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Harnessing Ocean Power: Triboelectric Nanogenerators in Marine Innovation

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Abstract: The marine environment poses distinct challenges and possibilities for technological advancement. Triboelectric nanogenerators have proven to be a promising answer, utilizing the triboelectric effect to convert mechanical energy into electrical power. The review delves into the multiple uses of TENGs in marine environments, showcasing their capacity to transform the collection of energy from waves, the operation of autonomous underwater vehicles, anti-biofouling systems, self-powered sensors, and desalination technologies powered by waste. TENGs provide a scalable, efficient, and cost-effective approach to producing sustainable energy through wave energy harvesting. AUVs gain advantages from TENGs in terms of improved self-sufficiency and energy efficiency, allowing for extended mission durations and decreased reliance on external power supplies. TENG-based anti-biofouling systems counter marine biofouling by generating electric fields, thus safeguarding marine infrastructure and sensors. Self-powered sensors that incorporate TENGs enable real-time tracking of environmental factors, all of which are essential for marine research and conservation efforts. Furthermore, TENG-driven desalination systems utilise mechanical energy from marine waste to produce drinkable water, thus resolving environmental pollution and water scarcity. The review highlights the pivotal role of TENGs in driving marine innovation forward, promoting sustainability, and tackling key issues in the marine environment.
Keywords: Triboelectric nanogenerators, Wave Energy Harvesting, Autonomous Underwater Vehicles, Anti-Biofouling Systems, Self-Powered Sensors, Waste-Driven Desalination.

I. INTRODUCTION

Modern technological growth has made finding clean, sustainable, and decentralized energy alternatives a high priority due to growing worries about climate change, environmental degradation, and the depletion of fossil resources. [1] Traditional energy infrastructures, which mostly rely on limited and polluting resources, are under increasing strain as global energy consumption continues to rise due to the extensive use of electronic devices, growing urban areas, and rapid industrial growth. To address these issues, researchers are concentrating on cutting-edge energy-harvesting systems that use ambient and natural energy sources in their surroundings. Among these, Triboelectric Nanogenerators (TENGs) have emerged as a cutting-edge innovation that utilizes mechanical movements to generate electrical energy. TENGs was introduced by Wang and his research group in 2012, TENGs operate based on two core principles, triboelectrification where materials exchange charge upon contact and electrostatic induction, which facilitates the flow of electrons through an external circuit once a potential difference is established. [2] TENGs stand out due to their low cost, structural simplicity, flexibility, and compatibility with various materials, including biodegradable and eco-friendly options. Their ability to respond to diverse mechanical stimuli, such as vibrations, pressure, and motion, makes them ideal for powering small electronic devices and sensors. This adaptability is particularly beneficial in settings where traditional energy sources are unavailable.[3]

Mechanical energy harvesting is the process of absorbing and converting kinetic energy from the surroundings, which is frequently wasted or underutilized, into electrical energy. TENGs are especially well-suited for this task since they can generate high voltages from low-frequency vibrations prevalent in natural surroundings. As a result, they are extremely effective in converting mechanical energy from the environment into useful power. TENGs have four operational modes contact separation, lateral sliding, single-electrode, and freestanding triboelectric layer that enable design flexibility across a wide range of applications. TENGs can be integrated into a variety of systems, including wearable devices, smart infrastructure, biomedical instruments, and vehicles. In many applications, they perform two functions: energy generation and active sensing. Their power output, while often moderate in current, can be stored in capacitors or batteries for practical usage, allowing for self-powered operation in a variety of applications.[4] The ocean, which covers more than two-thirds of the Earth's surface, represents an enormous and mostly untapped reservoir of mechanical energy. Ocean waves, currents, tides, and even the movement of marine life can all provide reliable kinetic energy.

However, the harsh marine environment, which includes corrosion, fouling by marine organisms, and uneven mechanical pressures, complicates the efficient and sustainable extraction of this energy. TENGs are a viable solution because of their durability, compact size, and effectiveness under low-frequency mechanical input. In marine environments, wave energy harvesting is a common application for TENGs. Marine systems like buoys, signal transmitters, and sensor arrays can be powered by these gadgets, which can use the up-and-down motion of the waves to create electricity. For distant ocean monitoring and long-term deployments that don't require frequent maintenance or battery replacement, TENG-based systems are particularly helpful due to their small size and autonomous operation. In addition, Autonomous Underwater Vehicles (AUVs) benefit significantly from the integration of TENGs. By converting movement and environmental motion into electricity, TENGs help extend AUV operation times and reduce dependency on external power sources. TENGs are also being incorporated into anti-biofouling systems, where they generate weak electric fields that prevent the accumulation of marine organisms on equipment surfaces, thus improving the durability and efficiency of underwater infrastructure. Self-powered maritime sensors using TENGs are another new field. In order to provide marine science and conservation with useful real-time data, these sensors track variables such as water temperature, salinity, pH, and pollution levels. Also being investigated as an eco-friendly way to meet the increasing need for fresh water are TENG-driven desalination plants.[5] To combat water scarcity and marine pollution, these devices use mechanical energy from ocean motion or marine debris to power water purification. Overall, the integration of TENGs into marine technologies not only enhances their sustainability but also introduces new possibilities for energy independence and environmental protection in ocean-based applications. This review will explore the progress and potential of TENGs in marine environments, examining both current advancements and the challenges that need to be addressed for broader implementation.

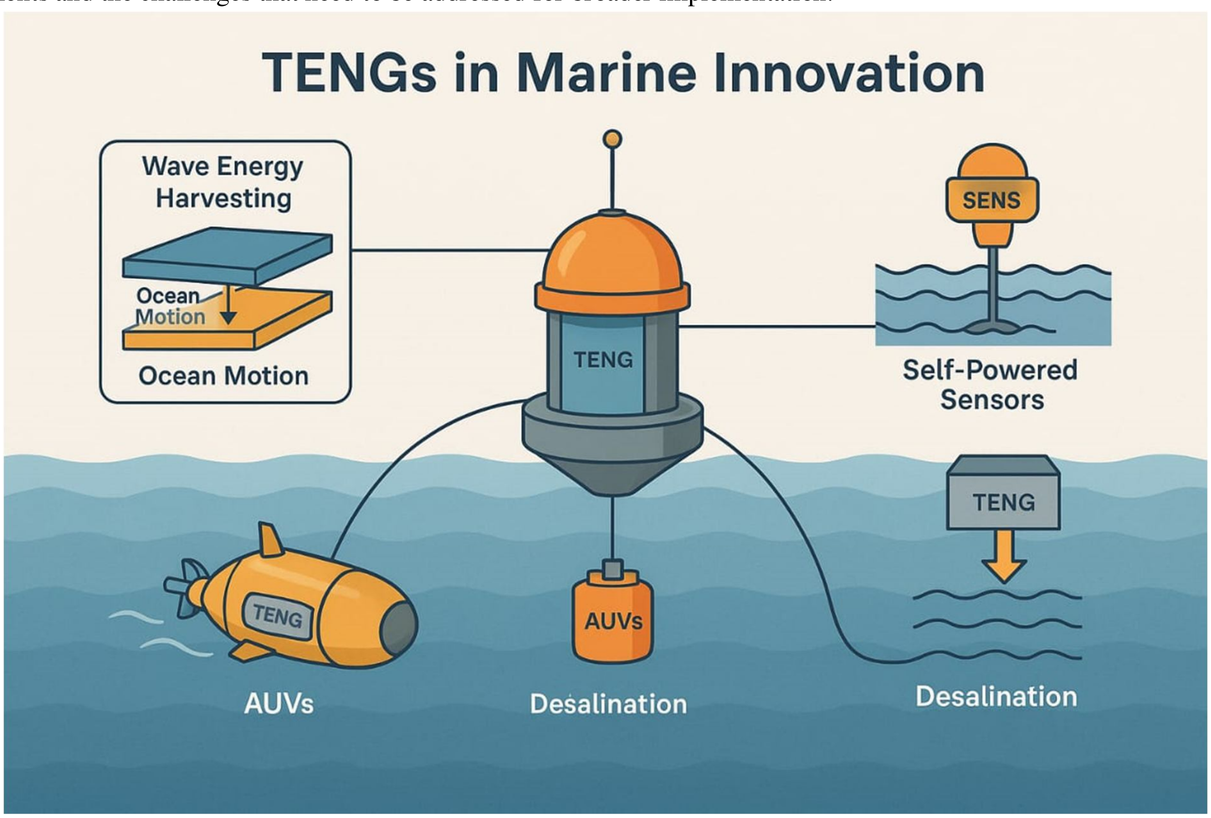

Figure 1: TENGs Application in marine technology: Sustainable power for ocean system

II. WORKING OF TRIBOELECTRIC NANOGENERATORS

Triboelectric Nanogenerators (TENGs) operate based on a combination of two fundamental physical phenomena: triboelectrification and electrostatic induction. Triboelectrification refers to the process by which certain materials become electrically charged after they come into frictional contact with a different material. This contact results in the transfer of electrons from one surface to the other, depending on their positions in the triboelectric series. When the two materials are subsequently separated, a potential difference is created due to the imbalance of charges, which can be harvested via electrostatic induction through an external circuit to generate an electric current.

TENGs are particularly effective at converting low-frequency mechanical energy from motion, vibration, or pressure into electrical energy.[6] Their performance depends on material selection, surface morphology, and the structural design of the device. One of the major advantages of TENGs is their compatibility with flexible, lightweight, and cost-effective materials, making them suitable for use in a variety of environments, including underwater and marine systems. To maximize energy conversion under different mechanical motions, TENGs are typically designed in one of four fundamental working modes, each tailored to a specific kind of movement:

1) Contact-Separation Mode: This is the most basic and widely used TENG mode. It involves two triboelectric materials that come into repeated contact and then separate vertically. When the surfaces are in contact, charges are exchanged; upon separation, an electric potential is generated due to the charge imbalance. This mode is well-suited for harvesting vertical mechanical forces, such as footfalls, raindrops, or wave motion.
2) Lateral Sliding Mode: In this configuration, the two materials slide against each other laterally rather than making vertical contact. The relative motion results in a continuous variation in surface charge distribution, which drives a current through the external circuit. This mode is advantageous for harvesting energy from horizontal or rotational movements, such as ocean currents or sliding surfaces in marine systems.
3) Single-Electrode Mode: The single-electrode mode simplifies the design by allowing one of the electrodes to be grounded or shared with the environment. This mode is beneficial in situations where device miniaturization or simplification is critical, such as in wearable or underwater systems. It enables energy harvesting from arbitrary surfaces, even when one triboelectric surface is free to move relative to a fixed electrode.
4) Freestanding Triboelectric-Layer Mode: This mode features a freely moving triboelectric layer that alternates its position between two fixed electrodes. As it moves, it induces an alternating potential between the electrodes due to the asymmetric charge distribution. This mode is highly efficient for applications involving continuous motion, like vibrating structures or floating marine devices. Each mode has its unique mechanical and electrical characteristics, and hybrid designs that combine multiple modes are also being explored to enhance energy harvesting efficiency. These working modes allow TENGs to adapt to a broad spectrum of real-world mechanical stimuli, laying the foundation for their integration into advanced marine technologies and energy systems.

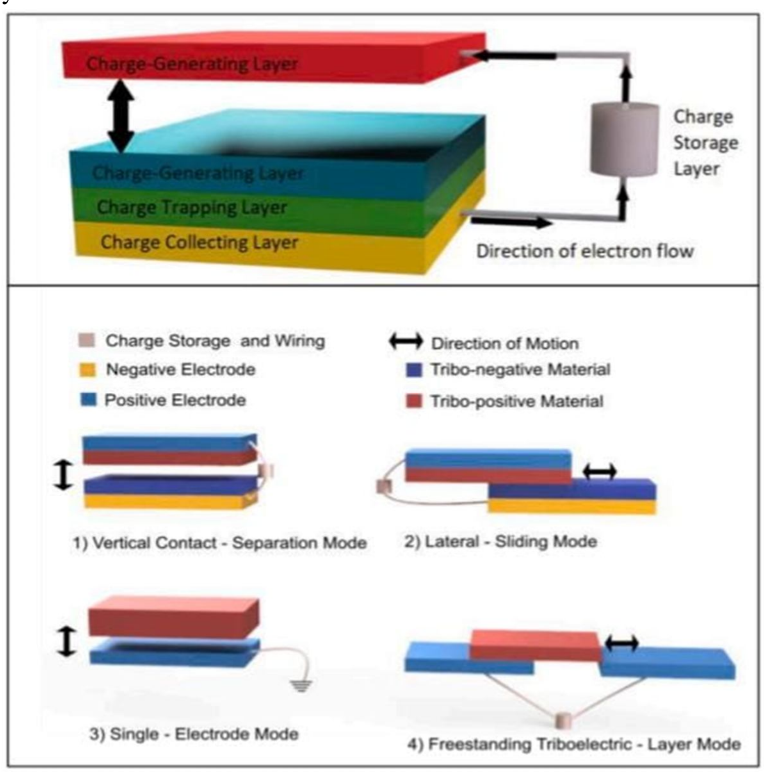

Figure 2: Basic TENG design by operating layer and the four basic TENG design modes.

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III. TENGS IN MARINE INNOVATION

A. *Case Study 1: Tengs In Wave Energy Harvesting*

Triboelectric nanogenerators (TENGs) are cutting-edge devices designed to convert mechanical energy into electrical power using the triboelectric effect and electrostatic induction principles. In marine settings, they harness wave-induced motions such as vertical displacement, tilting, and rolling to trigger repeated contact and separation between materials with contrasting electron affinities.[8] This interaction creates a charge imbalance, leading to an electron flow and, consequently, electricity generation. TENGs can be engineered as floating devices, incorporated into buoys, or embedded within underwater structures, enabling them to harvest energy from the continuous motion of ocean waves efficiently. To ensure long-term functionality in harsh marine environments, they are typically coated with hydrophobic polymers that protect against saltwater corrosion and mechanical wear. Their effectiveness at low wave frequencies (0.1–1 Hz), where traditional turbines are inefficient, coupled with their lightweight, flexible, and low-cost construction, makes them particularly suitable for deployment in remote or demanding oceanic conditions.[9]

The benefits of TENGs in marine energy applications are extensive. They provide an economical, scalable, and environmentally sustainable power solution for a variety of ocean-based systems. These include navigational buoys, autonomous underwater vehicles (AUVs), and self-powered sensors used for monitoring salinity, temperature, and marine pollution. By minimizing reliance on external power supplies and reducing the need for frequent maintenance, TENGs support extended operational periods and greater autonomy for marine technologies. Their modular nature allows for the creation of distributed "blue energy networks," enabling sustainable energy generation across large oceanic areas.[10] Moreover, hybrid systems that integrate TENGs with electromagnetic generators can improve energy capture across diverse sea conditions. Overall, TENGs mark a significant advancement in marine technology, offering a reliable and clean energy source to address the dual challenges of environmental sustainability and operational efficiency in ocean environments.

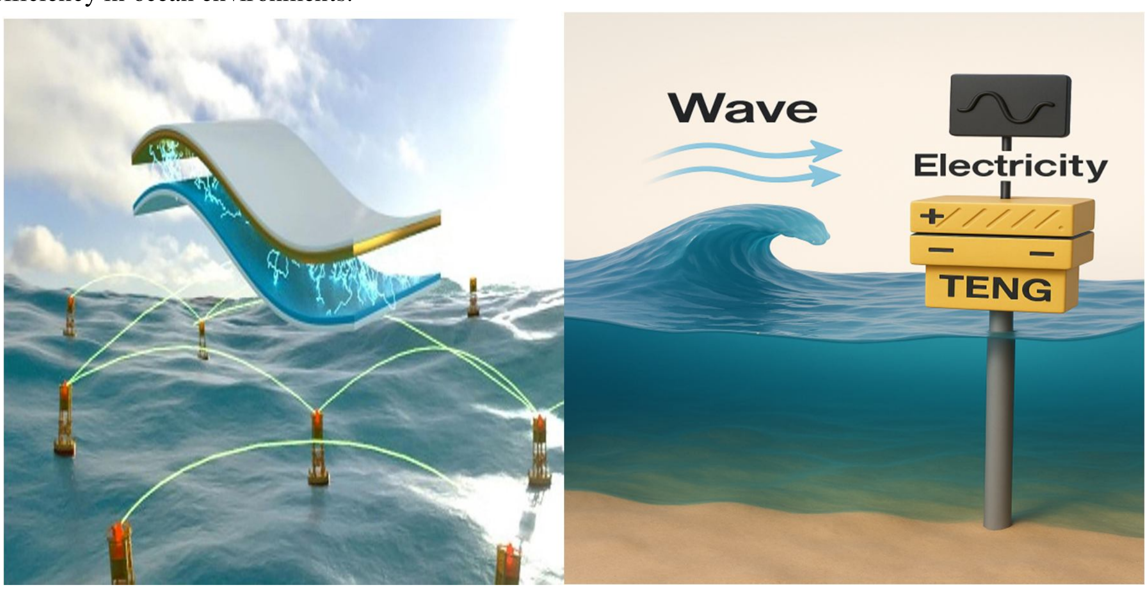

Figure 3: A) Sphere-based triboelectric nanogenerators that can be incorporated directly into navigational buoys to provide electricity from ocean waves. B) Representation of a Triboelectric Nanogenerator (TENG) System for Wave Energy Harvesting

B. *Case Study 2: TENGs In Autonomous Underwater Vehicles (AUVS)*

Triboelectric nanogenerators (TENGs) present a promising approach to improving the energy independence of Autonomous Underwater Vehicles (AUVs), which play a crucial role in ocean exploration, environmental monitoring, and underwater surveillance. Typically, AUVs depend on onboard batteries, which limit their operational time and require periodic retrieval for recharging. By integrating TENGs into AUV systems, mechanical energy from surrounding sources such as ocean currents, internal vibrations, and surface wave motion can be harvested. These nanogenerators can be embedded in the outer hull of the AUV or installed in tethering mechanisms to capture kinetic energy generated by the vehicle's movement or its interaction with underwater structures.[11] The electricity generated is stored in capacitors or batteries onboard, providing power to sensors, data loggers, and communication devices. Due to their effectiveness in low-frequency and low-amplitude mechanical environments, TENGs are well-suited to the variable conditions encountered by mobile underwater platforms.

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Incorporating TENGs into AUVs enhances their performance by reducing dependence on external power sources, extending mission duration, and enabling longer deployments in remote or deep-sea locations. Compared to traditional power systems, TENGs are lightweight, cost-effective, and can be seamlessly integrated into the AUV's design without adding significant bulk.[12] Their self-sustaining power generation supports extended autonomy, making them ideal for tasks such as long-range mapping, pipeline inspections, and marine ecosystem monitoring. Furthermore, TENGs can be employed to energize self-cleaning surfaces, anti-biofouling coatings, and emergency locator beacons. This technology paves the way for the development of fully autonomous, low-maintenance marine robots. With ongoing improvements in material robustness, energy storage solutions, and device miniaturization, TENG-powered AUVs are expected to become essential tools in ocean technology, offering sustainable, efficient, and resilient platforms for future marine innovation.[13]

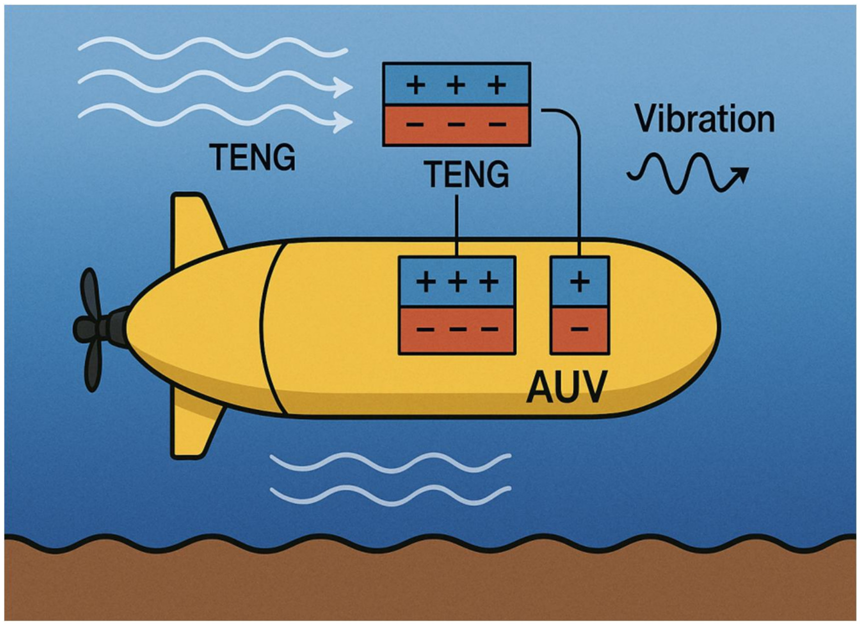

Figure 4: Integration of Triboelectric Nanogenerators (TENGs) in an Autonomous Underwater Vehicle (AUV) for Energy Harvesting from Water Flow and Vibrations

C. *Case Study 3: TENGs for Anti-Biofouling Applications*

Triboelectric nanogenerators (TENGs) have emerged as an innovative and effective solution to address marine biofouling while simultaneously harvesting sustainable energy from ocean movements. These devices operate based on the triboelectric effect, where mechanical energy from waves, currents, or fluid flow induces repeated contact and separation between materials with different electron affinities, generating electrical energy through electrostatic induction.[14] In anti-biofouling applications, the electrical output from TENGs produces localized electric fields or micro-vibrations on submerged surfaces. These physical effects inhibit the attachment and growth of microorganisms, algae, barnacles, and other marine organisms by disrupting biofilm formation and preventing settlement. This approach acts as a non-chemical deterrent, offering a cleaner and longer-lasting alternative compared to traditional antifouling methods that rely on toxic paints or frequent maintenance.[15]

The advantages of TENG-based anti-biofouling systems are significant. They provide a non-toxic, energy-efficient, and self-powered solution that protects critical marine infrastructure such as ship hulls, underwater sensors, pipelines, and offshore platforms. Because TENGs harvest energy directly from the marine environment, they operate autonomously, making them highly suitable for remote and hard-to-access locations. Their scalable and adaptable design enables integration into various marine devices, including autonomous underwater vehicles (AUVs) and floating buoys. By reducing biofouling, TENGs help decrease drag on vessels, minimize sensor inaccuracies caused by fouling, and prevent corrosion-related damage. Ongoing research aims to enhance the robustness of TENG materials to withstand harsh saltwater conditions and to improve energy conversion efficiency for wider application. Overall, TENGs represent a sustainable technological advance, combining energy harvesting and eco-friendly antifouling strategies to promote marine environmental protection and operational efficiency.[16]

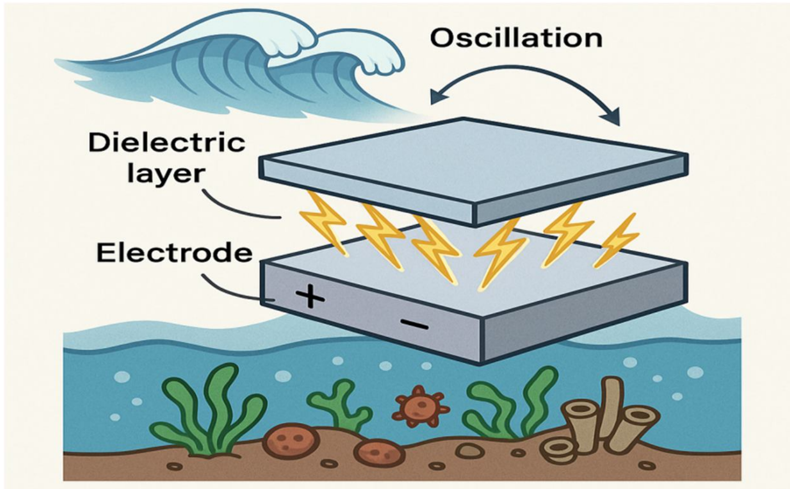

Figure 5: TENGs For Anti-Biofouling Applications

D. Case Study 4: Teng-Based Self-Powered Sensors For Marine Monitoring

The marine environment poses distinctive challenges as well as opportunities for sustainable technological innovation. Among the most promising advances in this domain is the use of Triboelectric Nanogenerators (TENGs), which convert mechanical energy from natural oceanic motions such as waves, currents, and vibrations into electrical energy by harnessing the triboelectric effect.[17] These devices are especially advantageous in marine settings where conventional power sources are difficult to maintain or replace. TENGs facilitate the deployment of self-powered sensors capable of real-time and autonomous monitoring of critical marine parameters, including temperature, salinity, pH, dissolved oxygen, and pollutant concentrations. Their lightweight, flexible, and cost-effective design allows them to function reliably under harsh oceanic conditions. By directly harvesting energy from wave motion, TENGs provide an ideal power solution for remote sensing networks spanning vast oceanic regions, eliminating reliance on batteries or frequent maintenance and thereby significantly reducing operational costs. [18]

Beyond environmental monitoring, TENGs contribute to powering autonomous underwater vehicles (AUVs), enhancing their energy autonomy and enabling extended mission durations by continuously harvesting ambient mechanical energy. Additionally, they offer effective solutions to marine biofouling by generating localized electric fields that inhibit the accumulation of microorganisms on submerged surfaces. Moreover, TENG-based technologies are being explored for desalination systems that utilize wave-induced power to convert seawater into potable water, tackling the dual challenges of water scarcity and marine pollution. Together, these diverse applications position TENGs as a cornerstone of sustainable marine technologies, integrating clean energy harvesting with intelligent environmental monitoring.[19] As ocean exploration and climate studies advance, TENG-powered systems are expected to play a vital role in fostering a self-sufficient, eco-friendly blue economy and strengthening the resilience of marine operations.

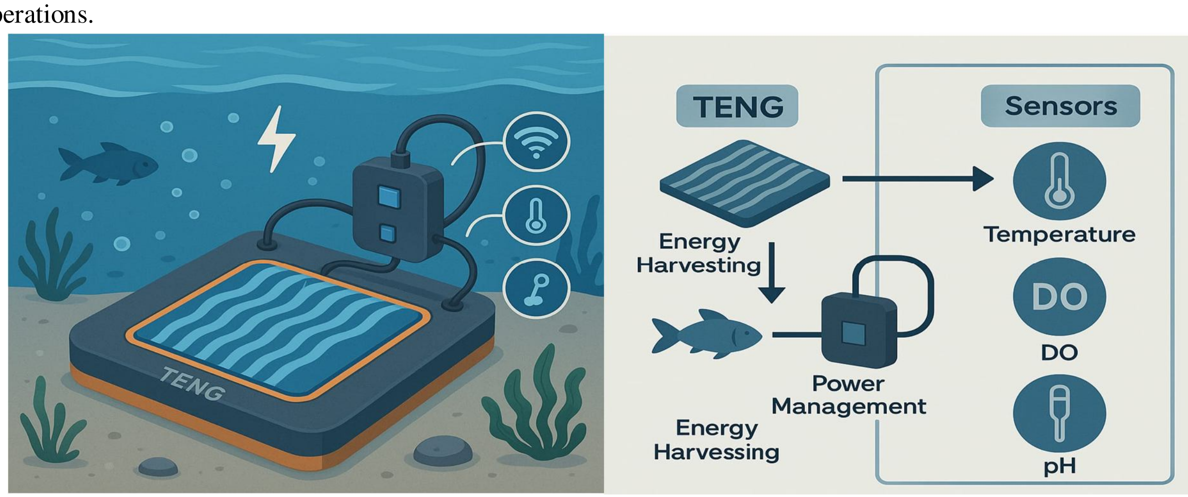

Figure 6: TENG- Based Self Powered Sensors For Marine Monitoring

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E. Case Study 5: TENGs For Waste-Driven Desalination

The marine environment presents both significant challenges and valuable opportunities for the development of sustainable technologies. Triboelectric Nanogenerators (TENGs) have emerged as a promising approach by converting mechanical energy from oceanic sources such as waves, tides, and the movement of marine debris into electrical energy through the triboelectric effect. This ability to capture energy from otherwise wasted mechanical motions makes TENGs especially suitable for powering low-energy applications in remote and harsh marine settings.[20] Among these applications, TENG-driven desalination stands out as an innovative solution that simultaneously tackles two urgent global issues: marine pollution and freshwater scarcity. By harnessing mechanical energy generated by marine waste, TENGs can efficiently power desalination techniques such as electrodialysis and capacitive deionization, providing clean drinking water in a sustainable manner.

This waste-driven desalination technology offers multiple benefits, including reduced dependence on fossil fuels, cost-effectiveness, and scalability for off-grid marine environments. Additionally, TENGs contribute to the enhancement of marine infrastructure by enabling self-powered sensors and anti-biofouling systems, increasing their multifunctionality within ocean ecosystems. Nevertheless, challenges remain, particularly related to low power density, material durability under saline conditions, and effective energy management. Ongoing research focusing on advanced materials and improved system integration holds promise for overcoming these hurdles and enabling broader deployment of TENG-powered desalination units.[21] Ultimately, TENGs represent a crucial advancement in sustainable ocean energy utilization, offering a dual solution to energy harvesting and environmental pollution mitigation while facilitating decentralized access to potable water.

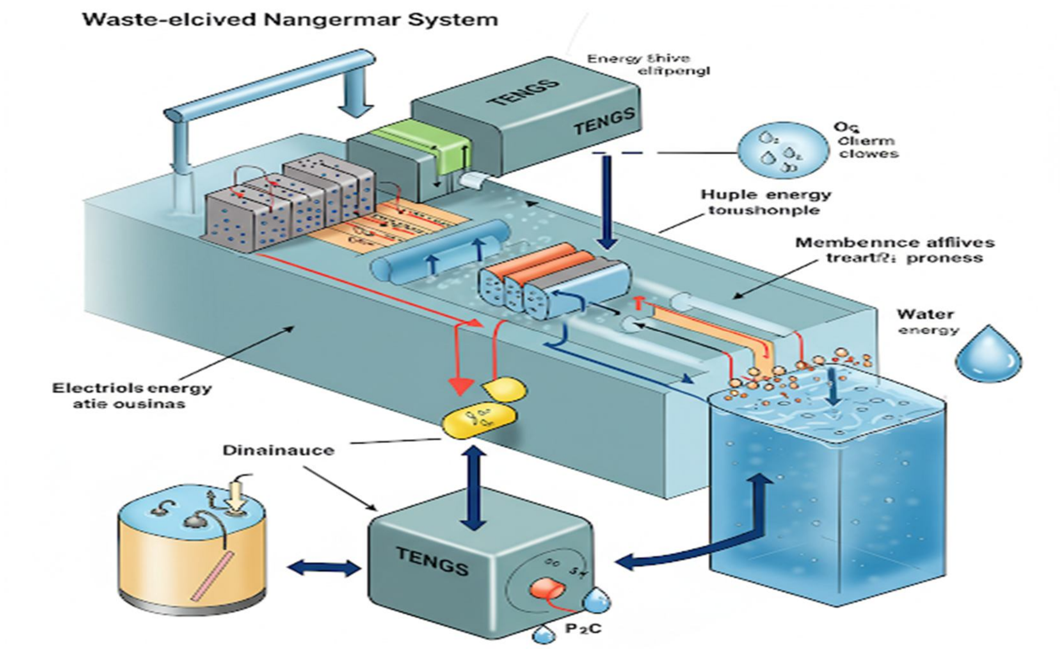

Figure 7: Waste-elcived Nangermar System for waste-driven desalination using TENGs (Triboelectric Nanogenerators).

IV. FUTURE TRENDS OF TENGs IN MARINE INNOVATION

The future of triboelectric nanogenerators (TENGs) in marine applications is poised for significant advancement as demand grows for sustainable, autonomous, and smart ocean technologies. Future designs will emphasize miniaturization, durability, and hybridization with other energy-harvesting methods to enhance output and reliability. Materials will evolve to include biodegradable, corrosion-resistant, and self-healing polymers, ensuring long-term performance in harsh marine environments. AI-integrated TENG systems may enable real-time energy management and adaptive operation based on ocean conditions. TENG networks could form the backbone of decentralized blue energy grids, powering distributed sensor arrays, underwater communication systems, and autonomous platforms. Advanced anti-biofouling coatings powered by TENGs will protect marine infrastructure without chemicals. In desalination, waste-to-energy TENG systems may revolutionize clean water access from ocean plastics. Ultimately, TENGs will play a central role in shaping intelligent, self-sustaining ocean ecosystems merging clean energy, automation, and environmental protection into one powerful marine innovation platform.

V. CONCLUSION

Triboelectric nanogenerators (TENGs) represent a cutting-edge advancement with immense potential for solving key challenges in marine environments. By harvesting mechanical energy from ocean waves, currents, and other marine movements, TENGs offer a sustainable and eco-friendly alternative to conventional energy sources. This paper highlights their broad applicability, particularly in enhancing the autonomy and operational efficiency of autonomous underwater vehicles (AUVs), reducing their dependence on external power supplies. TENG-based systems also serve as a promising approach to biofouling prevention by generating electric fields that deter biological accumulation on submerged surfaces. Furthermore, the integration of TENGs into self-powered sensing platforms allows for continuous, real-time monitoring of marine environments critical for oceanographic research, environmental protection, and disaster prevention. In addition, this review explores how TENGs can drive low-cost, energy-efficient desalination systems by utilizing mechanical energy from marine waste, thus addressing both environmental pollution and freshwater scarcity. Their multifunctionality, scalability, and cost-effectiveness make TENGs a practical tool for accelerating innovation in ocean energy harvesting and marine technologies. As discussed throughout this paper, TENGs offer a promising pathway to reduce reliance on traditional energy infrastructure, support sustainable practices, and enable more resilient marine operations. With continued research, development, and field validation, TENGs are expected to become a cornerstone of future marine energy systems, contributing significantly to the advancement of blue economy technologies and global ocean sustainability goals.

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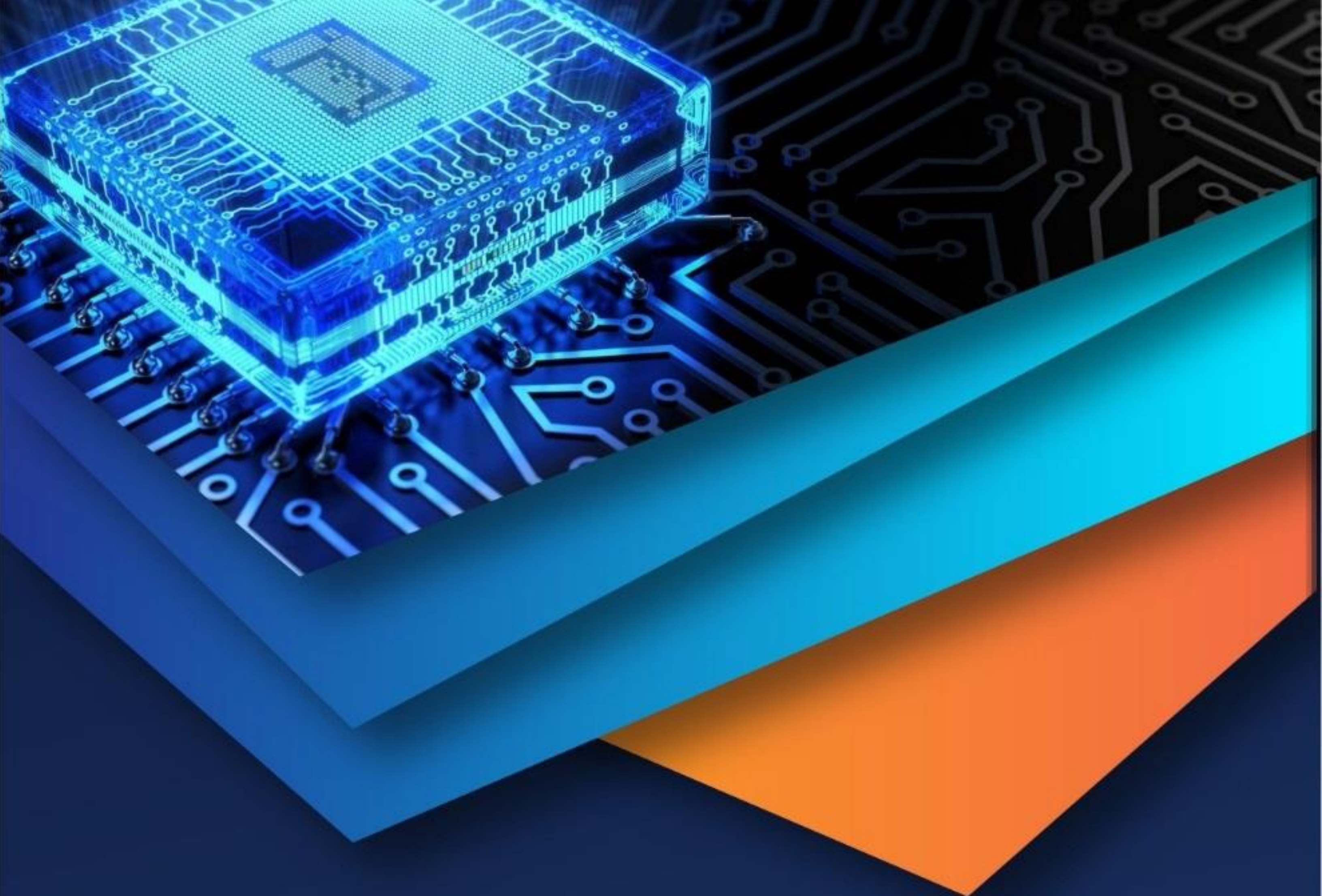

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