

Review on MXene–Starch Based Packaging Systems for Sustainable and Biodegradable Electronics

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Abstract

To address the growing demand for sustainable and high-performance materials in electronics packaging, starch-based MXene bio-composite films emerge as a promising alternative to conventional synthetic polymers. This work provides a comprehensive review of the integration of MXenes with starch matrices for enhancing functional properties critical to electronics packaging. Improvements in mechanical strength, electrical conductivity, thermal stability, barrier performance, and environmental sustainability are critically analysed. Also, different MXene compositions, and incorporation strategies are compared to identify the most effective approaches. It is observed that starch–MXene films hold significant potential for replacing petroleum-based materials in electronic device packaging. Besides, the interactive effect of MXenes can modify starch films for advanced applications by balancing biodegradability with performance, making them a strong candidate for next-generation sustainable electronics packaging.

Keywords

Starch, MXene, Biodegradable, EMI shielding, WVP.

1. Introduction

Non-biodegradable traditional petroleum-based packaging materials contribute significantly to the growing global e-waste problem, projected to reach 82 million metric tons by 2030 (Baldé et al., 2024). Sustainable changes are critically needed to combine environmental friendliness with effective protection for sensitive electronic components. MXenes, particularly $Ti_3C_2T_x$, are promising for electronic packaging due to their high electrical conductivity ($\sim 10,000$ S/cm) and strong mechanical properties (Liu et al., 2023). A biodegradable polysaccharide, starch provides a renewable matrix but suffers from low tensile strength and high permeability (Dong et al., 2024).

Combination of MXenes with starch in nanocomposite films enhances mechanical strength, reduces water vapor permeability, and can enable electromagnetic interference shielding, even though maintaining biodegradability (Dong et al., 2024). Such MXene-starch composites represent a sustainable and effective solution for electronic device packaging. This review critically studies these recent developments, highlighting synthesis strategies, property enhancement mechanisms, and practical applications. It also explores limitations, safety and biodegradability considerations, and pathways toward commercialization, aiming to provide materials scientists and polymer engineers with a comprehensive understanding of this emerging field and its potential to transform sustainable electronics packaging (Figure 1).

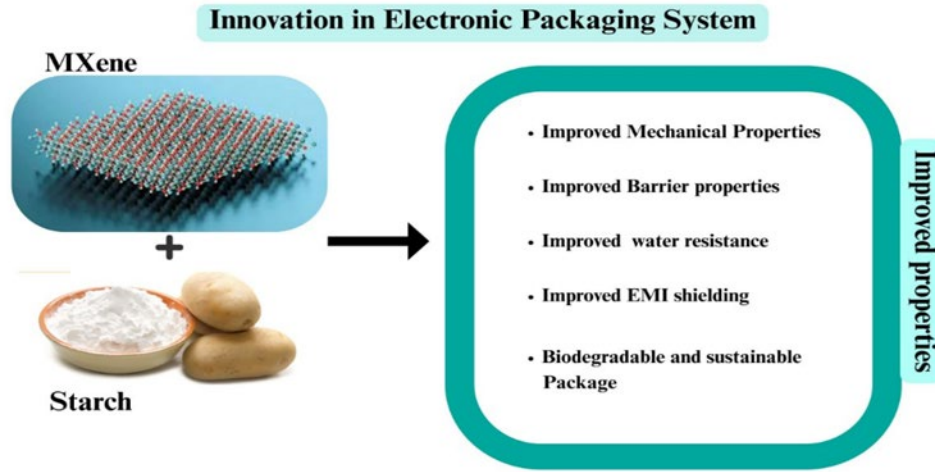


Figure 1. Innovation in Electronic Packaging System through MXene-Starch

2. Conventional Packages VS MXene Starch Based Packages

When it comes to performance, well established manufacturing infrastructure and scalability the conventional (polymer laminates, metallized films, foams and polymer/metal stacks etc.) excels. Also the mechanical properties and dimensional abilities in case of (Polymers, PET, PE) provides exceptional results and long shielding life. ESD, EMI and thermal management (-40°C to +150°C) are proficient too but when it comes too the sustainability the lack of environmental protection as (it is expected to have about 82 million metric tons of e-waste by 2030 (Baldé et al., 2024) makes a major issue for the future .So in regards to find a better solution which is more sustainable without the huge performance sacrifice, the multifunctionality (tensile strength 300% increase, 90% reduction in WVP) and light weight EMI , ESD shielding solution(exceptional electrical conductivity upto 20,000 S/cm (Liu et al., 2023). MXene takes the spot. If we think about the future proof solution for the green and sustainable solution driven electronics (approximately 90% lower CO₂ emissions compared to petroleum-based materials) the MXene-Starch based system could be the appropriate solution. When it comes to solutioning the long-term stability, cost ((~\$0.5-2/kg for conventional polymers vs \$50-200/kg for MXene materials)) and practical application; MXene oxidation, moisture sensitivity and industry standard processing must be to applicable standard (Table 1).

3. Literature Review

Table 1. Comparison among properties based on various MXene - starch based systems

| Year | Material System | Fabrication Method + MXene Loading | Barrier Improvement | Mechanical Performance | Antistatic / EMI | Biodegradability / Stability |
|-------------|-----------------|------------------------------------|--------------------------|------------------------|----------------------|---------------------------------|
| 2024 (Dong) | Starch/MXene | Solution casting; 2.5–10 wt% | WVP ↓92.9% (291.9→20.6); | YM ↑321.4% (456→1923) | Not reported (MXene) | Fully degraded in soil within 6 |

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|----------------------------|---|---|--|---|---|--|
| et al., 2024) | (Ti ₃ C ₂ T _x) nanocomposite films | | OP ↓74% (51.8→13.5) at 10 wt% | MPa); TS ↑92.9% (9.9→19.1 MPa) | conductive) | weeks |
| 2025 (Dong et al., 2025) | PVA/starch/sorbitol + MXene (Ti ₃ C ₂ T _x) | Solution casting; 2.5–10 wt% | WVP ↓91% (469.9→41.4); OP ↓79% (24.5→5.1) at 10 wt% | YM ↑669% (255.7→1965 MPa); TS ↑292% (9.2→36.1 MPa); EAB ↓ (76.5%→12.9%) | 10 ⁶ –10 ⁸ Ω/sq (ESD suitable) | Biodegradable; MXene oxidizes to TiO ₂ /C; recyclable |
| 2025 (Haddad et al., 2025) | Starch acetate (SA) + MXene-QDs (with LiPF ₆) | CuAAC click grafting; 10–50 wt% | Not reported (battery focus) | SA/MXene50: high strength, smooth surface after 1000 cycles | Electrically insulating (<10 ⁻⁹ S/cm) | Biodegradable SA; thermally stable >200 °C |
| 2025 (Munshi et al., 2025) | Chitosan (biomass) + MXene nanoparticles | Solution casting (CS in acetic acid); 0.005–0.04 wt% | UV/HEBL shielding: 99.55% (UV-A), 100% (UV-B/C), ~97.5% HEBL; ↓ moisture absorption (8.5%) & solubility (2.3%) | TS: 80.1 MPa (↑303%); YM: 19.7 MPa (↑830%); high flexibility | Not reported | Biobased, thermally stable (T _{so} ↑444→495 °C) |
| 2024(Wei et al., 2024) | Filter paper + TOCN/C S/MXene gel + nacre + TOCN/C S hydrogel film | Layer-by-layer coating; 20 g·m ⁻² | Hydrogel protected MXene & preserved EMI SE in water, HCl, ethanol | TS: 11.7 MPa (vs. 6.4 MPa raw paper) | EMI SE: 40.3 dB @ 0.1894 mm; up to ~70 dB with stacking | Hydrogel enhanced durability; flexible & stable in liquids |
| 2022 (Chen et al., 2022) | MXene (Ti ₃ C ₂ T _x) + hemicellulose (xylo-oligosaccharide) | Vacuum-assisted self-assembly; 1.5–10 wt% | Not reported | TS: 19→125 MPa (with hemi loading); YM ↑ | High conductivity : 361,218→64,300 S/m; strong humidity sensing | Bio-based binder; hygroscopic |
| 2025 (Wang et al., 2025) | Hollow egg-box MXene & MSPP (AMMF) composite films | Vacuum-assisted self-assembly + low-T annealing; MSPP 2.5–12.5 mg (MXene wt% not given) | Not reported for O ₂ /H ₂ O; improved water resistance vs. pure MXene | Improved YM & strength; high MSPP ↓ TS & YM; ↑ strain at break | EMI SE: up to 69.2 dB @ 12.4 GHz; SSE/t 27,888 dB·cm ² ·g ⁻¹ ; conductivity | Lightweight, stable, thermally robust |

| | | | | | maintained | |
|------------------------------|--|--|---|--|---|---|
| 2023 (Peng et al., 2023) | MXene (Ti ₃ C ₂ T _x) + Fe ₃ O ₄ + bacterial cellulose (BC) + MTMS (SBTF _x -Y) | Layered film (solution-based); MXene/Fe ₃ O ₄ ratio varied | Not reported | Excellent flexibility, robust stratified structure | EMI SE: 68 dB @ 45 μm; high conductivity; absorption-dominant | BC bio-based; hydrophobic with MTMS |
| 2024 (Xie et al., 2024) | Starch + TEMPO-CNF + nanomontmorillonite + rGO | Self-assembly (nacre-like); rGO loading not given | Excellent water resistance | TS: 37.39 MPa | EMI SE >35 dB @ 0.5 mm | Biodegradable, water-stable |
| 2022 (Hu et al., 2022) | MXene (Ti ₃ C ₂ T _x) + Aramid Nanofiber (ANF) + OPSZ hydrophobic coating | Vacuum-assisted filtration + dip coating; 5–40 wt% MXene (opt. 20 wt%) | Not reported; OPSZ improves oxidation & water stability | TS: 302.1 MPa @ 20 wt%; excellent flexibility | EMI SE: 46.1–53.1 dB; >85% reflection; conductivity 82.9 S/cm | Not biodegradable; stable EMI performance |
| 2020 (Zhou et al., 2020) | MXene (Ti ₃ C ₂ T _x) + Cellulose Nanofiber (CNF) | Alternating vacuum filtration (AVF); MXene 50 mg + CNF 50 mg | Not reported | TS: 112.5 MPa; Toughness: 2.7 MJ/m ³ ; withstands >1000 folds | EMI SE: ~40 dB; SSE/t up to 7029 dB·cm ² ·g ⁻¹ ; stable after 1000 bends | CNF provides robustness; not focused on biodegradability |
| 2025 (Huang et al., 2025) | Pure MXene (Ti ₃ C ₂ T _x) nanosheets | Continuous centrifugal spraying; dispersion 2 mg/mL; thickness-controlled (e.g., MX-80 ≈25 nm) | Not reported | Bendable (no specific metrics) | Conductivity: 1.03×10 ⁶ S/m; EMI SE: 45–59 dB; SSE/t: 1.545×10 ⁶ dB·cm ² ·g ⁻¹ ; IR emissivity: 0.1 | Not biodegradable; oxidation stable (sheet R ↑40% after 26 wks) |

3.1 Reasons for The Results among The MXene Starch Based Systems

From Table 1, In case of the starch/sorbitol with MXene based system (2.5–10 wt% loading) showed strong starch-MXene H-bonding, homogeneous dispersion and alignment, improved water resistance and tortuous diffusion path and efficient load transfer via interfacial bonding (Dong et al., 2024). For the enhancement of thermal and mechanical stability, loading of (10,30,50) wt% with the system of starch acetate and MXene quantum dots (QD) (LiPF₆) was perfect as it showed high modulus fillers and with better uniform dispersion and strong crosslinking forms 3D network (Hadad et al., 2025). Another chitosan and MXene (.005-0.04 wt%) based system pulled the results of better UV/high-energy blue light (HEBL) shielding as the d-orbital adsorption and MXene functional groups (-OH,-O,-F) creates

multilayer of dispersions, better mechanical property because of H-bonding , interlocking and filler effects and with the thermal stability because of MXene crosslinking (Munshi et al., 2025).

Filter paper and MXene gel layer with the nacre structure showed high EMI shielding efficiency and better barrier protecting. MXene with hemicellulose (xylo- oligosaccharide) system has a reinforced concrete effect because the hemicellulose acts as molecular binder H-bonding. Also the short chains avoid insulating phase ; MXene spacing is enlarged because of the hygroscopic sites (Chen et al., 2022). Hollow egg-box MXene& hollow microparticles (MSPP (AMMF))composite films MSPPs created extra scattering and reflection, making the heterogenous interfaces polarization losses, hollow MSPPs making it lightweight and extended electromagnetic path feasible and strong bonding makes the mechanical bonding much more durable (Wang et al., 2025). MXene with bacterial cellulose (BC) with the other reinforcements as Fe₃O₄ and methyltrimethoxysilane (MTMS) (SBTF_x-Y layered films) has increased the with efficient EMI absorption , whereas the Fe₃O₄ and BC outer layer reduces reflectance and as per usual the dispersion is uniform and with superior mechanical integrity (Peng et al., 2023) . With the loading of 5-40% of hydrophobic coating MXene with aramid nanofiber (ANF) showed tensile strength of 20%, enhanced mechanical strength. The MXene in this system creates conductive paths and the reason for showing better tensile strength holds as the sandwich structure in ANF layer which acts as reinforcement (Hu et al., 2022). Cellulose Nanofiber (CNF) and MXene system has the hierarchical nacre like structure and because of the zigzag reflection process there has been multiple EMI reflections. CNF layers act as robust mechanical frame, prevent crack propagation and transfer load among the structure (Zhou et al., 2020).

The results from the table of pure MXene nanosheets was because of improved alignment, thickness and compactness (denser film) making its ultra-low IR emissive and efficient regarding the electrothermal performance (Figure 2 and Figure 3).

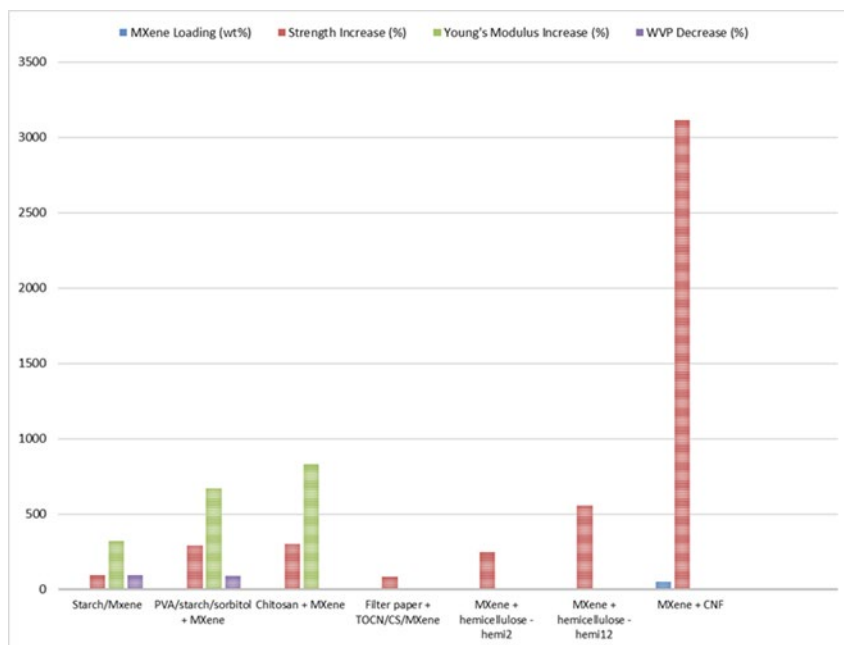


Figure 1. Comparison among properties based on various MXene - starch based systems

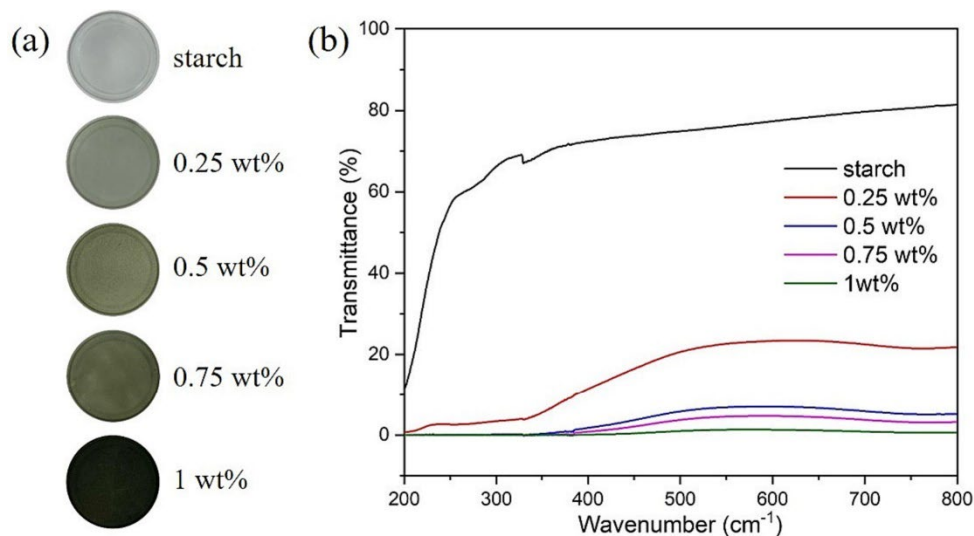


Figure 2. Photographs of the produced nanocomposite films. (b) UV-vis transmittance of starch and starch/Ti3C2Tx nanocomposites with different filler loadings (0.25, 0.5, 0.75, and 1 wt%) (Dong et al., 2024).

With the recent discovery of MXene the amount of work in the science world based on improving electronic property and improving electric application has been increased exponentially. The recent approach to biodegradable and sustainable packaging for electric based properties has been improving every day. With these high hopes we propose couple of pathways which might help to bring light to the discovery of new and improved packaging system.

There has been a severe lack of information and research in the sector of MXene/Starch based packaging systems when it comes to inclusion of machine learning and artificial intelligence. Which can drastically improve the research quality, expected results for biodegradability, and a sustainable approach in regard to electronic packaging.

The cost efficiency has been another issue in the case of packaging including MXene. Which is why various loading and synthesis processes have been explored. But it would be greatly beneficial if future research also focuses on the nanostructure of these MXene based systems.

Various 3D structure-based systems should also be explored as such was done in hollow egg shaped MXene composite. Inspiration can be taken from the CNT 3d structures and 3d graphene foam (Baldé et al., 2024), (Liu et al., 2023) etc. Even though various structures were followed with various MXene loading percentage, we can safely assume from the provided data below 10% was the appropriate range when the concern is to improve cost efficiency and better result in the electronic property section. Which is why shifting the focus on low-cost synthesis approach with the below 10% weight loading of MXene might be crucial.

4. Conclusion

In this review paper we focused on the packaging system which combines the multifunctionality of MXene and the biodegradability of starch, making a perfect combination for the issue in electronic packages. We have found even in small amounts of MXene (2.5-10 wt%) into starch matrices has resulted in almost 300% tensile strength increase from (from ~9 MPa to >36 MPa), exponential raise in Young's modulus by almost 600% (from ~250 MPa to ~1965 MPa) and reducing WVP to astonishing 90%. These improvements address the limitations in the starch films (poor mechanical strength, High permeability etc.) and maintains the biodegradability and recyclability. Such combination of composite is the best candidate for the application in flexible electronics and sustainable packaging. However, challenges remain in proper homogenous dispersion, oxidation controlling and long-term stability, scaling issues and reducing costs. Which is why future work should prioritize on 3d nanostructured systems, 3D architectures (hollow eggs, nacre-like designs etc.) and data driven optimization like ML and AI inclusion. Which can smoothen the way for the MXene and starch-based packaging system in the upcoming days. By these various composites based on

MXene and starch systems, material science and industrial appropriate designs can improve the quality of the nature one step at a time.

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Biographies

Nafees Ibne Alam is an undergraduate student at Rajshahi University of Engineering and Technology (RUET) with a strong interest in advanced materials, particularly in MXene, and a strong ambition/desire to become a profound researcher. He is motivated and driven by a desire to contribute to the future world through the application of machine learning (ML) and artificial intelligence (AI) with the incorporation in advanced materials. He possesses an exceptional understanding of visual representation and simulations, enabling him to grasp and convey complex abstract concepts effectively. With his passion for research and technological advancements, he aims to make a meaningful impact on the future world.

Maisha Chowdhury Karabi is an undergraduate student at Rajshahi University of Engineering and Technology (RUET), currently working on starch-based packaging. She has a strong ambition to become more proficient in the research world and is actively involved in various research projects based on sustainability, advanced materials and green source-based energy sectors etc. She is dedicated to advancing her knowledge and skills, aiming to make meaningful contributions to the field of sustainable materials and packaging. With her passion for research, she strives to have a positive impact on the future.

Sabiqune Nahar Niti is an undergraduate student at Rajshahi University of Engineering and Technology (RUET), currently focusing on sustainable packaging through starch-based materials. She is dedicated to growing as a researcher and is actively involved in various projects aimed at finding eco-friendly solutions. She is passionate about expanding her knowledge in the research field and aspires to contribute to the development of more sustainable,

environmentally-friendly materials. With a strong desire to make a positive impact, she is eager to enhance both her academic and practical understanding of the field.