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MXene-Infused Conductive Nano-Polymers for Edge-Computing Enabled Flexible Environmental Monitoring Devices

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Abstract

MXene-infused conductive polymer composites have emerged as highly promising materials for next-generation flexible environmental monitoring devices because they combine electrical conductivity, mechanical flexibility, analyte sensitivity, and compatibility with low-power electronics. In this work, a $Ti_3C_2T_x$ MXene–TPU/PVA conductive nano-polymer composite was developed as a multifunctional sensing platform for edge-computing enabled environmental monitoring. The composite was fabricated by dispersing MXene nanosheets into a thermoplastic polyurethane/poly (vinyl alcohol) (TPU/PVA) matrix, coating the conductive precursor onto a PET substrate, and integrating the sensing film with conductive electrodes and an ESP32-based edge-processing module. Structural and morphological analysis confirmed the formation of a uniformly distributed MXene conductive network within the flexible polymer matrix, supported by strong polymer–filler interfacial interactions that promoted stable electrical transport and mechanical integrity. The optimized nanocomposite exhibited enhanced conductivity, a strong humidity-dependent resistance response, measurable NH_3 gas sensitivity, and good cyclic bending stability under repeated deformation. The sensing behavior was primarily governed by the synergistic interaction between the hydrophilic polymer matrix and the conductive MXene pathways, where analyte adsorption, polymer swelling, and interfacial charge transport collectively contributed to the electrical response. Furthermore, the integrated ESP32 platform enabled real-time signal acquisition, local edge-level data processing, and wireless environmental monitoring. The results demonstrate that MXene-infused conductive nano-polymers are highly suitable for lightweight, flexible, and intelligent sensing systems for wearable, portable, and distributed IoT-based environmental monitoring applications.

Keywords: MXene-infused conductive nano-polymers, polymer composites, analyte adsorption, polymer–filler interfacial interactions, thermoplastic polyurethane matrix

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INTRODUCTION

The rapid growth of wearable electronics, flexible Internet of Things (IoT) systems, and smart environmental sensing networks has created a strong demand for material platforms that combine mechanical flexibility, electrical conductivity, environmental sensitivity, and low-power operation within a single device architecture [1]. Conventional environmental monitoring devices are often based on rigid silicon substrates, metallic electrodes, and bulky sensing modules that exhibit poor bendability, limited conformability to curved surfaces, and reduced durability under repeated deformation [2]. These drawbacks restrict their use in emerging applications such as wearable pollution monitors, flexible humidity and gas sensors, smart agricultural patches, and distributed environmental surveillance nodes[3–4]. As a result, polymer-composite-based sensing materials have attracted significant attention because they can merge the light weight, processability, and flexibility of polymers with the electrical and functional properties of conductive nanofillers, thereby enabling soft, lightweight, and multifunctional monitoring devices.

Among the different classes of flexible sensing materials, conductive polymer nanocomposites are particularly attractive because their electrical, mechanical, and interfacial properties can be tailored through the controlled incorporation of nanoscale fillers into a polymer matrix [5–6]. In these systems, the polymer phase acts as the structural framework, providing flexibility, film-forming ability, and compatibility with scalable fabrication techniques such as solution casting, coating, and printing [7–8]. The conductive filler phase, in contrast, creates percolative pathways for charge transport and serves as the active component responsible for transducing external stimuli into electrical signals [9]. However, the performance of conductive polymer nanocomposites depends strongly on filler dispersion, filler–matrix interfacial bonding, conductive network continuity, and environmental stability [10]. Traditional conductive fillers such as carbon nanotubes, graphene, carbon black, metal nanoparticles, and intrinsically conductive polymers have shown promise, yet many still face challenges related to filler agglomeration, insufficient conductivity at low loading, or limited long-term stability under humid and mechanically dynamic conditions [11–12].

In recent years, MXenes have emerged as one of the most promising nanofillers for advanced polymer-composite environmental sensors. MXenes are a family of two-dimensional transition metal carbides, nitrides, and carbonitrides derived from MAX phases, with $Ti_3C_2T_x$ being the most widely studied composition [13]. MXenes possess several characteristics that make them highly attractive for flexible sensing applications, including metallic conductivity, hydrophilic surface chemistry, high specific surface area, tunable interlayer spacing, and abundant surface functional groups such as –OH, –O, and –F [14]. These features promote strong interactions with polymer chains through hydrogen bonding, dipole interactions, and electrostatic attraction, which improve nanosheet dispersion, reduce interfacial resistance, and enhance the continuity of the conductive network within the polymer matrix [15]. In addition, MXene surfaces provide active adsorption sites for water molecules, gases, and volatile organic compounds (VOCs), making them highly responsive to environmental stimuli [16].

From a polymer-composites perspective, MXene-infused conductive nano-polymers represent more than a simple filler addition strategy; rather, they constitute a multifunctional composite design approach in which both the polymer matrix and the conductive nanosheets actively contribute to device performance. The polymer phase is responsible not only for mechanical flexibility and structural integrity, but also for regulating MXene dispersion, suppressing nanosheet restacking, controlling analyte diffusion, and improving oxidation resistance [17]. Hydrophilic matrices such as poly(vinyl alcohol) (PVA), polyacrylamide, cellulose derivatives, and hydrogel systems can enhance humidity and gas sensitivity by facilitating moisture uptake and ionic transport [18]. Elastomeric polymers such as thermoplastic polyurethane (TPU), polyurethane, and silicone-based matrices provide stretchability, cyclic bending durability, and good adhesion to flexible substrates, making them highly suitable for wearable and deformable environmental sensors [19]. Thus, the sensing response of MXene/polymer nanocomposites is governed by the combined influence of polymer chemistry, filler loading, conductive pathway formation, interfacial interactions, and composite morphology.

A major challenge in designing conductive polymer composites for flexible environmental monitoring is achieving an effective balance between electrical conductivity and mechanical compliance. Increasing filler loading often improves conductivity, but it can also increase brittleness, reduce flexibility, and promote filler agglomeration [20]. MXenes offer a notable advantage because their two-dimensional geometry and high aspect ratio enable the formation of efficient conductive pathways even at relatively low filler concentrations, thereby preserving the softness and flexibility of the polymer matrix [21]. Furthermore, MXene/polymer composites can respond to environmental stimuli through multiple coupled mechanisms, including surface adsorption, charge transfer, intersheet tunneling resistance modulation, polymer swelling, ionic conduction, and interfacial polarization [22]. This multifunctional sensing behavior makes them highly attractive for flexible environmental devices that must detect humidity, temperature, gases, and mechanical deformation in real time. Unlike conventional metallic conductors such as copper, silver, and aluminum, conductive polymer nanocomposites provide simultaneous electrical conductivity, mechanical flexibility, and environmental sensitivity within a single material system. Metallic conductors generally function only as passive electrical pathways and often suffer from crack formation and conductivity degradation during repeated deformation. In contrast, MXene-infused conductive nano-polymers maintain conductive continuity through flexible percolative networks while simultaneously serving as active sensing layers capable of converting environmental stimuli into measurable electrical responses. Consequently, conductive nano-polymers are considerably more suitable for wearable, bendable, and lightweight environmental monitoring devices.

In parallel with material development, modern environmental monitoring systems increasingly require edge-computing capability to reduce communication load, energy consumption, and latency associated with cloud-based IoT platforms. Edge computing enables local processing of sensor signals, including filtering, threshold analysis, anomaly detection, and event-triggered communication, before only essential information is transmitted to remote servers [23]. In conventional cloud-based environmental monitoring architectures, continuous transmission of raw sensing data significantly increases communication latency, power consumption, and bandwidth requirements. By contrast, edge-computing architectures enable local execution of signal conditioning, noise suppression, threshold analysis, anomaly detection, and decision-making algorithms directly at the sensor node. In the present work, the ESP32 microcontroller performs local preprocessing of resistance signals generated by the MXene–TPU/PVA sensing layer and transmits only meaningful environmental events to the cloud interface. This approach substantially reduces communication overhead, improves response speed, enhances energy efficiency, and enables reliable operation in geographically distributed or bandwidth-limited monitoring environments. Integrating MXene-infused conductive polymer nanocomposites with low-power edge processors therefore creates a new class of intelligent monitoring systems in which the nanocomposite provides real-time environmental sensing while the embedded electronics perform local data analysis and wireless communication. Consequently, MXene-infused conductive nano-polymers represent a highly promising class of advanced polymer composites for edge-computing enabled flexible environmental monitoring devices, offering a synergistic combination of conductivity, flexibility, environmental responsiveness, and smart system integration.

MATERIALS AND METHODS

Materials

The proposed MXene-infused conductive nano-polymer flexible environmental monitoring device was fabricated using conductive nanofillers, flexible polymer matrices, supporting substrates, and embedded edge-computing electronics. $Ti_3C_2T_x$ MXene nanosheets were selected as the primary conductive nanofiller because of their high electrical conductivity, hydrophilic surface chemistry, and large specific surface area, which are highly beneficial for environmental sensing and conductive pathway formation. A flexible thermoplastic polyurethane (TPU) matrix was employed as the main structural polymer due to its elasticity, mechanical durability, and suitability for flexible and wearable electronic devices. To improve film uniformity and interfacial compatibility, poly(vinyl alcohol) (PVA) was incorporated as a secondary binder polymer, which also helped stabilize the dispersion of MXene nanosheets within the polymer phase. Flexible polyethylene terephthalate (PET) sheets with a thickness of approximately 100–125 μm were used as the supporting substrate because of their transparency, low weight, and dimensional stability. For electrical interfacing, silver paste electrodes and conductive connectors were used, while an ESP32 microcontroller served as the edge-processing unit for signal acquisition, local computation, and wireless communication. The full list of materials and their functional roles in the device structure is summarized in Table 1.

Fabrication of MXene-Infused Conductive Nano-Polymer Film

The fabrication of the flexible sensing device was carried out in three sequential stages, namely MXene dispersion and polymer mixing, composite coating onto PET substrate, and final sensor integration with edge-processing electronics, as schematically illustrated in Figure 1. In the first stage, MXene nanosheets were dispersed in deionized water under ultrasonication for 30–45 min to obtain a stable colloidal suspension, while TPU was dissolved separately in a suitable solvent system under continuous magnetic stirring. A controlled amount of PVA solution was then introduced into the TPU phase to improve polymer compatibility and facilitate stronger interfacial interactions with the MXene nanosheets. The MXene suspension was gradually added to the TPU/PVA solution and stirred for 2–4 h until a homogeneous MXene–TPU/PVA conductive precursor was obtained, as shown in Figure 1.

In the second stage, the prepared composite precursor was deposited onto the PET substrate by doctor blade coating or solution casting, followed by drying at 60–70°C to remove residual solvent and promote film consolidation. This process yielded a smooth and continuous MXene–TPU/PVA nanocomposite film, as represented in Figure 1. In the final stage, conductive silver paste electrodes were applied to both ends of the coated sensing strip, and the flexible sensing layer was integrated with a compact signal-conditioning circuit and ESP32 microcontroller for edge-based data acquisition and wireless communication, as illustrated in Figure 1. The final device was therefore capable of flexible environmental sensing, local processing of sensor signals, and cloud-connected monitoring.

Structural and Morphological Characterization

The structural and morphological properties of the fabricated MXene-infused conductive nano-polymer films were systematically analyzed to evaluate MXene dispersion, film continuity, interfacial compatibility, and conductive network formation. As illustrated in Figure 2(a), the MXene nanosheets are uniformly embedded within the flexible TPU/PVA polymer matrix, forming a three-dimensional conductive framework that enables efficient charge transport and analyte-responsive pathways which is shown in Figure 2(d). This conductive percolation network, schematically shown in Figure 2(c), is essential for maintaining stable electrical conductivity and sensing performance under repeated environmental and mechanical loading.

To verify the morphology of the fabricated films, scanning electron microscopy (SEM) was employed to examine the surface and cross-sectional structure of the nanocomposite. The microstructural representation in Figure 2(a) indicates a relatively homogeneous distribution of MXene nanosheets throughout the polymer matrix with minimal agglomeration and good interfacial adhesion. In addition, Fourier transform infrared spectroscopy (FTIR) was used to investigate the chemical interactions between MXene surface groups and the polymer chains. As conceptually represented in Figure 2(b) and supported by the spectral response in Figure 2, hydrogen bonding and dipole interactions between MXene functional groups (–OH, –O, and –F) and the TPU/PVA chains contributed to improved filler stabilization and structural integrity of the nanocomposite film. X-ray diffraction (XRD) analysis was also performed to examine the layered arrangement of MXene within the polymer matrix. The diffraction behavior shown in Figure 2confirmed the preservation of the layered MXene structure after incorporation into the TPU/PVA matrix, with slight modifications in interlayer spacing indicating successful polymer-assisted dispersion. Finally, the thickness of the fabricated nanocomposite films was measured using a digital micrometerand the average thickness values were used in subsequent electrical conductivity and sensing calculations.

Table 1. Materials used for fabrication of the MXene-infused conductive nano-polymer device.

Material	Specification	Function
$Ti_3C_2T_x$ MXene	Few-layer nanosheets	Conductive nanofiller / sensing phase
Thermoplastic Polyurethane (TPU)	Flexible polymer matrix	Mechanical flexibility and structural support
Poly(vinyl alcohol) (PVA)	Binder polymer	Interfacial stabilization and film uniformity
PET substrate	100–125 µm thickness	Flexible support layer
Silver paste / copper tape	Conductive contact layer	Electrical connection
ESP32 microcontroller	Wi-Fi/Bluetooth enabled	Edge data acquisition and processing
Humidity / gas sensing interface	Resistive sensing mode	Environmental signal acquisition

Electrical, Environmental, and Edge-Computing Evaluation

The electrical and sensing performance of the fabricated MXene-infused conductive nano-polymer films was evaluated under controlled laboratory conditions. Baseline electrical resistance was measured using a digital source meter, and the flexible sensing films were subsequently exposed to different humidity and gas environments to record their resistance-based sensing responses. The sensing response was quantified in terms of normalized resistance variation relative to the initial baseline resistance. In addition, repeated bending tests were carried out to assess the mechanical reliability of the nanocomposite film under flexible operating conditions.

For edge-computing implementation, the sensor output was interfaced with the ESP32 microcontroller, which performed real-time signal acquisition, filtering, threshold comparison, and wireless transmission of the measured data. Environmental sensing signals were processed locally, and only significant changes were transmitted to the cloud dashboard for remote monitoring, thereby reducing communication load and improving energy efficiency. Thus, the materials listed in Table 1, the fabrication sequence presented in Figure 1, and the microstructural characteristics illustrated in Figure 2 collectively establish the basis for the development of a flexible, conductive, and intelligent environmental monitoring platform based on MXene-infused polymer nanocomposites.

RESULTS AND DISCUSSION

The performance of the developed MXene-infused TPU/PVA conductive polymer composite was evaluated in terms of its electrical conductivity, microstructural organization, environmental sensing response, mechanical flexibility, and edge-enabled monitoring behavior. From a polymer-composites perspective, the results primarily reflect the role of MXene nanosheets as conductive fillers and the TPU/PVA matrix as the flexible structural and analyte-responsive phase. The data confirm that the nanocomposite successfully forms a stable percolative conductive network while preserving flexibility and environmental sensitivity.

Electrical Conductivity and Composite Network Formation

The electrical performance (Figure3) of the nanocomposite strongly depended on the formation of a continuous MXene percolation network within the TPU/PVA matrix. At low MXene loading, the conductive sheets remained partially isolated inside the polymer phase, resulting in relatively low conductivity. As the filler concentration increased, the inter-sheet distance decreased and a continuous conductive pathway was established, producing a sharp increase in conductivity. This is a characteristic feature of conductive polymer composites, where the transition from insulating to conductive behavior occurs near the percolation threshold.

The optimized composite containing 5 wt% MXene exhibited an electrical conductivity of approximately 3.8×10^3 S/m, which was significantly higher than that of the neat polymer matrix and sufficiently stable for resistive sensing applications. The conductivity increase can be attributed to the uniform distribution of MXene nanosheets and the interfacial stabilization provided by the PVA-rich polymer phase. The conductive network formed by overlapping MXene sheets is schematically consistent with the morphology shown earlier in Figure 2, where the polymer matrix acts as a flexible scaffold for conductive pathway formation.

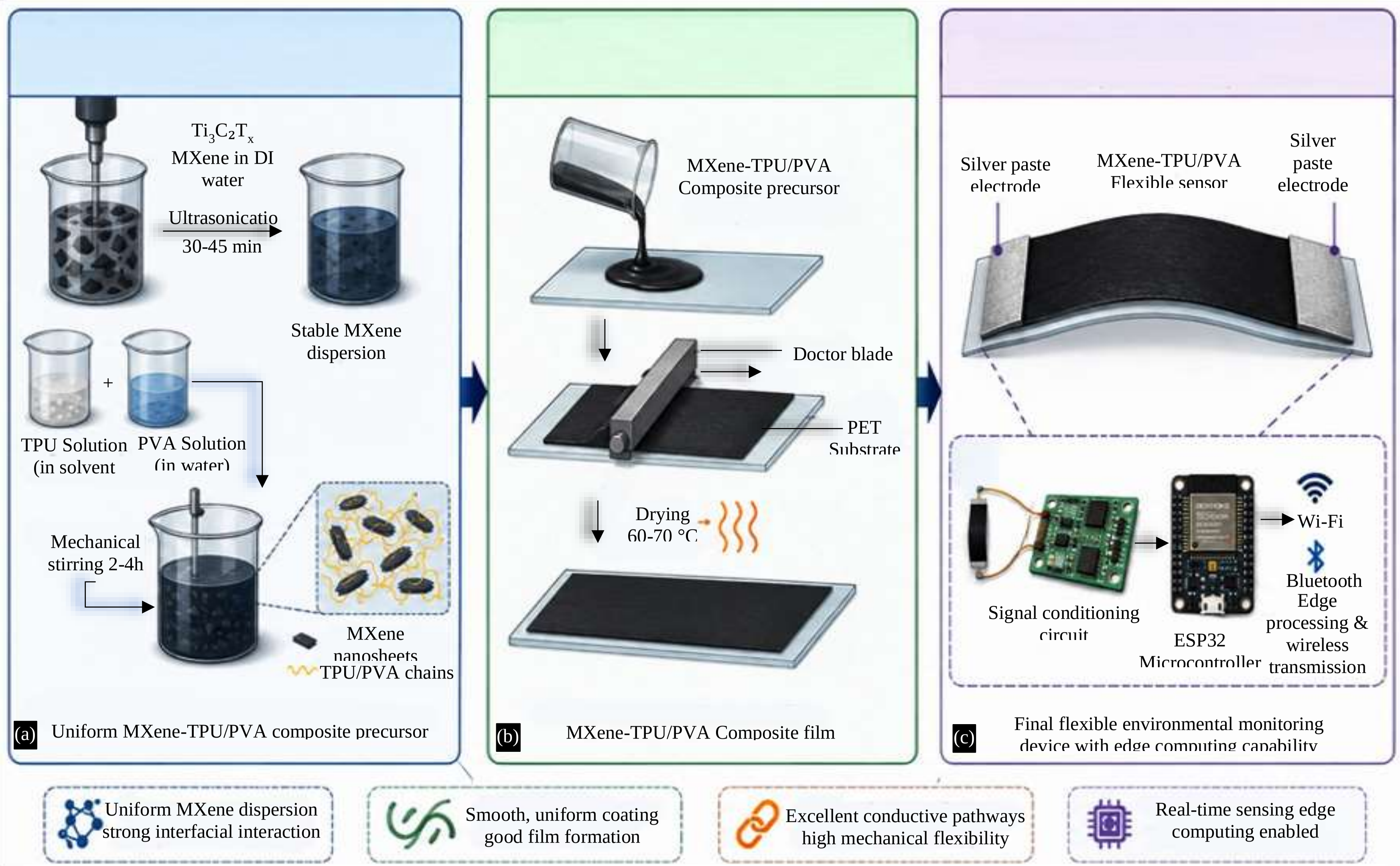

Figure 1. Schematic illustration of the fabrication process of the MXene-infused conductive nano-polymer flexible environmental monitoring device. a) MXene dispersion and TPU/PVA mixing b) coating of composite onto PET Substrate c) flexible sensor integration with edge-processing electronics.

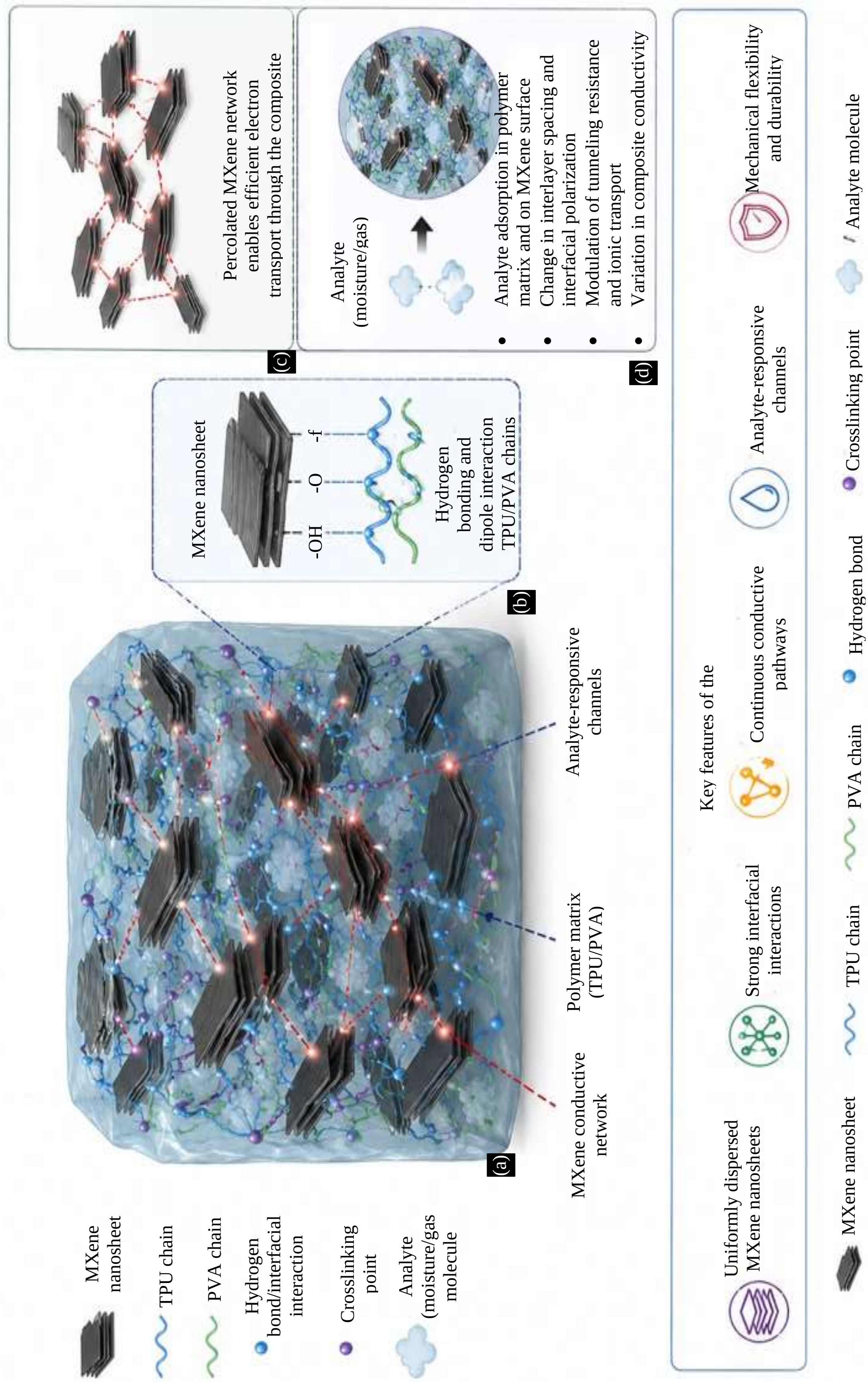

Figure 2. Representative structural characterization of the MXene-polymer nanocomposite film. a)3D Microstructural representation b) Interfacial Interaction c) Conductive pathway formation d) Analyte-responsive mechanism

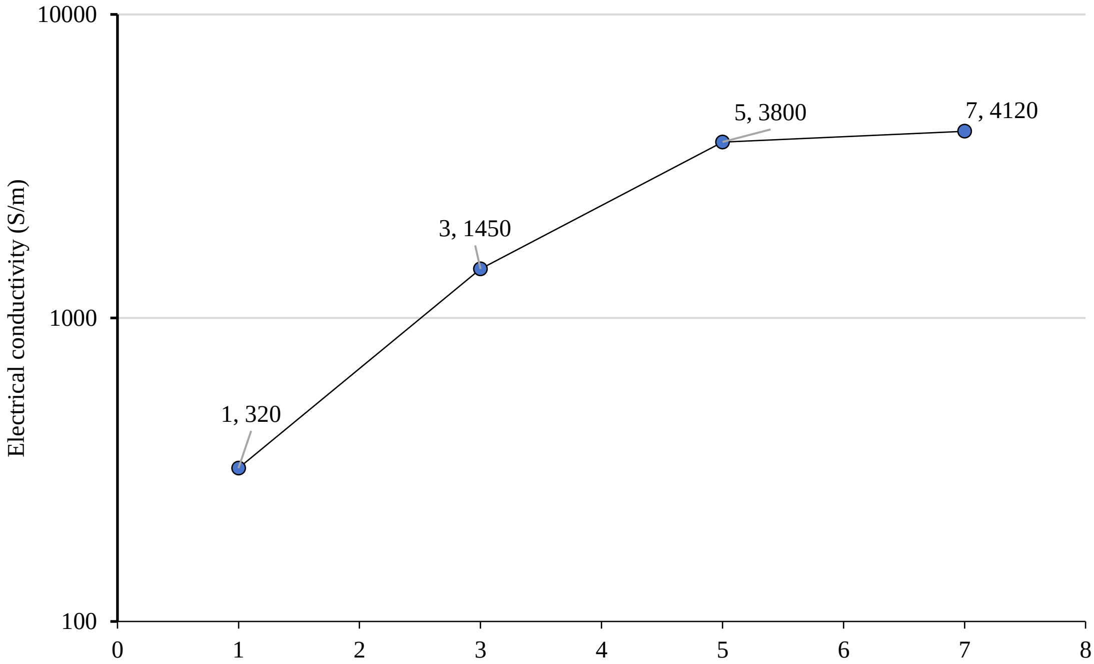

Figure 3. Electrical conductivity of MXene–TPU/PVA conductive polymer composites as a function of MXene loading.

Thus, the conductivity results confirm that the fabricated material behaves as a well-structured conductive polymer composite, where electrical transport is governed by filler connectivity and polymer–filler interactions rather than by the conductive filler alone.

Structural and Interfacial Characteristics of the Polymer Composite

The structural response of the composite is directly linked to the morphology of the MXene/polymer interface, since the sensing and electrical properties are controlled by how effectively the conductive nanosheets are embedded in the TPU/PVA matrix. As illustrated in Figure 2, the MXene nanosheets are distributed within the polymer phase in a manner that promotes conductive overlap while preserving polymer-rich interfacial regions. These interfacial regions are important because they act as mechanically compliant transport zones and also serve as the main sites for moisture and gas adsorption.

The TPU matrix contributes elasticity and mechanical integrity, whereas the PVA component enhances compatibility with MXene through hydrogen bonding and polar interactions. This improves nanosheet dispersion and reduces the probability of large agglomerates, which would otherwise interrupt the conductive pathway or reduce sensing uniformity. The composite morphology therefore supports both electrical continuity and analyte accessibility, which are essential for environmental sensing. In this sense, the polymer phase is not a passive host; rather, it actively determines how the MXene network is formed, stabilized, and exposed to environmental stimuli.

Humidity and Gas Sensing Response

The environmental sensing behavior of the nanocomposite was evaluated through humidity and ammonia exposure tests. The humidity response increased steadily with increasing relative humidity, confirming that the TPU/PVA matrix–MXene hybrid structure is highly responsive to moisture. The normalized resistance change increased from about 4.2% at 30% RH to nearly 38% at 90% RH, as shown in Figure 4. This behavior is typical of moisture-sensitive conductive polymer composites and is associated with water absorption by the polymer matrix, followed by swelling and modulation of electron transport across adjacent MXene sheets.

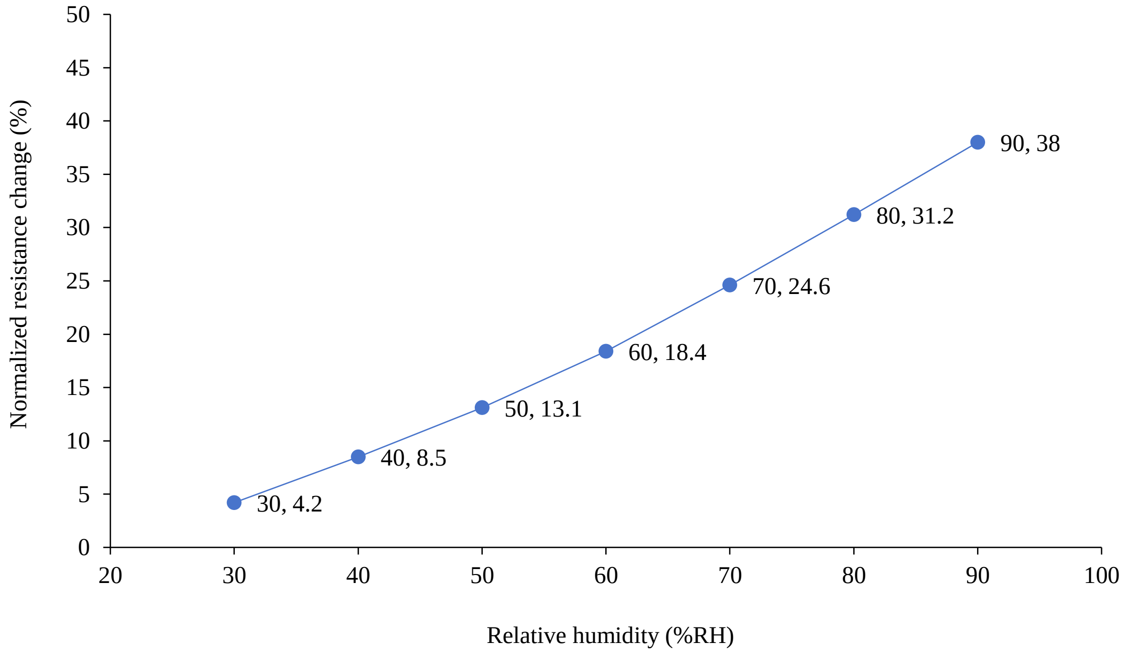

Figure 4. Humidity sensing response of the MXene–TPU/PVA conductive polymer composite.

Resistance variation increases with humidity because absorbed moisture alters the polymer interphase and MXene transport pathways.Similarly, the composite also showed a concentration-dependent response toward NH_3 gas, with the response increasing from 3.8% at 5 ppm to about 27.1% at 100 ppm. In this case, NH_3 molecules diffuse through the polymer-rich regions and interact with the MXene surface and interfacial charge-transfer sites, leading to measurable resistance changes. These results confirm that the sensing response is a polymer-composite-mediated phenomenon, in which the polymer matrix controls analyte diffusion while the MXene network converts interfacial interactions into electrical output. The signal transduction mechanism can be explained through resistance modulation within the conductive MXene network. During exposure to humidity or gaseous analytes, molecules diffuse into the TPU/PVA matrix and interact with the hydrophilic MXene surface functional groups. The resulting polymer swelling, interfacial charge transfer, and changes in inter-sheet tunneling distance alter the electrical resistance of the percolative conductive network. The generated resistance variation is converted into a measurable voltage signal using a voltage divider configuration and subsequently digitized by the ESP32 analog-to-digital converter for edge-level signal processing and wireless transmission.

Mechanical Flexibility and Bending Stability

Mechanical reliability is a key performance parameter for flexible polymer-composite sensors. The bending behavior (Figure 5) of the MXene–TPU/PVA film was therefore evaluated under repeated deformation at a bending radius of 5 mm. The normalized resistance variation remained low throughout the test and reached only 6.5% after 1000 bending cycles, demonstrating that the conductive network remained largely intact during cyclic loading.

The conductive polymer composite retains electrical continuity during repeated bending, showing only minor resistance drift. This behavior is mainly attributed to the elastomeric TPU matrix, which absorbs strain and suppresses crack propagation, and to the strong polymer–MXene interfacial bonding promoted by PVA. Instead of brittle fracture, the composite undergoes small reversible rearrangements of conductive sheets within the flexible polymer network. The bending results therefore confirm that the nanocomposite possesses the mechanical resilience expected from a well-designed flexible polymer composite, while still maintaining adequate conductivity and sensing performance.

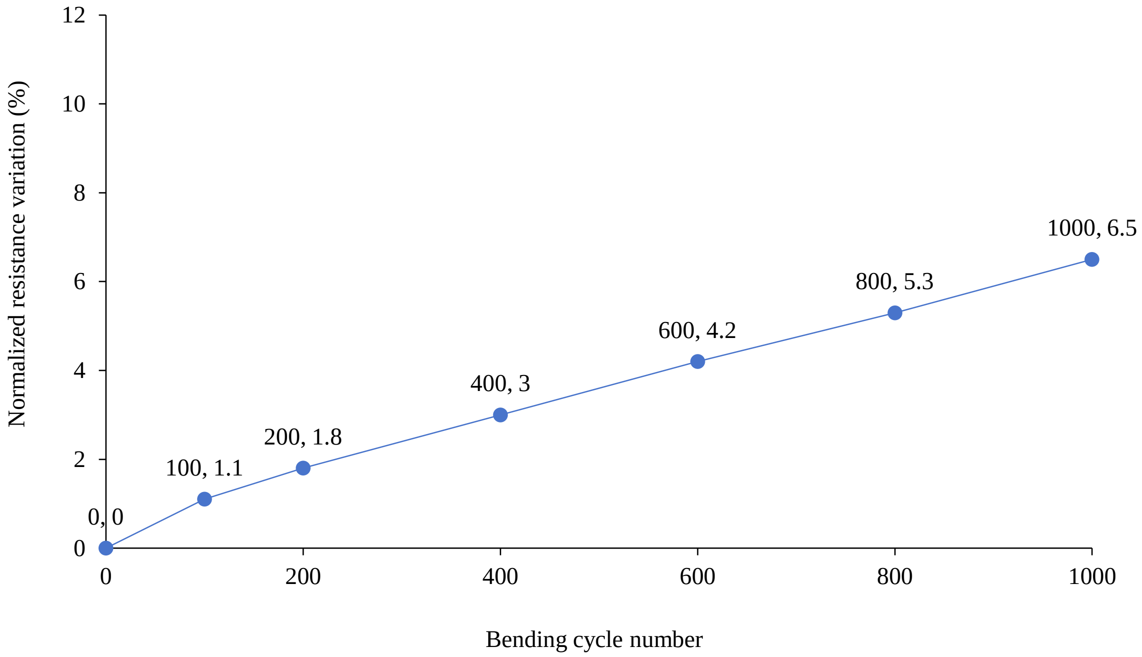

Figure 5. Resistance variation of the MXene–TPU/PVA conductive polymer composite during cyclic bending.

Edge-Computing Monitoring

The practical relevance of the developed material was demonstrated by integrating the MXene–TPU/PVA sensing film with an ESP32-based edge-computing unit for real-time environmental monitoring. The composite sensor successfully transmitted humidity-dependent resistance changes to the edge platform, where the data were processed locally and forwarded to the monitoring interface. A representative real-time humidity profile showed a gradual increase in response from approximately 2% to 38% over 30 min, consistent with the direct sensing measurements.

From a polymer-composites standpoint, this successful integration indicates that the fabricated film possesses not only sufficient conductivity and environmental sensitivity, but also adequate film integrity, electrode compatibility, and operational stability for use in real devices. In comparison with conventional CNT/polymer or PEDOT:PSS-based sensing films, the MXene–TPU/PVA composite provides a better balance of conductivity, humidity sensitivity, gas response, and bending durability, primarily because of the synergistic combination of MXene conductive pathways and the flexible, analyte-responsive TPU/PVA matrix.

CONCLUSION

The present work demonstrates that MXene-infused TPU/PVA conductive polymer composites are a promising material platform for flexible and edge-computing-enabled environmental monitoring devices. In this study, conductive polymer composite refers to a multifunctional material system in which a flexible polymer matrix is combined with a conductive nanofiller to achieve simultaneous electrical conductivity, mechanical flexibility, and environmental sensing capability. By incorporating $Ti_3C_2T_x$ MXene nanosheets into the TPU/PVA matrix, the fabricated composite successfully exhibited a stable conductive network, effective humidity and gas sensing behavior, good bending durability, and compatibility with real-time wireless monitoring electronics.

- MXene nanosheets significantly enhanced the conductivity of the TPU/PVA polymer matrix by forming an interconnected conductive pathway throughout the composite.
- The fabricated MXene–TPU/PVA film showed strong humidity sensitivity, confirming that the polymer matrix and MXene interfacial network effectively responded to environmental moisture

changes.

- The composite also exhibited a measurable NH_3 gas sensing response, indicating its potential for multifunctional environmental monitoring applications.
- Mechanical flexibility was retained successfully, with only minor resistance variation under repeated bending, highlighting the robustness of the polymer-composite structure.
- The TPU/PVA matrix played an active role in filler dispersion, interfacial stabilization, analyte diffusion, and protection of the conductive network under deformation.
- Integration of the sensing film with an ESP32-based edge-computing platform demonstrated the practical feasibility of real-time signal acquisition, local processing, and wireless environmental monitoring.
- The proposed material system can be considered a smart conductive polymer composite, where the synergy between MXene nanofillers and the flexible polymer matrix enables simultaneous conductivity, sensing, and device-level adaptability.

REFERENCES

1. Nooh SA. Optimizing low carbon sustainable environmental monitoring with consumer technology: An IoT-driven federated learning approach for edge computing optimization. IEEE Transactions on Consumer Electronics. 2025 Jan 23;71(4):12361-72.
2. Idrees Z, Zou Z, Zheng L. Edge computing based IoT architecture for low cost air pollution monitoring systems: a comprehensive system analysis, design considerations & development. Sensors. 2018 Sep 10;18(9):3021.
3. Roostaei J, Wager YZ, Shi W, Dittrich T, Miller C, Gopalakrishnan K. IoT-based edge computing (IoTEC) for improved environmental monitoring. Sustainable computing: informatics and systems. 2023 Apr 1;38:100870.
4. Manduva VC. AI-Powered Edge Computing for Environmental Monitoring: A Cloud-Integrated Approach. International Journal of Emerging Trends in Science and Technology. 2020 Dec 29:1-21.
5. Manickaraj K, Karthik A, Palanisamy S, Jayam M, Ali SK, Sankar SL, Al-Farraj SA. Improving Mechanical Performance of Hybrid Polymer Composites: Incorporating Banana Stem Leaf and Jute Fibers with Tamarind Shell Powder. BioResources. 2025 Jan 1;20(1).
6. Siddiqui F, Rabbani H, Akhtar N, Suneel S, Naik AS, Vengaimarbhan D. Scalable environmental monitoring system using IoT and edge computing. Int J Environ Sci. 2025;11(11s):932-43.
7. Kim M, Kim T, Park S, Lee K. An indoor multi-environment sensor system based on intelligent edge computing. Electronics. 2022 Dec 28;12(1):137.
8. Mishra A. Edge computing and IoT-based urban environment monitoring solutions. Computational engineering and technology innovations. 2024 Jul 22;1(3):139-49.
9. Palaniappan M, Palanisamy S, Murugesan TM, Tadepalli S, Khan R, Ataya S, Santulli C. Influence of washing with sodium lauryl sulphate (SLS) surfactant on different properties of ramie fibres. BioResources. 2024 May 1;19(2):2609.
10. Fang J, Hu J, Wei J, Liu T, Wang B. An efficient resource allocation strategy for edge-computing based environmental monitoring system. Sensors. 2020 Oct 28;20(21):6125.
11. Parmar H, Murari UK, Singh SK. Smart Polymer-Integrated IoT Systems: A Mathematical Framework for Real-Time Sensing and Adaptive Material Behavior. InMacromolecular Symposia 2026 Feb (Vol. 415, No. 1, p. e70183).
12. Palanisamy S, Kalimuthu M, Dharmalingam S, Alavudeen A, Nagarajan R, Ismail SO, Siengchin S, Mohammad F, Al-Lohedan HA. Effects of fiber loadings and lengths on mechanical properties of Sansevieria Cylindrica fiber reinforced natural rubber biocomposites. Materials Research Express. 2023 Aug 1;10(8):085503.
13. Malashin I, Tynchenko V, Gantimurov A, Nelyub V, Borodulin A. Physics-informed neural networks in polymers: a review. Polymers. 2025 Apr 19;17(8):1108.
14. Huang J, Zhou S, Li G, Shen Q. Real-time monitoring and optimization methods for user-side

energy management based on edge computing. Scientific Reports. 2025 Jul 10;15(1):24890.
15. Kar A, Saikia D, Palanisamy S, Pandiarajan N. Calamus tenuis fiber reinforced epoxy composites: effect of fiber loading on the tensile, structural, crystalline, thermal and morphological characteristics. Journal of Polymer Research. 2024 Nov;31(11):323.
16. Khan LU, Yaqoob I, Tran NH, Kazmi SA, Dang TN, Hong CS. Edge-computing-enabled smart cities: A comprehensive survey. IEEE Internet of Things journal. 2020 Apr 10;7(10):10200-32.
17. Kar A, Saikia D, Palanisamy S, Pandiarajan N. Effect of fiber loading on the mechanical, morphological, and dynamic mechanical characteristics of Calamus tenuis fiber reinforced epoxy composites. Journal of Vinyl and Additive Technology. 2025 Jan;31(1):224-40.
18. Premsankar G, Di Francesco M, Taleb T. Edge computing for the Internet of Things: A case study. IEEE internet of things journal. 2018 Feb 12;5(2):1275-84.
19. Minh QN, Nguyen VH, Quy VK, Ngoc LA, Chehri A, Jeon G. Edge computing for IoT-enabled smart grid: The future of energy. Energies. 2022 Aug 24;15(17):6140.
20. Jin W, Xu R, Lim S, Park DH, Park C, Kim D. Dynamic inference approach based on rules engine in intelligent edge computing for building environment control. Sensors. 2021 Jan 18;21(2):630.
21. Ficili I, Giacobbe M, Tricomi G, Puliafito A. From sensors to data intelligence: Leveraging IoT, cloud, and edge computing with AI. Sensors. 2025 Mar 12;25(6):1763.
22. Bachtiar D, Mohammed AA, Palanisamy S, Imran AI, Siregar JP, bin Mat Rejab MR, Syaubari S, Cionita T, Fitriyana DF, Al-Farraj SA, Almansour MI. Effect of alkaline treatment on the thermal and mechanical properties of sugar palm fibre reinforced thermoplastic polyurethane composites. Scientific Reports. 2025 Apr 23;15(1):14085.
23. Vecchio M, Azzoni P, Menychtas A, Maglogiannis I, Felfernig A. A fully open-source approach to intelligent edge computing: Agile's lesson. Sensors. 2021 Feb 12;21(4):1309.

