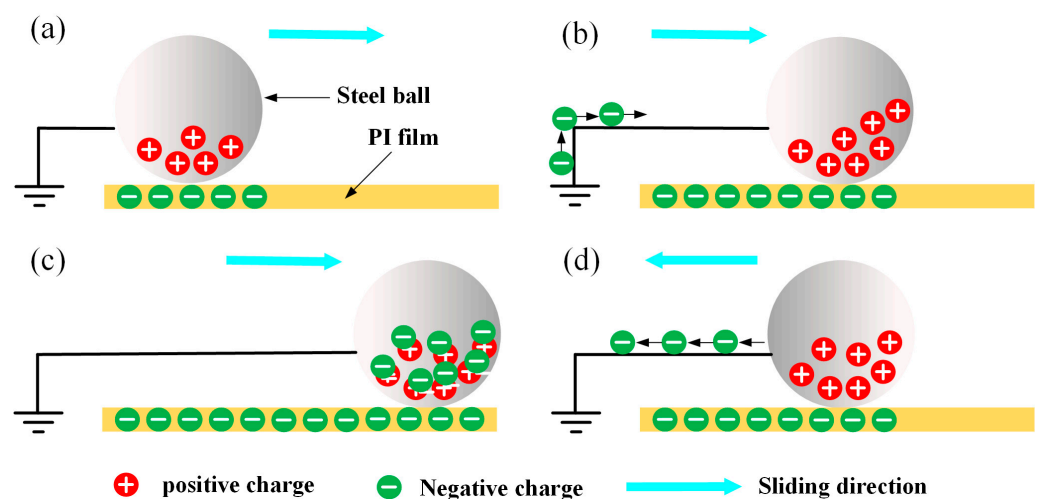


Figure 2. Schematic diagram of the distribution of tribocharges generated by the sliding friction mode at different stages under dry friction conditions. (a) Come into contact. (b,c) Sliding forward (d) Sliding along opposite direction.

Figure 3 shows the triboelectrical and tribology performances of four polymer (PDMS, TPU, PTFE, and PI) films sliding against a steel ball under dry conditions with a load of 5N and a sliding speed of 40 mm/s. The output short-circuit current and open-circuit voltage of the various PTFE films in contact with the steel ball under dry conditions are shown in Figure 3a–c. As it can be seen from Figure 3a–c, PTFE exhibits the highest voltage magnitude among the different tested materials, followed by PI, TPU, and PDMS. Consequently, the corresponding maximum short-circuit current shows a similar trend, PTFE shows the

highest current, and the PI material is second, with an amplitude of 0.7 nA. This aligns with its high voltage triboelectric properties, as a higher voltage typically correlates with an increased current. The current difference between TPU and PTFE is not large, and PDMS shows the smallest current among the tested materials. The charge observed shows that PI exhibits the highest charge magnitude, indicating its effectiveness in accumulating charge during the triboelectric process. Due to the electron-withdrawing nature of the amide group, PI generally has a strong electron-withdrawing capacity. This property allows the polyimide material to efficiently capture and store charges during friction. Though PTFE has superior performances in voltage and current generation, the effective charge of PTFE is much lower than that of PI, with a difference of approximately 0.4 nC. The reason for this may be attributed to the dissipation of the generated charge during friction through the air or other mediums. The difference in the triboelectrical performance is related to the interactions between the contact pair during the sliding process as well as the chemical compositions. However, further exploration is still required.

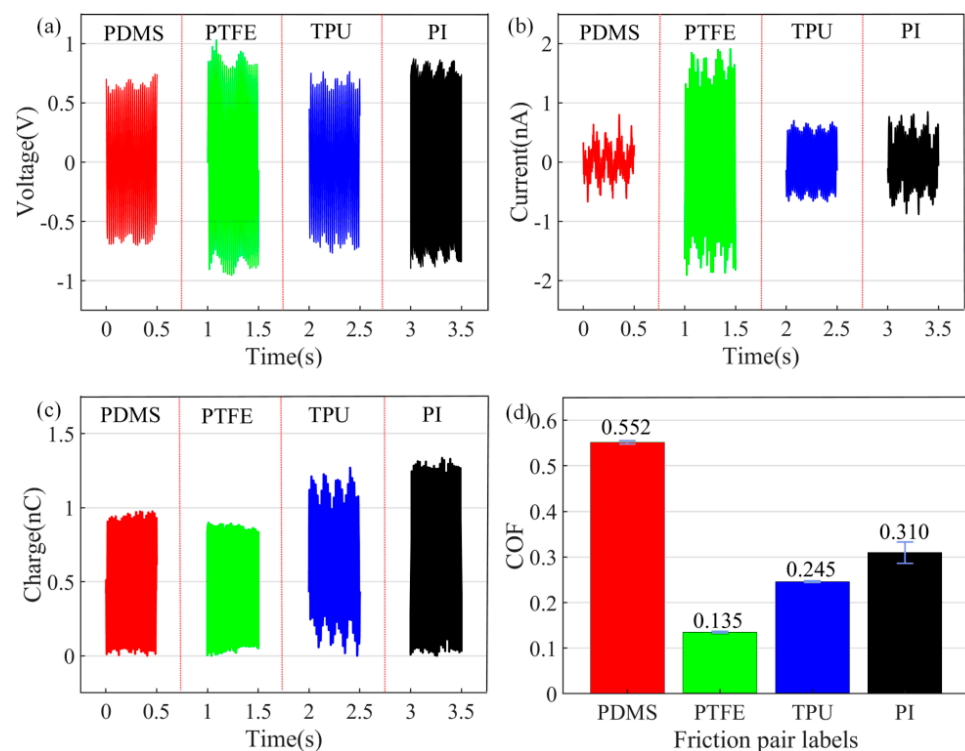


Figure 3. Triboelectrical and tribology performances of the four polymer (PDMS, TPU, PTFE, and PI) films sliding against a steel ball under dry conditions with a load of 5N and a sliding speed of 40 mm/s. (a) Output short-circuit current. (b) Output open-circuit voltage. (c) Effective charge. (d) Average COF.

Due to PI's electron-withdrawing nature, TENGs have a higher voltage output. The tribological behaviors of the contact pair play a key role in the life duration of TENGs. The variation curves of COF of the four polymer materials (PDMS, PTFE, TPU, and PI) are shown in Figure S3, and the average COF at the steady state is shown in Figure 2d. PTFE demonstrates the lowest coefficient, followed by TPU, PI, and PDMS. The electrical output properties of the different materials of TENGs are different, possibly because the roughness of the material surface is also an influencing factor [35,36]. Generally, the COF, to some degree, reflects the performance of wear resistance. Though the PI material has excellent triboelectrical performance, the poor performances of the friction and wear resistance could affect the life duration, thus limiting the application of the PI material in TENGs.

3.2. Effect of Load and Sliding Speed on the Triboelectrical Performances of PI Films

In order to determine the appropriate parameters for the subsequent experiments, the influence of the load and velocity on the triboelectric properties of the PI film sliding with a steel ball under dry conditions was investigated. Figure 4 illustrates the triboelectric performances of the PI film and a 304 stainless steel ball at various sliding velocities (20 mm/s, 40 mm/s, 60 mm/s, 80 mm/s, 100 mm/s) and different loads (1N, 2N, 3N, 4N, and 5N). Based on the observed results depicted in Figure 4a–c, it is evident that the voltage, current, and charge generated by the TENGs under a 1N load are consistently lower compared to those under a 5N load. This indicates that the mechanical force applied to the TENGs affects their electrical output, with higher loads resulting in an increased electrical output performance. Similarly, as illustrated in Figure 4d–f, the voltage, current, and charge output of the TENGs at a velocity of 20 mm/s are consistently lower than those generated at a velocity of 100 mm/s. This suggests that the velocity of operation also influences the electrical output performance of TENGs, with higher frequencies leading to an enhanced electrical output.

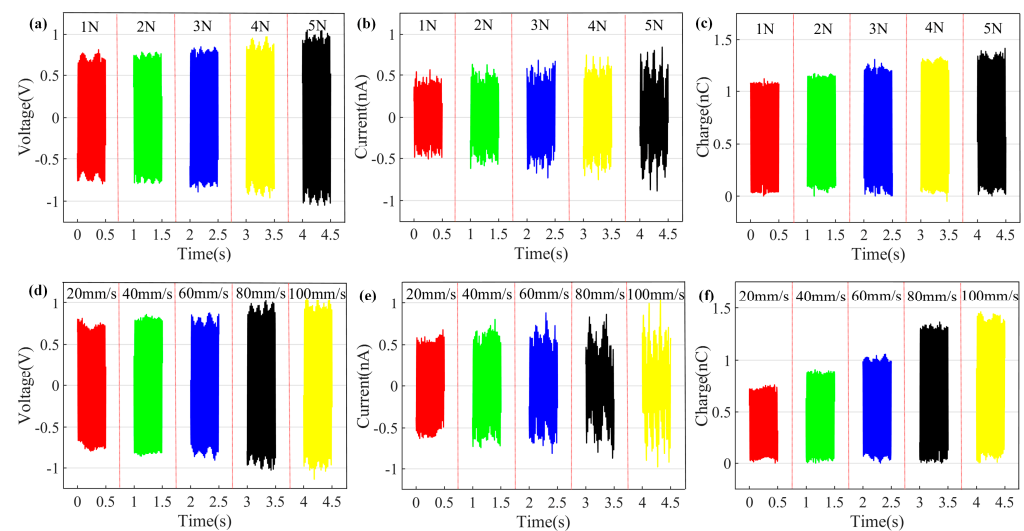


Figure 4. Triboelectrical performances of the PI film sliding against a steel ball under dry conditions with varied loads and sliding velocities. (a) Open-circuit voltage with varied loads (1N to 5N). (b) Short-circuit current with varied loads (1N to 5N). (c) Transferred charge with varied loads (1N to 5N). (d) Open-circuit voltage with varied sliding velocities (20 mm/s to 100 mm/s). (e) Short-circuit current with varied sliding velocities (20 mm/s to 100 mm/s). (f) Transferred charge with varied sliding velocities (20 mm/s to 100 mm/s).

Furthermore, the results indicate that higher loads and frequencies exacerbate the abrasion of the PI film, which is a crucial component of the TENGs. The escalating abrasion of the PI film leads to more electrical energy being released during the wear process, resulting in an increase in the values of voltage, current, and charge detected by the electrometer. However, it is noteworthy that, in the practical operation of our TENGs, a velocity of 80 mm/s imposes a lesser burden compared to a velocity of 100 mm/s. Therefore, we maintained the TENGs at a load of 5N and a velocity of 80 mm/s in subsequent experimental trials to ensure consistent and reliable results.

3.3. Effect of Lubrication with TiO₂-Doped Oleic Acid on the Triboelectrical Performances

Compared to the dry conditions, liquid lubricants could effectively reduce the friction and wear of sliding contacts. The presence of the lubricant forms a protective layer between the contacting surfaces, minimizing direct contact and reducing frictional forces. Zero-dimensional materials with a spherical microstructure have been extensively used as additives to improve the tribological behavior. In this study, TiO₂-doped oleic acid

at different concentrations was used to investigate the influence on the tribological and triboelectrical performances. Figure 5 shows the triboelectrical performances of the PI film sliding against a steel ball under TiO_2 -doped oleic acid with a concentration of 0–2 wt%. As it can be seen in Figure 5a, as the concentration of TiO_2 increases, the output open-circuit voltage gradually increases and then decreases. The lubrication with a concentration of 0.1% exhibits the best performance, which is better than under dry conditions. This trend suggests that the presence of TiO_2 nanoparticles enhances the frictional electrification effect of the oleic acid lubricant, leading to a notable increase in voltage generation. Similarly, Figure 5b–c present similar trends in current and charge data, indicating that the incorporation of TiO_2 nanoparticles promotes electron flow and charge accumulation within the TENGs. The triboelectrical amplitudes of the TENG with the PI sliding against the steel ball lubricated with TiO_2 -doped oleic acid with various TiO_2 weights (including (a) voltage, (b) current, and (c) charge) are plotted in Figure S4. As it can be seen, the voltage, current, and charge increase with the increase in the content of TiO_2 before 0.1 wt%; then, they reach a certain value. Note that oleic acid lubrication alone could not greatly improve the triboelectrical performance. Especially for the output open-circuit voltage, the value of the amplitude under oleic acid lubrication is much smaller than that under dry conditions. This discrepancy may be attributed to the larger surface contact area generated during dry friction, which enhances the frictional electrification effect and results in a higher voltage output. The surface roughness decreases and the enlarged wear surface area contributes in part to the improved output power of the TENGs [37]. Consequently, the surface appearance changes in the material have a great influence on the output performance of the TENGs [38–40]. It was found that the lubrication with 0.1 wt% TiO_2 in the oleic acid greatly improved the triboelectrical performances, including voltage, current, and charge. The key determinant of power output on the TENGs is the amount of charge transferred per unit time [41]. This phenomenon may be due to the increase in the mass fraction of titanium dioxide in oleic acid, which isolates the contact between the PI film and the 304 stainless steel ball, affecting the rate of charge transfer.

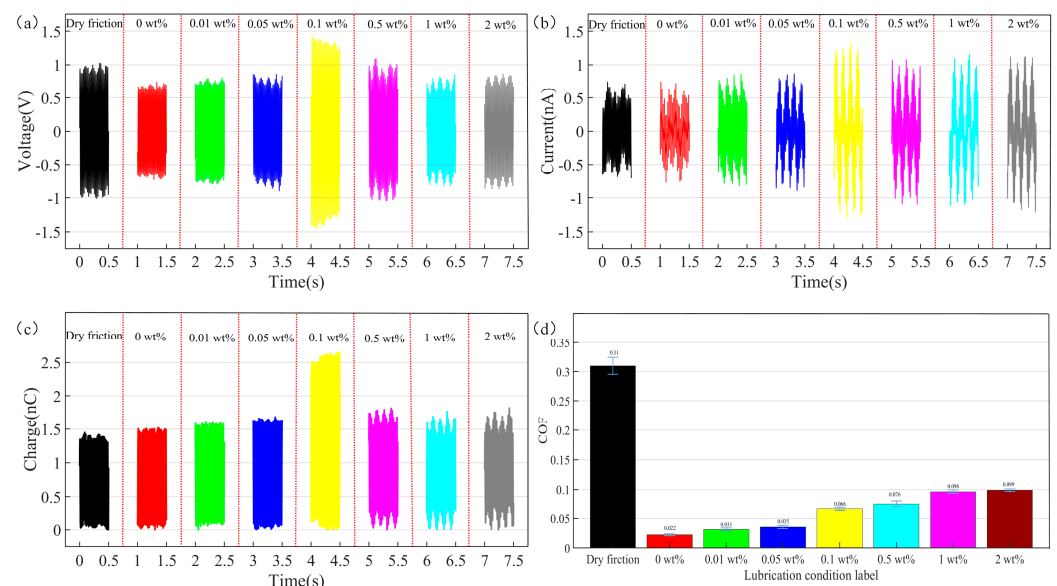


Figure 5. Triboelectrical performances of the PI film sliding against a steel ball under TiO_2 -doped oleic acid (TiO_2 concentration of 0–2 wt%) lubrication, with a load of 5N and a velocity of 80 mm/s. (a) Output short-circuit current. (b) Output open-circuit voltage. (c) Effective charge. (d) Average COF.

The variation of the COF curve of the TENG of the PI sliding against the steel ball lubricated with TiO_2 -doped oleic acid with various TiO_2 weights is shown in Figure S5, and the average COF at the steady state is shown in Figure 5d. A substantial decrease in the COF is observed from dry friction to the oleic acid lubrication, which can be attributed to the

improved lubricating effect of introducing oleic acid. However, as the TiO_2 concentration increases, the COF gradually rises, indicating that the addition of TiO_2 nanoparticles increases friction. The increased wear trace may be attributed to the excessive addition of solid lubricant compared to liquid lubricants, which may result in an increase in the COF [42,43]. In the case of titanium dioxide particles, their uneven distribution in oleic acid or interaction with the sample surface may lead to the accumulation of excessive solid particles on the friction surface, thereby increasing friction. These interactions may cause changes in surface roughness and exacerbate wear, ultimately reducing the effectiveness of oleic acid lubrication.

Subsequently, the worn surface was analyzed. Three worn surfaces and their corresponding cross-sectional profiles under typical lubrication conditions, for which the concentrations were dry friction, 0 wt%, and 0.1 wt%, are plotted in Figure 6.

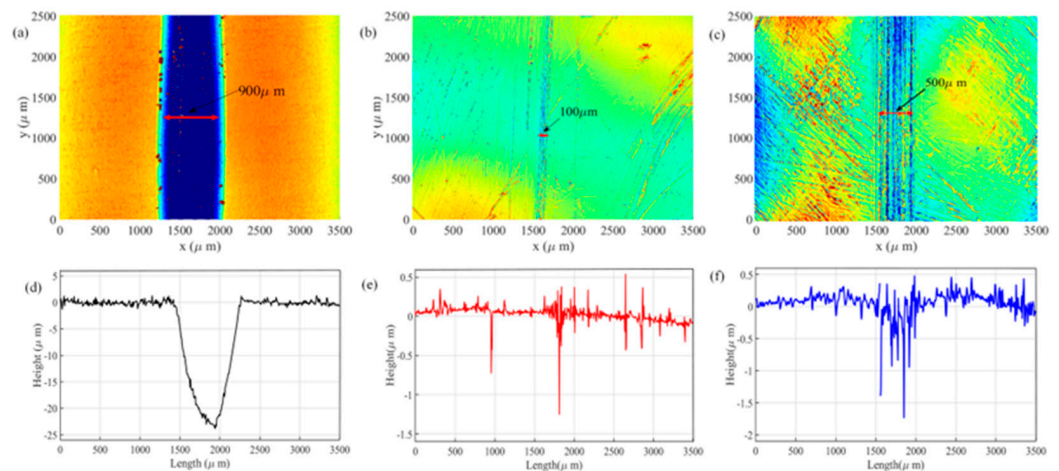


Figure 6. The worn surface topographies (a–c) and cross-sectional profiles (d–f) under various lubrication conditions. (a,d) Dry friction, (b,e) oleic acid lubrication, and (c,f) TiO_2 0.1 wt%-doped oleic acid lubrication.

In Figure 6a,d, corresponding to dry friction conditions, the sample surface exhibits wide and deep wear traces, indicating substantial material loss and surface damage resulting from friction. As shown in Figure 6b,e, the widths and depths of the wear traces significantly decrease. This reduction in wear trace dimensions suggests that the application of TiO_2 -doped oleic acid as a lubricant effectively reduces friction and slows down surface wear. As shown in Figure 6c,f, both of the widths and depths of the wear traces under lubrication at a concentration of 2 wt% are larger than that at a concentration of 0.1 wt%. More scratch marks were observed, which were mainly caused by the TiO_2 nanoparticles sandwiched between the PI film and steel ball. The hardness of the TiO_2 nanoparticles is much greater than that of the PI, which results in abrasive wear during the sliding process.

In order to verify the durability of the output performances of the TENG lubricated with TiO_2 0.1 wt%-doped oleic acid, a test lasting 3600 s was performed. As it can be seen from Figure 7, no significant change was observed in the voltage, current, and charge after sliding for a long time.

Overall, the lubrication with TiO_2 -doped oleic acid improved the triboelectrical performances and tribological behavior. However, the addition of TiO_2 nanoparticles to the oleic acid lubricant slightly impaired the friction and wear behaviors. The concentration of TiO_2 has a significant influence on the surface wear and frictional behaviors of the friction pairs of TENGs. This observation suggests that the inclusion of TiO_2 particles in the lubricant may have contributed to a heightened surface roughness, thereby exacerbating the severity of wear experienced by the samples.

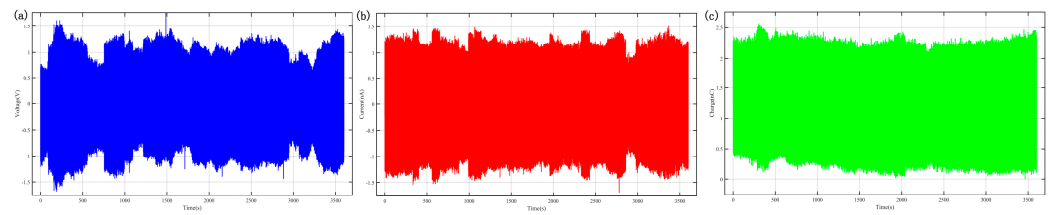


Figure 7. The output performances of the TENG lubricated with TiO_2 0.1 wt%-doped oleic acid tested for a long time (3600 s).

4. Discussion

In order to gain more insights into the triboelectrical mechanisms of the PI film sliding against a steel ball lubricated with the TiO_2 -doped oleic acid, a comprehensive investigation was carried out from a microcosmic viewpoint.

4.1. Microstructures of the Worn Surface

Figure 8 shows the SEM image of the wear traces of the PI film under various magnifications under dry friction, oleic acid lubrication, and TiO_2 -doped oleic acid lubrication. As it can be seen from Figure 8a–c, plenty of fragments can be observed at the wear trace, which are formed by the detached chunks from the PI film during the sliding against the steel ball. It is conceivable that material worn off from the PI surface could adhere to the steel counterpart and then detach due to the shear force, ultimately leading to the formation of fragments. Adhesive wear is the main mechanism for this case. Upon the introduction of lubrication with oleic acid, as illustrated in Figure 8d–f, most of the large fragments disappeared, replaced by a variety of small fragments. In addition, more characteristics, such as parallel grooves, debris, and material removal, that left pits are shown. The grooves on the PI film are formed from what surfaced from the cutting or scraping action by the mating steel ball. The microvolume of the friction surface material is subjected to cyclic contact stress, resulting in repeated deformation, cracks and separation of micro-pits, and fatigue wear.

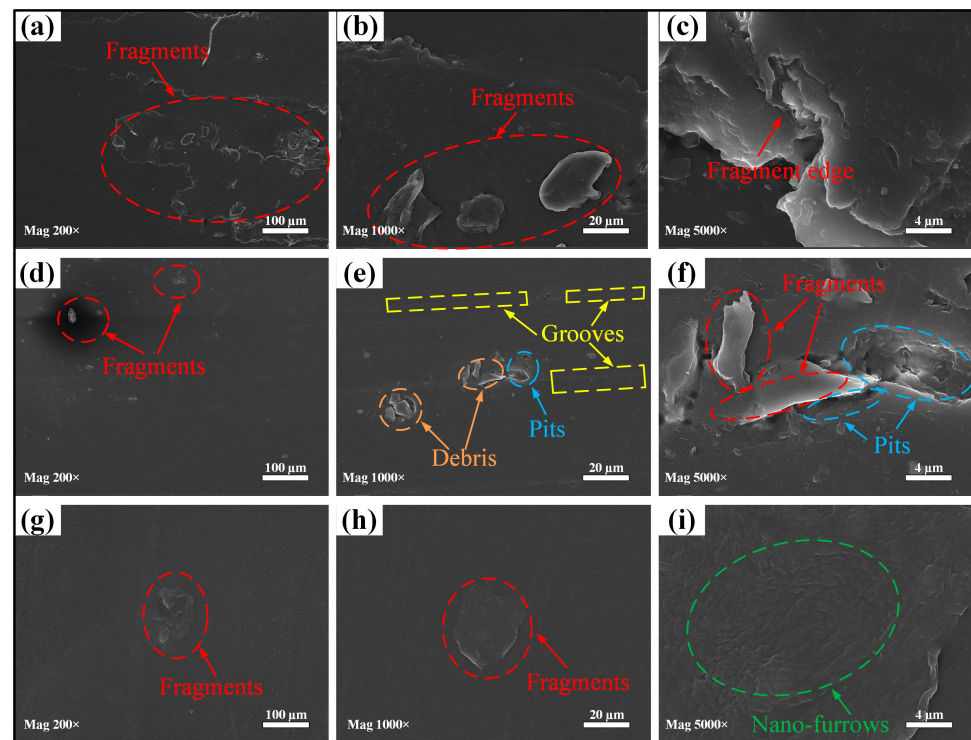


Figure 8. SEM images of wear traces on the PI film under dry friction (a–c), oleic acid lubrication (d–f), and oleic acid lubrication with 0.1 wt% TiO_2 (g–i), with magnifications of 200, 1000, and 5000.

Hence, this is the result of the coordinated interaction of the mechanisms of adhesive wear, abrasive wear, and fatigue wear. This may also be because of the adhesion and temperature [44–48] effects of steel on the PI film during wear, resulting in partial material detachment. In the case of oleic acid lubrication containing TiO_2 0.1 wt%, as shown in Figure 8g,h, the absence of local material defects suggests a modification in the properties at the friction interface attributed to the presence of TiO_2 particles. The wear trace becomes very smooth, and only a few fragments are detached. As it can be seen from Figure 8i, there are many tortuous routes on the surface; this is mainly because of the micro-cutting of TiO_2 nanoparticles during the friction process [43,49]. This lubrication may significantly reduce the interaction between the friction surfaces, thereby minimizing wear and detachment.

4.2. Composition Analysis of the Wear Surface

To determine the elemental composition and distribution on the entire wear trace, mapping using energy-dispersive spectrometry (EDS) was performed. The results of the elemental mapping obtained by analyzing the frictional contacts using EDS are presented in Figure 9. The contributions of the PI film (C, H, N, and O), oleic acid (C, H, and O), and TiO_2 nano-additives (Ti and O) are indicated in the EDS elemental maps. It can be seen from Figure 9a that numerous slight smooth scratches are located on the wear trace. The EDS mapping (Figure 9b–f) reveals that the characteristic elements, including the Ti element, are distributed on the wear trace uniformly and the TiO_2 aggregates in some regions.

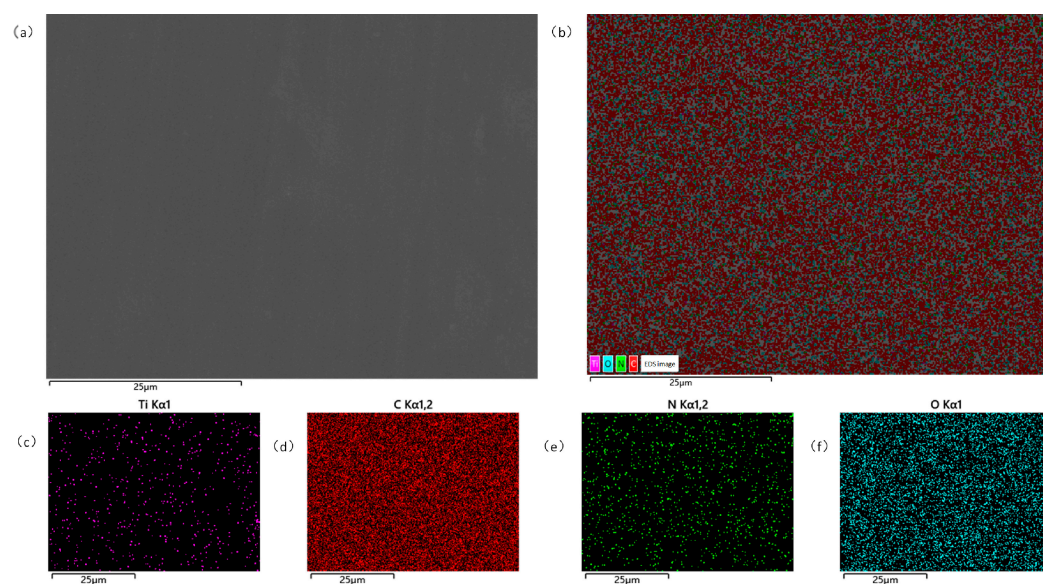


Figure 9. SEM image and EDS maps of the wear trace under the lubrication with TiO_2 0.1 wt%-doped oleic acid. (a) SEM image (b) EDS elemental mapping of all elements (c–f) EDS elemental mapping of Ti, C, N and O elements, respectively.

FTIR spectroscopy analysis was conducted to investigate the wear mechanism of TiO_2 -doped oleic acid lubrication during friction. The spectra of the wear tracks generated on the PI films under four different lubrication conditions—non-friction, dry friction, oleic acid lubrication, and oleic acid lubrication with the addition of TiO_2 nanoparticles—are shown in Figure 10. As shown in Figure 8, the peaks at 2960 cm^{-1} and 2870 cm^{-1} correspond to the asymmetric and symmetric stretching vibrations of $-\text{CH}_3$ groups, respectively. The peaks at 2922 cm^{-1} and 2853 cm^{-1} correspond to the asymmetric and symmetric stretching vibrations of $-\text{CH}_2$ groups, respectively. The carbonyl ($\text{C}=\text{O}$) and amido ($\text{N}-\text{H}$) stretching vibrational absorption peaks are observed at 1711 cm^{-1} and 3483 cm^{-1} . The characteristic peak of $[\text{CH}_2\text{CH}(\text{CH}_3)]_n$ of PI is also observed at 1165 cm^{-1} . A blank spectrum of the PI film was used as a benchmark. The presence of absorption peaks at 2960 cm^{-1} , 2922 cm^{-1} , 2870 cm^{-1} , and 2855 cm^{-1} related to the stretching vibrations of the C-H groups is observed,

indicating that the molecular radicals appeared after the sliding test. Compared to the dry conditions, the magnitude ratio of CH_3 , $A_{\text{CH}_3, \text{As}}/A_{\text{CH}_3, \text{s}}$, decreased slightly, while the magnitude ratio of CH_2 , $A_{\text{CH}_2, \text{As}}/A_{\text{CH}_2, \text{s}}$, decreased. This indicates that the addition of oleic acid changed the molecular vibrational state. The stretching vibrational absorption of (C=O) became stronger, which suggests that the PI film is covered with plenty of oleic acid molecules. For the case of TiO_2 -doped oleic acid lubrication, most of the vibration peaks became weaker with the addition of TiO_2 nanoparticles. Especially, the vibrational absorption peak of N-H disappeared. The reason for this might be that some nanoparticles were immersed in the PI film, resulting in the intermolecular space, further reducing the vibration of molecular groups. Moreover, the absorption peaks related to the stretching vibrations of the C-H groups increased dramatically, may because the TiO_2 nanoparticles increased the dispersion and stability of the lubricant, which enhanced the signal intensity of the C-H group molecule in the absorption spectrum measurement.

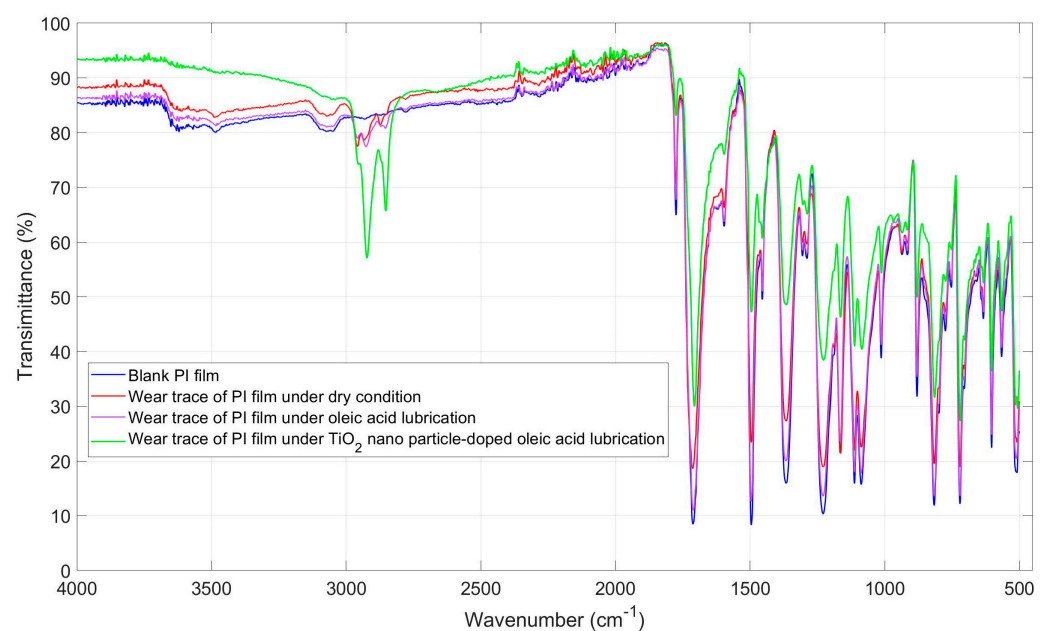


Figure 10. The FTIR spectra of wear traces generated on PI films under various lubrication conditions.

4.3. Mechanism of TENG Performance Improvement

According to the above analysis, the behavioral models of the TENG interface under dry friction, oleic acid lubrication, and TiO_2 -doped oleic acid lubrication are presented in Figure 11. Similar to [30], under dry friction, the friction generates a triboelectric charge accompanied with voltage and current. However, the high friction also leads to the severe wear of the PI film, and some wear debris transfers from the PI onto the steel surface. Some of the debris are scattered and adhere to the PI film again and then form fragments, as shown in Figure 11a. Thus, the coverage of the wear debris and fragments prevents the further generation of the triboelectric charge. The main mechanism is abrasive wear. As shown in Figure 11b, the wear debris and the fragments are drastically reduced with oleic acid lubrication. The main mechanism is change to fatigue wear, resulting in the emergence of cracks in and material removal from the PI interface. Furthermore, the triboelectrical performances change little from those of dry friction. As shown in Figure 11c, the addition of TiO_2 nanoparticles reduces the formation of debris from the PI film due to the ratio of TiO_2 nanoparticles, therefore increasing the generation of charge as well as voltage and current. In addition, the sliding of TiO_2 nanoparticles can make the PI surface furrow, known as the micro-machining effect. Therefore, the contacting area is increased, which ceases the improvement in the triboelectrical performances. Overall, the reduced wear and increased output performances are the combined effect of oleic acid and TiO_2

nanoparticles. In addition, the polarity of oleic acid directly affects the generation of friction charge when it comes into contact with a solid material. Oleic acid has properties between polar and non-polar. It not only increases the total triboelectrical charge amount, but also has good lubrication properties, which can reduce the wear of the interface. The surface wettability [50] and molecular behaviors [51] have an effect on lubrication, and may also be closely related to the triboelectrical performances of TENGs. The underlying mechanism is much more complex and still needs exploration.

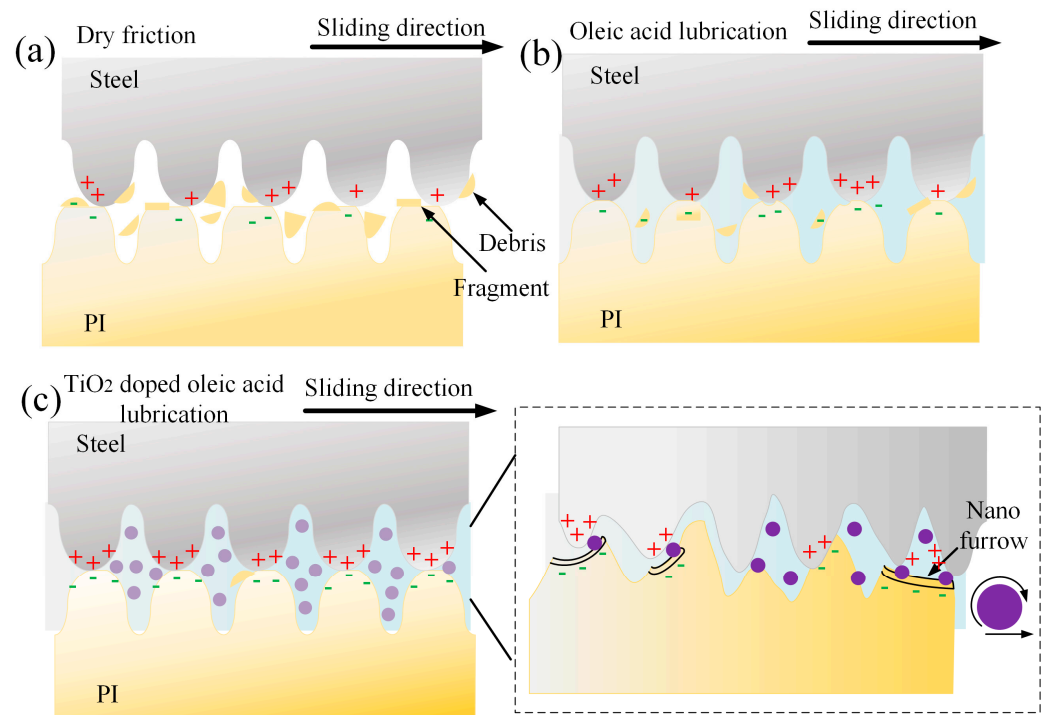


Figure 11. Mechanism of wear and output performances under various condition. (a) Dry friction. (b) Under oleic acid lubrication. (c) Under TiO_2 -doped oleic acid lubrication.

5. Conclusions

Our comprehensive investigation of the electrical output performance, wear resistance performance, and surface composition of TENG systems led to the following conclusions:

- (1) Different materials, such as PTFE, PDMS, TPU, etc., demonstrate distinct variations in voltage, current, and charge generation, which are closely associated with their unique surface properties.
- (2) The voltage, current, and charge generation of TENGs are significantly influenced by the load and velocity conditions. Higher loads and frequencies exacerbate the wear of PI films, resulting in higher electrical energy release.
- (3) The triboelectrical performances of the PI film sliding against a steel ball under 0.1 wt% TiO_2 -doped oleic acid are significantly improved compared to those under dry conditions, with the growth rates of 35.2%, 103.6, and 85.6%.
- (4) The COF of the TENG lubricated with 0.1 wt% TiO_2 -doped oleic acid dropped from 0.31 to 0.066 compared to that under dry conditions. The EDS analysis revealed a uniform distribution of Ti elements on the surface of wear marks, and the addition of 0.1 wt% TiO_2 resulted in deeper and wider wear marks on the PI films. The FTIR spectra indicated changes in the molecular structure of the surface wear marks of the PI films after friction, suggesting that TiO_2 nanoparticles enhance the interaction between oleic acid and the PI films during friction.
- (5) The enhancement mechanism of TiO_2 -doped oleic acid in TENGs was also analyzed. TiO_2 -doped oleic acid significantly improved the tribological behaviors and triboelec-

triboelectrical performances of TENGs. The introduction of oleic acid reduced the amount of segments, which are usually created under dry friction condition. Incorporating the appropriate amount (0.1 wt%) of TiO₂ into the oleic acid lubricant can reduce surface damage, but it may result in more nano-furrows. The corresponding contact area increases, thereby increasing the voltage, current, and charge generated by the TENGs.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/lubricants12080269/s1>, Figure S1: The experiment setup for measuring triboelectrical performances and coefficient of friction; Figure S2: The 3D topography of PI film; Figure S3: The COF varies with time of four polymer materials; Figure S4: The triboelectrical amplitudes of TENG of PI sliding against steel ball lubricated by TiO₂-doped oleic acid with various TiO₂ weights; Figure S5: The variation COF curve of TENG of PI sliding against steel ball lubricated by TiO₂-doped oleic acid with various TiO₂ weights.

Author Contributions: Conceptualization, all authors; methodology and investigation, J.S., G.Y., and X.W. (Xianzhang Wang); data curation, formal analysis, and resources, Y.H., J.L., M.H., and X.W. (Xianmin Wang); writing—original draft preparation, J.S.; writing—review and editing, X.W. (Xianzhang Wang); supervision, G.Y.; project administration and funding acquisition, P.Z. and X.W. (Xianzhang Wang). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The Tribology Science Fund of State Key Laboratory of Tribology in Advanced Equipment, grant number SKLTKF22B14; Guangdong Colleges and universities in Guangdong province “characteristic innovation” Project, grant number 2023KTSCX045; Guangdong province graduate education innovation program project, grant number 2023JGXM_75; Doctoral Research Start-up Project of Guangdong Ocean University, grant number 060302012005; Guangxi Science and technology planning project of Key research and development, grant number 2022AB20112; and Zhanjiang Key Laboratory of Modern Marine Fishery Equipment, grant number 2021A05023.

Data Availability Statement: The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors greatly appreciate the technical support and constructive suggestions from Liran Ma’s group at Tsinghua University.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Xia, X.; Liu, Q.; Zhu, Y.Y.; Zi, Y. Recent advances of triboelectric nanogenerator based applications in biomedical systems. *EcoMat* **2020**, *2*, e12049. [\[CrossRef\]](#)
2. Yan, L.X.; Mi, Y.J.; Lu, Y.; Qin, Q.H.; Wang, X.Q.; Meng, J.J.; Liu, F.; Wang, N.; Cao, X. Weaved piezoresistive triboelectric nanogenerator for human motion monitoring and gesture recognition. *Nano Energy* **2022**, *96*, 107135. [\[CrossRef\]](#)
3. Kim, D.Y.; Kim, H.S.; Kong, D.S.; Choi, M.; Kim, H.B.; Lee, J.H.; Murillo, G.; Lee, M.; Kim, S.S.; Jung, J.H. Floating buoy-based triboelectric nanogenerator for an effective vibrational energy harvesting from irregular and random water waves in wild sea. *Nano Energy* **2018**, *45*, 247–254. [\[CrossRef\]](#)
4. Cheng, P.; Liu, Y.N.; Wen, Z.; Shao, H.Y.; Wei, A.M.; Xie, X.K.; Chen, C.; Yang, Y.; Peng, M.; Zhuo, Q.; et al. Atmospheric pressure difference driven triboelectric nanogenerator for efficiently harvesting ocean wave energy. *Nano Energy* **2018**, *54*, 156–162. [\[CrossRef\]](#)
5. Bai, Y.; Xu, L.; He, C.; Zhu, L.P.; Yang, X.D.; Jiang, T.; Nie, J.; Zhong, W.; Wang, Z.L. High-performance triboelectric nanogenerators for self-powered, in-situ and real-time water quality mapping. *Nano Energy* **2019**, *66*, 104117. [\[CrossRef\]](#)
6. Han, J.J.; Liu, Y.; Feng, Y.W.; Jiang, T.; Wang, Z.L. Achieving a large driving force on triboelectric nanogenerator by wave-driven linkage mechanism for harvesting blue energy toward marine environment monitoring. *Adv. Energy Mater.* **2023**, *13*, 202203219. [\[CrossRef\]](#)
7. Zhou, Z.H.; Li, X.S.; Wu, Y.F.; Zhang, H.; Lin, Z.W.; Meng, K.Y.; Lin, Z.; He, Q.; Sun, C.; Yang, J.; et al. Wireless self-powered sensor networks driven by triboelectric nanogenerator for in-situ real time survey of environmental monitoring. *Nano Energy* **2018**, *53*, 501–507. [\[CrossRef\]](#)
8. Wu, Z.Y.; Guo, H.Y.; Ding, W.B.; Wang, Y.C.; Zhang, L.; Wang, Z.L. A hybridized triboelectric-electromagnetic water wave energy harvester based on a magnetic sphere. *ACS Nano* **2019**, *13*, 2349–2356. [\[CrossRef\]](#)
9. Li, X.Y.; Tao, J.; Wang, X.D.; Zhu, J.; Pan, C.F.; Wang, Z.L. Networks of high performance triboelectric nanogenerators based on liquid-solid interface contact electrification for harvesting low-frequency blue energy. *Adv. Energy Mater.* **2018**, *8*, 1800705. [\[CrossRef\]](#)

10. Chen, P.F.; An, J.; Shu, S.; Cheng, R.W.; Nie, J.H.; Jiang, T.; Wang, Z.L. Super-durable, low-wear, and high-performance fur-brush triboelectric nanogenerator for wind and water energy harvesting for smart agriculture. *Adv. Energy Mater.* **2021**, *11*, 2003066. [\[CrossRef\]](#)
11. Chen, B.D.; Tang, W.; He, C.; Deng, C.R.; Yang, L.J.; Zhu, L.P.; Chen, J.; Shao, J.J.; Liu, L.; Wang, Z.L. Water wave energy harvesting and self-powered liquid-surface fluctuation sensing based on bionic-jellyfish triboelectric nanogenerator. *Mater. Today* **2018**, *21*, 88. [\[CrossRef\]](#)
12. Wang, W.L.; Yang, D.F.; Yan, X.R.; Wang, L.C.; Hu, H.; Wang, K. Triboelectric nanogenerators: The beginning of blue dream. *Front. Chem. Sci. Eng.* **2023**, *17*, 635–678. [\[CrossRef\]](#)
13. Liu, X.; Yu, A.F.; Qin, A.M.; Zhai, J.Y. Highly Integrated Triboelectric Nanogenerator for Efficiently Harvesting Raindrop Energy. *Adv. Mater. Technol.* **2019**, *4*, 1900608. [\[CrossRef\]](#)
14. Wang, J.L.; Yu, X.; Zhao, D.; Yu, Y.; Gao, Q.; Cheng, T.H.; Wang, Z.L. Enhancing Output Performance of Triboelectric Nanogenerator via Charge Clamping. *Adv. Energy Mater.* **2021**, *11*, 2101356. [\[CrossRef\]](#)
15. Feng, J.R.; Zhou, H.L.; Cao, Z.; Zhang, E.Y.; Xu, S.X.; Li, W.T.; Yao, H.L.; Wan, L.Y.; Liu, G.L. 0.5 m Triboelectric Nanogenerator for Efficient Blue Energy Harvesting of All-Sea Areas. *Adv. Sci. Wein.* **2022**, *9*, 202204407. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Chen, X.; Cao, B.; Yang, C.; Zhang, H.N.; Fang, L.; Chen, C.; Wang, Z.X.; He, W.; Wang, P.H. Broadband and Multi-Cylinder-Based Triboelectric Nanogenerators for Mechanical Energy Harvesting with High Space Utilization. *Materials* **2023**, *16*, 3034. [\[CrossRef\]](#)
17. Yuan, Z.; Guo, L. Recent advances in solid–liquid triboelectric nanogenerator technologies, affecting factors, and applications. *Sci. Rep.* **2024**, *14*, 10456. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Lin, S.H.; Chen, X.Y.; Wang, Z.H. Contact Electrification at the Liquid–Solid Interface. *Chem. Rev.* **2022**, *122*, 5209–5232. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Chatterjee, S.; Burman, S.R.; Khan, I.; Saha, S.; Choi, D.; Lee, S.; Lin, Z.H. Recent advancements in solid–liquid triboelectric nanogenerators for energy harvesting and self-powered applications. *Nanoscale* **2020**, *12*, 17663–17697. [\[CrossRef\]](#)
20. Kulandaivel, A.; Potu, S.; Babu, A.; Madathil, N.; Velpula, M.; Rajaboina, R.K.; Khanapuram, U.K. Advances in ferrofluid-based triboelectric nanogenerators: Design, performance, and prospects for energy harvesting applications. *Nano Energy* **2024**, *120*, 109110. [\[CrossRef\]](#)
21. Tan, J.; Sun, S.; Jiang, D.Y.; Xu, M.Y.; Chen, X.Y.; Song, Y.C.; Wang, Z.H. Advances in triboelectric nanogenerator powered electrowetting-on-dielectric devices: Mechanism, structures, and applications. *Mater. Today* **2022**, *58*, 201–220. [\[CrossRef\]](#)
22. Wu, J.; Xi, Y.H.; Shi, Y.J. Toward wear-resistive, highly durable and high performance triboelectric nanogenerator through interface liquid lubrication. *Nano Energy* **2020**, *72*, 104659. [\[CrossRef\]](#)
23. Wang, K.Q.; Li, J.J.; Li, J.F.; Wu, C.Y.; Yi, S.; Liu, Y.F.; Luo, J.B. Hexadecane-containing sandwich structure based triboelectric nanogenerator with remarkable performance enhancement. *Nano Energy* **2021**, *87*, 106198. [\[CrossRef\]](#)
24. Liu, X.; Zhang, J.; Zhang, L.; Feng, Y.; Feng, M.; Luo, N.; Wang, D. Influence of interface liquid lubrication on triboelectrification of point contact friction pair. *Tribol. Int.* **2022**, *165*, 107323. [\[CrossRef\]](#)
25. Qiao, W.Y.; Zhou, L.L.; Zhao, Z.H.; Yang, P.Y.; Liu, D.; Liu, X.R.; Liu, J.Q.; Liu, D.Y.; Wang, Z.L.; Wang, J. MXene lubricated tribovoltaic nanogenerator with high current output and long lifetime. *Nano-Micro Lett.* **2023**, *15*, 218. [\[CrossRef\]](#)
26. Yang, D.L.; Zhang, L.Q.; Luo, N.; Liu, Y.; Sun, W.X.; Peng, J.L.; Feng, M.; Feng, Y.E.; Wang, H.F.; Wang, D.A. Tribological-behaviour-controlled direct-current triboelectric nanogenerator based on the tribovoltaic effect under high contact pressure. *Nano Energy* **2022**, *99*, 107370. [\[CrossRef\]](#)
27. Rajendhran, N.; Palanisamy, S.; Periyasamy, P.; Venkatachalam, R. Enhancing of the tribological characteristics of the lubricant oils using Ni-promoted MoS₂ nanosheets as nano-additives. *Tribol. Int.* **2018**, *118*, 314–328. [\[CrossRef\]](#)
28. Yin, X.; Jin, J.; Chen, X.C. Ultra-Wear-Resistant MXenes-Based Composite Coating via In-Situ Formed Nanostructured Tribofilm. *ACS Appl. Mater. Interfaces* **2019**, *11*, 32569–32576. [\[CrossRef\]](#)
29. Del, R.J.; López, E.R.; Fernández, J. Tribological properties of graphene nanoplatelets or boron nitride nanoparticles as additives of a polyalphaolefin base oil. *J. Mol. Liq.* **2021**, *333*, 115911.
30. Guo, Y.F.; Zhang, L.Q.; Du, C.H.; Feng, Y.E.; Yang, D.; Zhang, Z.T.; Feng, M.; Wan, Y.; Wang, D.A. Onion-like carbon as nano-additive for tribological nanogenerators with enhanced output performance and stability. *Nano Energy* **2022**, *104*, 107900. [\[CrossRef\]](#)
31. Guo, L.H.; Zhang, Y.M.; Zhang, G.; Wang, Q.H.; Wang, T.M. MXene-Al₂O₃ synergize to reduce friction and wear on epoxy-steel contacts lubricated with ultra-low sulfur diesel. *Tribol. International* **2021**, *153*, 106588. [\[CrossRef\]](#)
32. Chen, J.Z.; Zhao, Y.; Wang, R.R.; Wang, P.F. Super-Low Friction Electrification Achieved on Polytetrafluoroethylene Films-Based Triboelectric Nanogenerators Lubricated by Graphene-Doped Silicone Oil. *Micromachines* **2023**, *14*, 1776. [\[CrossRef\]](#)
33. Li, S.Y.; Fan, Y.; Chen, H.Q.; Nie, J.H.; Liang, Y.X.; Tao, X.L.; Zhang, J.; Chen, X.Y.; Fu, E.G.; Wang, Z.L. Manipulating the triboelectric surface charge density of polymers by low-energy helium ion irradiation/implantation. *Energy Environ. Sci.* **2020**, *13*, 896–907. [\[CrossRef\]](#)
34. Takada, T.; Kikuchi, H.; Miyake, H.; Tanaka, Y.; Yoshida, M.; Hayase, Y. Determination of Charge-trapping Sites in Saturated and Aromatic Polymers by Quantum Chemical Calculation. *IEEE Trans. Dielectr. Electr. Insul.* **2015**, *22*, 1240–1249. [\[CrossRef\]](#)
35. Albina, A.; Taberna, P.L.; Cambronne, J.P.; Simon, P.; Flahaut, E.; Lebey, T. Impact of the surface roughness on the electrical capacitance. *Microelectron. J.* **2006**, *37*, 752–758. [\[CrossRef\]](#)

36. Macuk, A.L. Electrical Characteristics and Surface Properties of Polycrystalline Silicon Exposed to Morphological Alteration with Applications in Micro- and Nanotechnology. Master's Thesis, Bradley University, Peoria, IL, USA, 2014.
37. Lee, B.Y.; Kim, D.H.; Park, J.; Park, K.I.; Lee, K.J.; Jeong, C.K. Modulation of surface physics and chemistry in triboelectric energy harvesting technologies. *Sci. Technol. Adv. Mater.* **2019**, *20*, 758–773. [[CrossRef](#)]
38. Yu, J.B.; Hou, X.J.; He, J.; Cui, M.; Wang, C.; Geng, W.P.; Mu, J.L.; Han, B.; Chou, X.J. Ultra-flexible and high-sensitive triboelectric nanogenerator as electronic skin for self-powered human physiological signal monitoring. *Nano Energy* **2020**, *69*, 104437. [[CrossRef](#)]
39. Kim, D.; Jeon, S.B.; Kim, J.Y.; Seol, M.L.; Kim, S.O.; Choi, Y.K. High-performance nanopattern triboelectric generator by block copolymer lithography. *Nano Energy* **2015**, *12*, 331–338. [[CrossRef](#)]
40. Cheng, G.G.; Jiang, S.Y.; Li, K.; Zhang, Z.Q.; Wang, Y.; Yuan, N.Y.; Ding, J.N.; Zhang, W. Effect of argon plasma treatment on the output performance of triboelectric nanogenerator. *Appl. Surf. Sci.* **2017**, *412*, 350–356. [[CrossRef](#)]
41. Zhang, C.; Tang, W.; Han, C.B.; Fan, F.R.; Wang, Z.L. Theoretical Comparison, Equivalent Transformation, and Conjunction Operations of Electromagnetic Induction Generator and Triboelectric Nanogenerator for Harvesting Mechanical Energy. *Adv. Mater.* **2014**, *26*, 3580–3591. [[CrossRef](#)]
42. Bian, L.J.; Song, N.N.; Yu, L.G.; Zhang, Y.J.; Zhang, P.Y.; Zhang, S.M. Susceptibility of Poly-Alpha Olefin and Diisooctyl Sebacate Base Oils With Different Polarities to Oleic Acid Surface-Capped Ultra-Small Cerium Oxide Nanoparticle. *Lubr. Sci.* **2024**, 1–11. [[CrossRef](#)]
43. Raina, A.; Arland, A. Effect of nanodiamond on friction and wear behavior of metal dichalcogenides in synthetic oil. *Appl. Nanosci.* **2018**, *8*, 581–591. [[CrossRef](#)]
44. Ochoa, I.; Hatzikiriakos, S.G. Paste extrusion of polytetrafluoroethylene (PTFE): Surface tension and viscosity effects. *Powder Technol.* **2005**, *153*, 108–118. [[CrossRef](#)]
45. Yin, X.; Mu, L.; Jia, Z.; Pang, H.; Chai, C.; Liu, H.; Liang, C.; Zhang, B.; Liu, D. Nanostructure of superlubricating tribofilm based on friction-induced a-C:H films under various working conditions: A review of solid lubrication. *Lubricants* **2024**, *12*, 40. [[CrossRef](#)]
46. Choi, J.; Morishita, H.; Kato, T. Frictional properties of bilayered mixed lubricant films on an amorphous carbon surface: Effect of alkyl chain length and SAM/PFPE portion. *Appl. Surf. Sci.* **2004**, *228*, 191–200. [[CrossRef](#)]
47. Tsybanev, G.V.; Belas, O.N. A study of the influence of a lubricant composition on fatigue and wear processes jointly or severally occurring in steel 45. *Strength Mater.* **2009**, *41*, 377–386. [[CrossRef](#)]
48. Yuan, C.Q.; Peng, Z.; Zhou, X.C.; Yan, X.P. Effects of temperature on sliding wear process under contaminated lubricant test conditions. *Wear* **2004**, *257*, 812–822. [[CrossRef](#)]
49. Wu, C.; Li, S.S.; Ni, J.; Yao, L.D.; Xia, Q. Effect of structure of ZnO and SiO₂ core-shell composite nanoparticles as lubricant additive on tribological properties of greases. *Appl. Surf. Sci.* **2024**, *657*, 159745. [[CrossRef](#)]
50. Gao, M.; Li, H.Y.; Ma, L.R.; Gao, Y.; Ma, L.R.; Luo, J.B. Molecular behaviors in thin film lubrication—Part two: Direct observation of the molecular orientation near the solid surface. *Friction* **2019**, *7*, 479–488. [[CrossRef](#)]
51. Li, Y.Z.; Li, S.W.; Bai, P.P.; Jia, W.P.; Xu, Q.; Meng, Y.G.; Ma, L.W.; Tian, Y. Surface wettability effect on aqueous lubrication: Van der Waals and hydration force competition induced adhesive friction. *J. Colloid Interface Sci.* **2021**, *599*, 667–675. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.