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Fabrication of MXene-Based Nanogenerator for Biomechanical Energy Harvesting and Sustainable Power Generation

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Abstract:

This comprehensive review investigates the forefront of 2D MXene-based nanogenerators, highlighting their remarkable features like high electro negativity, superior metallic conductivity, mechanical flexibility, and adaptable surface chemistry. The initial section examines recent advancements in MXene nanogenerator applications. The secondary section underscores the critical role of sustainable energy, categorizes nanogenerators, explains their working principles, and outlines essential frameworks. Subsequent sections provide an in-depth analysis of substances used for energy harvesting and the synergistic combinations of MXenes with other active materials. The focus then shifts to the synthesis, intrinsic properties, and polymeric nanocomposites of MXenes, discussing both recent progress and existing challenges. The review concludes with a detailed exploration of design strategies, internal improvement mechanisms, and the incorporation of 3D printing technologies, offering novel insights into enhancing MXene-based nanocomposites for advanced nanogenerator performance.

Keywords **— 2DMXene-based nanogenerators, Highelectronegativity, Metallic conductivity, Adaptable surface chemistry, Energy harvesting materials, 3D printing technologies**

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I. INTRODUCTION

The drive towards sustainable development in contemporary lifestyles necessitates the integration of green and sustainable energy systems that are crucial in addressing the dual challenges of global warming and escalating power demands [1]. Addressing the power demand requires a comprehensive approach that meets diverse individual and societal needs, thereby intensifying the focus on various energy harvesting technologies [2]. Mechanical energy, abundant in the environment as minor and major disturbances, presents a significant yet largely untapped resource for conversion into usable energy [3, 4]. Unfortunately, a substantial portion of this mechanical energy is either wasted or only partially harnessed.

To leverage this plentiful resource, nanogenerators—like piezoelectric nanogenerators (PENGs) and triboelectric nanogenerators (TENGs)—have been improved to transform mechanical movements into electrical energy[5,6]. These nanogenerators utilize readily available materials such as ceramics, polymers, composites, and nanocomposites, making them versatile for deployment across various environments and applications [7]. Despite their potential, the current efficiency of nanogenerators is suboptimal, necessitating enhancements to maximize energy conversion efficiency [8]. This performance gap is especially pronounced in PENGs, although TENGs and pyroelectric nanogenerators, that produce electrical energy from friction and climatic changes respectively, also play pivotal roles [9, 10, 11].

We can harvest electricity from the footsteps and wind and other human activities such as walking, typing etc using nanogenerators for energy harvesting or self powered sensors or wearable electronics applications [12, 13 and 14]. In recent studies, MXenes have been suggested to be very suitable for energy harvesting because of their enormous mechanical elasticity, electrical conductivity, and thermal resistance. Notably, MXene-based composites have with high energy conversion efficiency compared with conventional materials, into mechanical energy from vibration and electric power from thermal [15].

Furthermore, the application of MXenes has been investigated in numerous energy conversion techniques such as piezoelectric energy harvesting techniques, electromagnetic wave energy harvesting techniques, and energy storage techniques. The research shows that incorporation of MXenes into piezoelectric materials improved energy conversion efficiency and increased the output power. From the above result, the application of energy harvesting of different energy types using MXiene can be significantly underlined. Promising further advancements in this area, ongoing research aims at developing more efficient and effective energy harvesting technologies to underpin the development of sustainable energy systems. This paper studies the up-to-date progresses on new developments in MXene based materials with a special emphasis on its application in triboelectric and piezoelectric nanogenerators. From the Figure 1 it is clear that MXene-based materials are comprehensive in their approach to meet all energy harvester requirements. This review begins with a brief description of piezoelectric and triboelectric nanogenerators based on primary parameters, working principles and issues in the two technologies.

Following this foundational background, the paper shows the exceptional features of MXene-basis substances, which make them particularly suitable for improving the performances of triboelectric and piezoelectric nanogenerators. These properties include high electrical conductivity, mechanical flexibility, and customizable surface chemistry, which contribute significantly to improved energy conversion efficiencies. In the subsequent sections, the review delves into the design strategies and mechanisms through which MXenes enhance the output performance of nanogenerators. It provides a comprehensive analysis of how these materials can be integrated into nanogenerator systems to maximize their efficiency and durability. Finally, the paper offers insights and recommendations for future design strategies. These suggestions aim to further the improvement of MXene-based composite substances, driving innovation of next-generation nanogenerators. The goal is to provide advanced, efficient, and sustainable solutions for energy harvesting, leveraging the unique advantages of MXene materials.

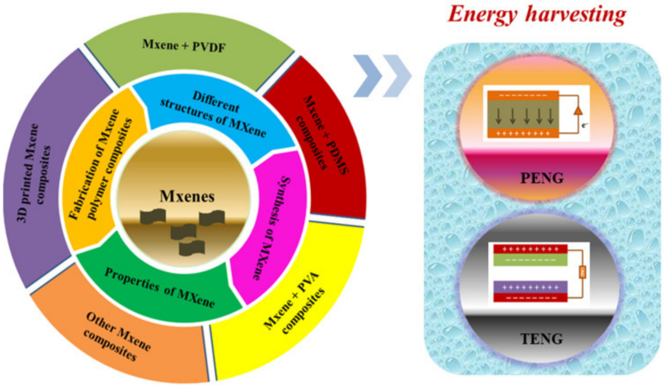

Figure 1: Summary of MXene-based materials for energy harvesting

II. RELATED WORK

MXenes are a relatively recent class of 2D materials based on transition metal carbides, nitrides and carbonitrides. As for the name, MXene, it has been defined based on the chemical formula of their precursors and these consist of a transition metal (M), a group element (Al or Si for instance), and carbon or nitrogen (X). These materials are nanomaterials with a layered structure represented by the formula Mn+1XnTx, in which n indicates the layered number, T stands for the surface' functional groups, and n + 1 points to the metal layers number. MXene materials are derived through the etching of layered ceramic precursors, their properties depend on the precursor used and how it is processed. MXenes are conducing metal carbides that possess large surface area and high thermal stability, thus they have potential uses in energy storage and conversion, electronics, and sensor applications.

They are particularly suitable for applications in energy storage devices such as supercapacitors and in energy conversion devices such as thermoelectric generators, solar cells, and batteries due to their high conductivity and surface area similar to metal nanoparticles. Apart from energy, the uses of MXenes are also implied in water purification, EMI shielding, and as a catalyst. However, several challenges have to be met, for instance, physical quality synthesis and minimized cost of production. More research is required to enhance their properties and also improve on the prospect of using them in the market.

MXenes can be produced in various forms, including thin nanosheets, hollow nanotubes, microspheres, thin films, and three-dimensional structures like aerogels, foams, and sponges. Each form has unique properties and applications. The synthesis process involves preparing the precursor, exfoliating it, and functionalizing the surface.

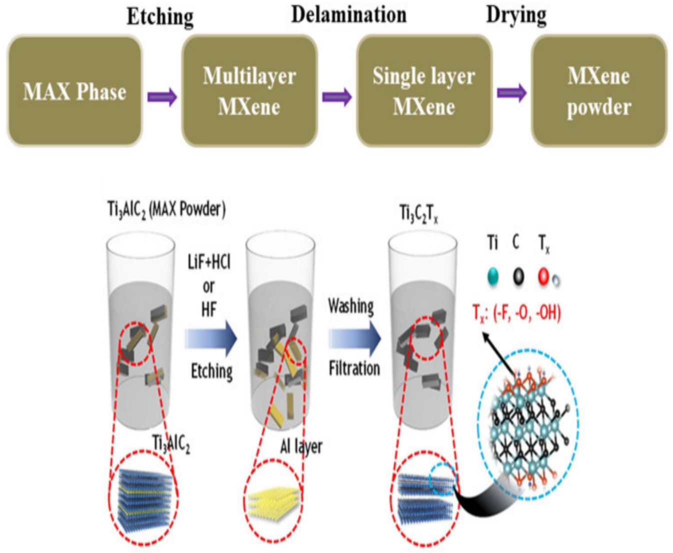

Figure 1 shows the production process of MXenes.

III. PROPOSED WORK

1. Manufacture of MXene/Polymer for Energy Harvesting

The formation of MXene–polymer composites includes using MXene 2D materials as reinforcements or additives added to the polymer matrix to enhance the material performance. The process starts with the formation of MXene suspensions in which MXene flake is disseminated in a solvent and usually surface-modified with stabilizers. The polymer matrix is processed by melt blending or solution coating according to the solvents of the MXene suspension. The preparation of the polymer matrix involves incorporating the MXene suspension into the polymer matrix by hand mixing, ultrasonic treatment, or mechanical blending. In short, the well-dispersed filler is embedded in the polymer matrix and solvent then evaporated to leave behind the composite material which is then sintered and pressed to give a dense composite.

Sometimes there are diverse methods, including spin coating, electrospinning and hot press methods that can be employed in this process. To assess the properties and the structure of the formed MXene-polymer composites one uses the following techniques: transmission electron microscopy, scanning electronic microscopy, X-ray diffraction, thermogravimetric analysis. Adjusting the mixing parameters, as well as the concentrations and types of MXenes and polymers in the composites can be controlled to produce components with desired characteristics.

For example, MXene-enhanced nanogenerators exhibit exceptional performance. The higher dielectric constant and surface charge density of MXene, along with hydrogen bonds in the composite, contribute to these properties. Trilochan Bhatta et al. incorporated MXene into PVDF fibers, significantly enhancing triboelectric performance. Additionally, integrating MXene with ferroelectric BTO reduces dielectric loss and enhances the overall output of nanogenerators. These instances underscore the importance of optimizing various parameters to enhance the performance of MXene-based nanogenerators. Figure 2 shows the steps involved in making MXene-polymer composites, including electrospinning, spin coating, and hot press procedures, among others.

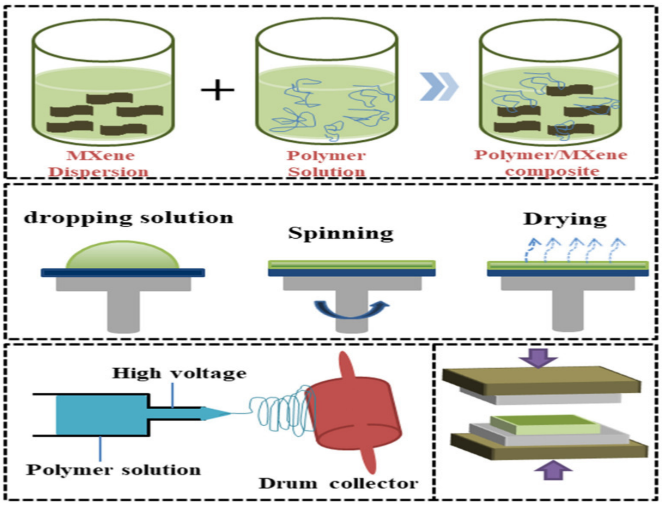

Figure 2: Manufacturing process of MXene–polymer composites.

2. MXene/PVDF composites

The crystalline (β-phase) and amorphous (α-phase) phases of PVDF, a semi-crystalline polymer, may be seen in Figure 3. PVDF is a semi-crystalline polymer comprising 2 distinct phases: the crystalline phase and the amorphous phase. The characteristics of PVDF are determined by the ratio of these phases. The crystalline phase features a highly ordered structure with aligned dipoles, contributing to PVDF's high electro activity. Conversely, the amorphous phase has randomly arranged dipoles and lacks these properties. The balance between these phases is affected by processing conditions, including temperature, heating and cooling rates, and strain.

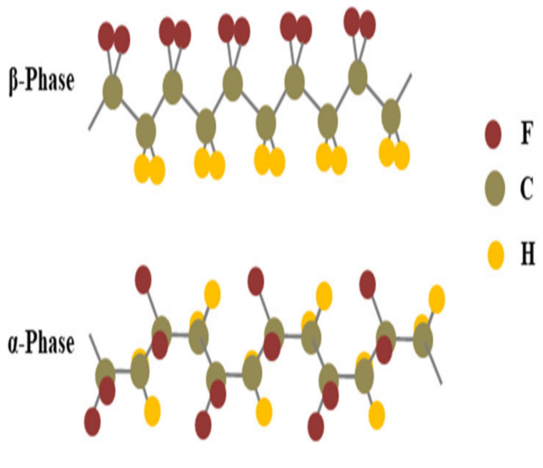

Figure 3: Molecular structure of PVDF β-phase and α-phase.

3. MXene/PDMS Composites for Energy Harvesting

PDMS, a type of silicone polymer, offers several advantageous features for energy conversion purposes. Its high elastic modulus enables flexibility and deformation under stress, making it adopt at transforming mechanical energy into electrical energy—an ideal trait for energy harvesting applications. Additionally, PDMS exhibits excellent dielectric properties, characterized by high electrical resistance, rendering it well-suited for energy storage within capacitors. Its transparency across the visible and near-infrared spectrum makes it valuable as a protective layer in solar cells, safeguarding against environmental damage and bolstering overall efficiency. PDMS retains its integrity over a broad temperature range, making it suitable for energy conversion in high-temperature environments. Furthermore, PDMS demonstrates remarkable chemical resistance, impervious to substances like water, oils, and most organic solvents, ensuring stability in chemical environments.

The synergistic blend of PDMS and MXene composites enhances energy harvesting capabilities. PDMS contributes mechanical flexibility and damping, complemented by MXene's electrical conductivity. However, further refinement is necessary to optimize performance and scalability for practical implementation. In Figure 4a–d, we can see the PDMS/MXene TENG's output performance at different mean pressures, light illuminations, and frequencies. Variations in voltage were recorded using TENG in response to various stimuli, including mechanical waves and light (Figure 4e, f)

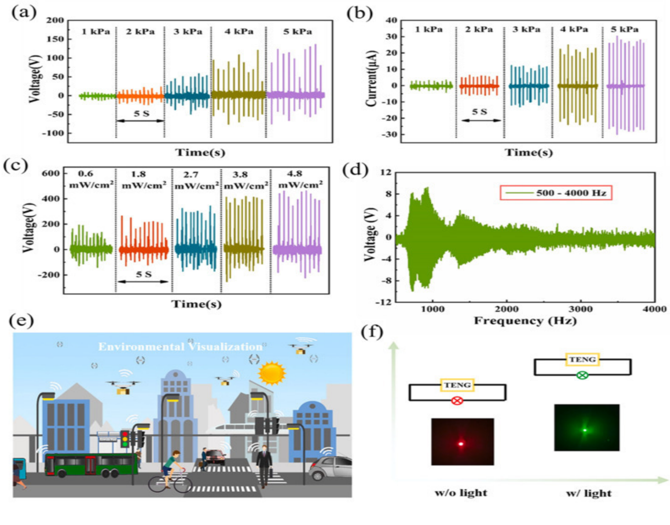

Figure 4: Fabrication of MXene/PDMS Composites

4. MXene/PVA Composites for Energy Harvesting

Polyvinyl Alcohol (PVA) is a synthetic polymer renowned for its versatility, water solubility, and biodegradability, synthesized from vinyl acetate monomers through hydrolysis. It boasts high tensile strength, flexibility, and resistance to diverse substances, providing an environmentally friendly alternative. Its molecular structure comprises vinyl alcohol monomers linked by ester linkages, endowing it with water solubility due to hydroxyl groups. PVA/Ag nanofiber and FEP film based TENG system has been designed to capture human respiration, motion, and toxic gases. The PVA/Ag nanofiber film fabricated by electrospinning improves the performance of the TENG with the maximum values of the voltage and the power density of 530 V and 359 mW/m², respectively, at the wind speed of 8 m/s. This independent sensor modulates output voltage depending with the wind speeds and humidity conditions. In addition, it is feasible to design a TENG-driven Ti3C2Tx MXene/WO3-based NO2 sensor with higher sensitivity than resistive sensors. To identify the directions of the wind and track the sources of the hazardous gases, a quadruple TENGs and a gas detection system are used.

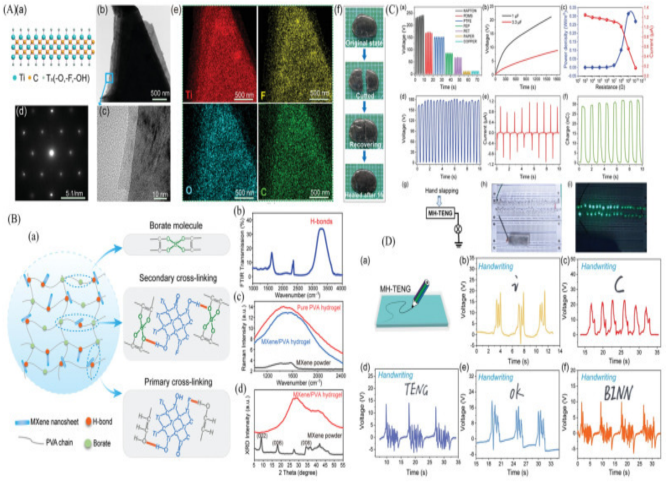

Figure 5: Fabrication of MXene/PVA Composites

5. Three-dimensional printed MXene composites for Energy Harvesting

3D printing is also suitable in the manufacturing of MXene composites in energy harvesting since it provides opportunities in geometrical precision especially in complex structures. This technology allows building structures of desired shape in order to provide the highest efficiency of energy collection. Furthermore, due to 3D printing, there is an opportunity to create composite materials by incorporating MXene with other materials, such as polymers or metals, and improve their characteristics. MXene components manufactured through a 3D technique can be used as piezoelectric or triboelectric nanogenerators, where layers of MXene are interleaved with layers of piezoelectric polymer, which produces electrical currents when subjected to mechanical forces. The self-powered toroidal sensor employing an MXene/Ecoflex nanocomposite with fabric electrodes provides high output and flexibility. The fabrication of glove included 3D printing process using TPU-95A material where the sensor package was printed separately along with the connection wire package and the fixation part of the glove was also separated for easy assembling. This is a wearable glove developed to apply strain through muscle release through finger bending and tightening.

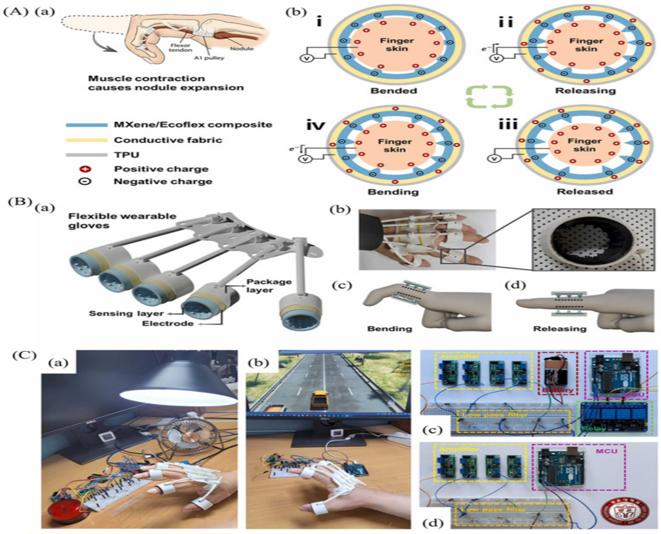

Figure 6: Fabrication of Three-dimensional printed MXene composites

IV. CONCLUSION

An analytical review examines composite materials based on MXene for TENGs and PENGs and demonstrates their future applicability for harvesting mechanical energy and multifunctional sensing. Enhancing the nanogenerator performance is attained through incorporating MXenes with various materials such as PVDF, PDMS, PTFE, PVA, Ag, Au, CNTs, and oxides exploiting electronegativity, conductivity, tunable surface chemistry, and mechanical flexibility. MXenes can enhance features such as electronegativity, conductivity, electron transportation speed, mechanical flexibility, surface charge regulation, and cycling stability in materials, thus improving the efficiency of nanogenerators. The information presented in this review would be instrumental in creating the next generation of nanogenerators that would be able to effectively convert mechanical energy. Opinions and ideas highlighted in the course of the work stress the need to consider natural sources for clean energy generation. MXene based e-skin and wearable energy harvesters are also promising technologies for future development. This work established the need for enhancing and standardizing the power output of MXene based nanogenerators due to the growing demand and integration of electronic devices in smart systems. These efforts should focus on optimizing the synthesis of MXene, as it greatly determines the properties and electrochemical performance. Parameters included are flake size distribution, defects and surface chemistry all of which are very vital. Moreover, when it comes to synthesized predicted MXenes and their derivatives, promising opportunities in the field of nanogenerator materials can be attributed..

REFERENCES

[1] [1. Owusu, Phebe Asantewaa, and Samuel Asumadu-Sarkodie. "A review of renewable energy sources, sustainability issues and climate change mitigation." Cogent Engineering 3, no. 1 (2016): 1167990.

[2] 2. Zakeri, Behnam, Katsia Paulavets, Leonardo Barreto-Gomez, Luis Gomez Echeverri, Shonali Pachauri, Benigna Boza-Kiss, Caroline Zimm et al. "Pandemic, war, and global energy transitions." Energies 15, no. 17 (2022): 6114.

[3] 3. Blanco, Herib, and André Faaij. "A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage." Renewable and Sustainable Energy Reviews 81 (2018): 1049-1086.

[4] 4. Noussan, Michel, Pier Paolo Raimondi, Rossana Scita, and Manfred Hafner. "The role of green and blue hydrogen in the energy transition—A technological and geopolitical perspective." Sustainability 13, no. 1 (2020): 298.

[5] 5. Korkmaz, Satiye, and İ. Afşin Kariper. "Pyroelectric nanogenerators (PyNGs) in converting thermal energy into electrical energy: Fundamentals and current status." Nano Energy 84 (2021): 105888.

[6] 6. Zi, Yunlong, and Zhong Lin Wang. "Nanogenerators: An emerging technology towards nanoenergy." Apl Materials 5, no. 7 (2017).

[7] 7. Deng, Shanggui, Sharad Bhatnagar, Shan He, Nabeel Ahmad, Abdul Rahaman, Jingrong Gao, Jagriti Narang, Ibrahim Khalifa, and Anindya Nag. "Development and applications of embedded passives and interconnects employing nanomaterials." Nanomaterials 12, no. 19 (2022): 3284.

[8] 8. Lu, Xu, Xiaowan Zou, Jialiang Shen, Lin Zhang, Li Jin, and Z-Y. Cheng. "High energy density with ultrahigh discharging efficiency obtained in ceramic-polymer nanocomposites using a non-ferroelectric polar polymer as matrix." Nano Energy 70 (2020): 104551.

[9] 9. Wang, Zhong Lin, Guang Zhu, Ya Yang, Sihong Wang, and Caofeng Pan. "Progress in nanogenerators for portable electronics." Materials today 15, no. 12 (2012): 532-543.

[10] 10. Sripadmanabhan Indira, Sridhar, Chockalingam Aravind Vaithilingam, Kameswara Satya Prakash Oruganti, Faizal Mohd, and Saidur Rahman. "Nanogenerators as a sustainable power source: state of art, applications, and challenges." Nanomaterials 9, no. 5 (2019): 773.

[11] 11. Han, Sang A., Jaewoo Lee, Jianjian Lin, Sang-Woo Kim, and Jung Ho Kim. "Piezo/triboelectric nanogenerators based on 2-dimensional layered structure materials." Nano Energy 57 (2019): 680-691.

[12] 12. Bagherzadeh, Roohollah, Shayan Abrishami, Armineh Shirali, and Amin Reza Rajabzadeh. "Wearable and flexible electrodes in nanogenerators for energy harvesting, tactile sensors, and electronic textiles: Novel materials, recent advances, and future perspectives." Materials Today Sustainability 20 (2022): 100233.

[13] 13. Covaci, Corina, and Aurel Gontean. "Piezoelectric energy harvesting solutions: A review." Sensors 20, no. 12 (2020): 3512.

[14] 14. Shi, Hu, Zhaoying Liu, and Xuesong Mei. "Overview of human walking induced energy harvesting technologies and its possibility for walking robotics." Energies 13, no. 1 (2019): 86.

[15] 15. Jamil, Furqan, Hafiz Muhammad Ali, and Muhammad Mansoor Janjua. "MXene based advanced materials for thermal energy storage: a recent review." Journal of Energy Storage 35 (2021): 102322.