

From 2D Layers to Flexible Devices: A Comprehensive Review on MXene-Based Supercapacitors

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Abstract

The increasing international need of energy storage technologies that are sustainable and efficient, has stimulated an extensive-research beyond the traditional batteries. The supercapacitors have become worthy of consideration because of power density and high charge discharge as well as long cycling life. More recently, a new category of two-dimensional transition metal carbides, nitrides, and carbonitrides (MXenes) have gained immense publicity as state-of-the-art electrode LiCoO₂ supercapacitor electrodes. Their exceptional combination of metallic conductivity, hydrophilicity, variable interlayer distance and mechanical flexibility, render them exceptionally appropriated in future flexible and wearable devices. In this review, a detailed study of MXene-based supercapacitors, strategy of synthesis, structure, and energy storage mechanisms, including electrical double-layer capacitance, pseudocapacitance, and hybrid processes are presented. The significant progress of pristine MXenes, surface-engineered MXenes, MXene-carbon composites, MXene-polymer composites, hierarchies are critically assessed, and their electrochemical performance indicators are presented. Moreover, complementary characterization techniques with high resolutions in the study of the MXene structure and surface chemistry, electrochemical activity are overviewed. Although there have been notable improvements, there remain the challenge of instability of oxidation, interlayer restacking, dangerous synthesis pathways, and scalability issues. The outlooks of the future imply the necessity of green synthesis, interlayer-engineering, hybridization with new materials, and AI/ML-based design solutions. All in all, MXenes have immense possibilities to transform the concept of high-performance flexible and sustainable energy storage

Keywords

MXenes, Supercapacitors, Flexible Energy Storage Devices, Electrode Materials, Green and AI-Assisted Synthesis.

1. Introduction

Energy is the fundamental need of society. Energy is required for society to function properly. But now we are facing a global energy crisis. We need more and more of energy storage devices to properly utilize the harvested energy. Batteries, supercapacitors, and hydrogen storage are energy storage devices.

Batteries cannot adapt to different types of power-consuming devices. But supercapacitors can be used in place of batteries as an alternative option because they are flexible and applicable in different systems. Supercapacitors exhibit properties like longer life cycle, shorter recharge time, and higher power storage. Supercapacitors work by storing electrostatic energy and using pseudo-capacitance (Tomy et al., 2021). Layered 2D materials have physicochemical qualities. MXenes have a 2D layered structure that gives them more capacity for active sites on their surfaces. MXenes have high electrical conductivity. Gogotsi's team successfully made MXene-based supercapacitors better with great chemical stability, electrical conductivity, and high ductility (Hu et al., 2018)

This review shows the MXene based supercapacitors discovery, fundamentals, properties, synthesis techniques and structural characteristics of MXene. It shows the methods for material manipulation, surface modification, carbon-based composites, the amalgamation of polymers with metals. The article discusses the methods for characterizing which related to stability, restacking, and large scale synthesis. This paper demonstrates the relation between classic capacitors and batteries, also indicating their potential to transform the future of portable devices, wearable electronics, and advanced energy storage technologies

2. MXenes: Fundamentals and properties

Industry specialists appreciate MXenes for their impressive surface tunability, high electrical conductivity, and remarkable affinity for water, and MXenes as a class of 2D materials, have thus captured global interest and attention (Shayesteh Zeraati et al., 2021).

2.1. Discovery and synthesis of MXenes (etching, delamination, scalable methods)

Naguib et al. (2011) first spoke about MXene. They reported that it can be synthesized by submerging Ti₃AlC₂ powders in HF solution. Ghidui et al. (2014) et al. expanded on MXene etching techniques by introducing of LiF and HCl as HF-etching MXene precursors. The separation of the layers removes bonds to produce the paper-like MXene sheets (Zhan et al., 2020). Mxene can be synthesized via top-down and bottom-up approaches, and more recently, the technique involving CVD growth, demonstrated by Xu et al. in 2015, permits the scalable synthesis of MXene nano-foils (Xu et al., 2015).

2.2. Structure and composition ($M_{n+1}X_nT_x$ formula, surface terminations)

The general formula of MXene is $M_{n+1}X_nT_x$, where M represents an early transition metal, X represents carbon or nitrogen, T_x represents the surface terminations, and $n = 1, 2, 3$. M can be Nb, Ta, Sc, Ti, Zr, Hf, V, Cr, Mo, and so on. Surface termination elements are -O, -OH, -F (Anasori & Gogotsi, n.d.). More accurately, octahedral interstitial sites of M are occupied by X in their hexagonal crystal sublattice, and the surface group occupies different sites of M (Lim et al., 2022).

2.3. Unique properties relevant to supercapacitors

MXenes excel in energy storage systems owing to the functional groups, electrochemically active surfaces, high conductivity, hydrophilicity, and impressive energy density alongside rapid charge-discharge capabilities (Yu et al., 2023). The surface terminations of MXenes have a direct effect on conductivity, hydrophilicity, electrochemistry and catalytic activity, surface termination also modifies interlayer spacing for optimal ion interlayer transport (Liang et al., 2021). Because MXenes have a natural two-dimensional structure, they are very flexible, which makes them great for use in flexible and wearable electronics (Ibrahim et al., 2020).

3. Mechanisms of energy storage in MXene-based supercapacitors

Supercapacitors work in two specific mechanisms – electric double-layer capacitance and pseudocapacitance (Yang et al., 2019).

3.1. Electrical Double Layer Capacitance (EDLC)

In EDLCs, positive and negative electrodes create a static electric field through a non-faradaic process. Here, ions are electrically absorbed, creating charges. The charge transfer between electrolytes and electrodes is zero, and separating two different charges creates electrostatic storage. For aqueous and nonaqueous electrolytes, the combination of metal ions with water and a high potential difference are respectively responsible for the formation of EDLCs on the surface of MXenes (Yang et al., 2019).

3.2. Pseudo-capacitance via redox reactions

In the case of pseudo-capacitors, electrons or charges transfer via a faradaic process. Intercalation or redox reactions on the electrode surface occur due to voltages. However, the cyclic stability of pseudo capacitors is less than that of EDLCs. Redox reaction may arise on the surface of MXene. MnO_2 , PPy, etc., are the pseudocapacitive materials that can be grafted easily onto the MXene surfaces (Yang et al., 2019).

3.3. Hybrid mechanisms

Hybrid SCs are a combination of EDLC and pseudocapacitance mechanisms, which consist of two different electrodes, which show the behaviour of electrostatic and electrochemical properties, respectively. Carbon and metal oxide-based materials are used, respectively, for the cathode and anode in these hybrids (Mandal et al., 2025). MXenes, with their impressive surface chemistry, can be a replacement for these electrodes as they are capable of both EDLC and pseudocapacitance.

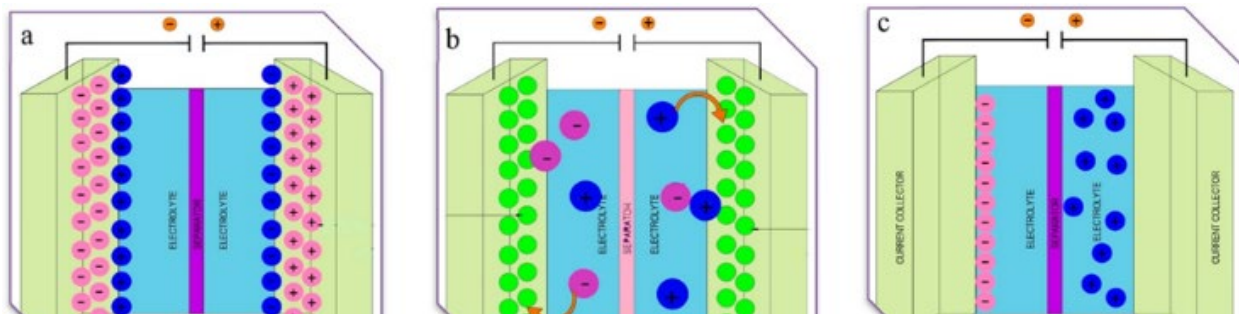


Figure 1: (a) EDLC, (b) pseudo-capacitor and (c) hybrid mechanism of MXene-based supercapacitors. The image is adapted with permission(Aravind et al., 2023). Copyright, 2023 The Authors.

4. MXene-based supercapacitors : recent progress

4.1. Pristine MXenes ($Ti_3C_2T_x$, Nb_2C , V_2C , Mo_2C)

Pristine $Ti_3C_2T_x$ films are improved $Ti_3C_2T_x$ films with superior properties. They are produced using proton acid colloidal processing method, which results in excellent mechanical strength and stability, as well as twice the conductivity of normally produced films (Hongwu Chen et al., 2020). Similarly, other MXenes, such as V_2C , Nb_2C , and Mo_2C are used for their uniqueness in their respective fields.

4.2. Surface engineering & chemical modification (O, S, Se terminations)

MXenes typically have $-O$, $-F$, and $-OH$ terminations. Oxygen (O) terminated MXenes are produced from the top-down method, which results in improved carrier mobility and semiconducting behavior with an average band gap. But recently, MXenes have become a suitable option for hosting sulfur (S) and Selenium (Se) for practical applications. Sulfur (S) terminated MXenes have a strong attraction between polysulfide and M atoms, which helps in maintaining a higher specific capacitance and improved cycling rate (Ougherb et al., 2022). On the contrary, selenium-terminated MXenes are produced by the selenization process, which enhances both capacity and structural stability of MXenes (Sha et al., 2022).

4.3. MXene composites with carbon materials

MXene-based composites with carbon materials, such as graphene, carbon nanotubes, and carbon aerogels, have demonstrated improved electrochemical performance in SC applications. Recently, Wen et al. fabricated a flexible MXene/Graphene composite electrode via an inkjet printing process, which was useful for wearable and flexible SC applications (Wen et al., 2022). Chen et al. designed an MXene/CNT nano-composite electrode through a vacuum filtration method, exhibiting high flexibility and stability (He Chen et al., 2020). MXene-carbon aerogels have also caught the attention of researchers in the field of SCs.

4.4. MXene/conducting polymer hybrids (polyaniline, polypyrrole)

Polymers of aniline (PANI), pyrrole (PPy), thiophene (PTh), etc., are the most studied conducting polymeric materials that form hybrids with MXenes for SC applications, which are more conductive and stable than pure MXenes. MXene/PANI composites can be fabricated through the chemical oxidation of aniline on MXene, which was studied by Xu et al. Jian et al. showed the co-electrodeposition method of MXene/PPy nanofilms, which was found to have better capacitance than pure MXene (Jian et al., 2019).

4.5. 3D and hierarchical architectures

MXene-based 3D printing devices like hydrogels, aerogels, and foams have captured the interest of researchers because of their simple fabrication methods, low weight, and enhanced performance. Huang et al. fabricated a 3D printable electrode based on MXene hydrogel alignment, which impacts faster ion transportation and diffusion (Huang et al., 2021). Ma et al. produced a modified $Ti_3C_2T_x/rGO$ 3D aerogel, which can also be called "MLSG", treating the materials hydrothermally, applicable in the field of energy storage (Ma et al., 2021). Various types of MXene-based foams are also used in supercapacitor application.

4.6. Performance metrics

The previously mentioned MXene-based supercapacitor electrode devices are tabulated in Error! Reference source not found. according to their electrochemical performances in different metrics such as capacitance, energy/power density, and cyclic stability.

Table 1 : Performance metrics of MXene-based supercapacitors

Author	Material/ Device	Synthesis Process	Capacitance	Energy/Power / density	Cycling Stability	Ref.
Wen et al.	MXene/Graphene composite	Inkjet printing	183.5 F cm ⁻³ at 5 mV s ⁻¹	0.1 mWhcm ⁻² energy density at 0.38 mWcm ⁻² power density	75% (3000 cycles)	(Wen et al., 2022)
Chen et al.	MXene/CNT Composite	Vacuum filtration	300 Fg ⁻¹ at 5 Vs ⁻¹	-	92% (10000 cycles, at 20 Ag ⁻¹)	(He Chen et al., 2020)
Xu et al.	Ti ₃ C ₂ T _x /PANI Composite	Chemically oxidized polymerization	556.2 Fg ⁻¹ at 0.5 Ag ⁻¹ current density	-	91.6% (5000 cycles, at 5 Ag ⁻¹)	(Xu et al., 2020)
Wu et al.	Ti ₃ C ₂ T _x /PPy Composite		184.36 Fg ⁻¹ at 2 mVs ⁻¹	-	83.33% (4000 cycles, at 1 Ag ⁻¹)	(Iqbal et al., 2021)
Huang et al.	MXene-hydrogel electrode	Unidirectional freezing	393 Fg ⁻¹ at 5 mVs ⁻¹	0.1 mWhcm ⁻² energy density at 0.38 mWcm ⁻² power density	90% (10000 cycles, 100 mV s ⁻¹)	(Huang et al., 2021)
Ma et al.	MXene/rGO	Hydrothermal treatment	386Fg ⁻¹ at 2 mVs ⁻¹	142 μWhcm ⁻² energy density at 4900 μWcm ⁻² power density	96.3% (10000 cycles)	(Ma et al., 2021)

5. Challenges and Limitations

Oxidation MXenes along with stability concerns in ambient air owing to the defects in the MXene conductivity and electrochemical performance resulting from HF etching on the MAX phase (Wu et al., 2019). Their two dimensional layered sheets are prone to restacking because of the van der Waals forces, which inhibits the movement of ions by surface area access restriction and diffusion blocking of the electrolyte pathways (Iqbal et al., 2021). Its scalability is obstructed by the synthesis of highly pure MX phase precursors and the synthesis of hazardous (e.g., concentrated HF) and expensive MXene along with the cumbersome, costly, and reproducible synthesis MXene in bulk (Hu et al., 2020). Subsequently, balancing energy density and power density while maintaining flexible mechanical device compatibility and durability remains a relentless dilemma foremost; the materials designed for high power density do not correspondingly high energy density, while flexible devices are strained and stability conservative (Nahiriak et al., 2023).

6. Conclusion

They have quickly transformed their structure and electrochemical characteristics into the new two-dimensional materials and have taken a lead in the study of supercapacitors. Their variable interlayer distance, high surface, and conductivity allow electrical double-layer capacitance, such as pseudocapacitive charge storage as they are flexible electrode products. The combination with carbonaceous and polymeric material, surface engineering and the development of three-dimensional architecture have been highly step forward and have led to an increase in capacitance, rate performance and mechanical flexibility. However, oxidation degradation, inter-layer restacking, scaling between layers, and threatening synthesis routes and scaling challenges are still important issues that do not allow the use in real life. To tackle these issues, such innovative technologies as green and scalable synthesis, interlayer adjustment, solid-state electrolyte synthesis, and intelligent material design due to the application of AI/ML paradigms will be required. It is hoped that the MXenes will be involved in the solution to flexible and wearable supercapacitors

in the future, and also in a bridge between academic research and practice. MXenes can transform the future of sustainable energy storage devices by addressing the existing shortcomings that they have, and play a significant role in the world-wide trend of clean and efficient energy technologies.

References

- Aravind, A. M., Tomy, M., Kuttapan, A., Kakkassery Aippunny, A. M., & Suryabai, X. T. Progress of 2D MXene as an electrode architecture for advanced supercapacitors: A comprehensive review. *ACS Omega*, 8(47), 44375–44394, 2023. <https://doi.org/10.1021/acsomega.3c02002>
- Chen, H., Wen, Y., Qi, Y., Zhao, Q., Qu, L., & Li, C. Pristine titanium carbide MXene films with environmentally stable conductivity and superior mechanical strength. *Advanced Functional Materials*, 30(5), 1906996, 2020.
- Chen, H., Yu, L., Lin, Z., Zhu, Q., Zhang, P., Qiao, N., & Xu, B. Carbon nanotubes enhance flexible MXene films for high-rate supercapacitors. *Journal of Materials Science*, 55(3), 1148–1156, 2020. <https://doi.org/10.1007/s10853-019-04003-8>
- Hu, M., Hu, T., Li, Z., Yang, Y., Cheng, R., Yang, J., Cui, C., & Wang, X. Surface functional groups and interlayer water determine the electrochemical capacitance of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. *ACS Nano*, 12(4), 3578–3586, 2018. <https://doi.org/10.1021/acsnano.8b00676>
- Hu, M., Zhang, H., Hu, T., Fan, B., Wang, X., & Li, Z. Emerging 2D MXenes for supercapacitors: Status, challenges and prospects. *Chemical Society Reviews*, 49(18), 6666–6693, 2020. <https://doi.org/10.1039/D0CS00175A>
- Huang, X., Huang, J., Yang, D., & Wu, P. A multi-scale structural engineering strategy for high-performance MXene hydrogel supercapacitor electrode. *Advanced Science*, 8(18), 2021. <https://doi.org/10.1002/advs.202101664>
- Ibrahim, Y., Mohamed, A., Abdelgawad, A. M., Eid, K., Abdullah, A. M., & Elzatahry, A. Recent advances in the mechanical properties of self-standing two-dimensional MXene-based nanostructures: Deep insights into the supercapacitor. *Nanomaterials*, 10(10), 2020. <https://doi.org/10.3390/nano10101916>
- Iqbal, A., Hong, J., Ko, T. Y., & Koo, C. M. Improving oxidation stability of 2D MXenes: Synthesis, storage media, and conditions. *Nano Convergence*, 8(1), 9, 2021. <https://doi.org/10.1186/s40580-021-00259-6>
- Jian, X., He, M., Chen, L., Zhang, M., Li, R., Gao, L., Fu, F., & Liang, Z. Three-dimensional carambola-like MXene/polypyrrole composite produced by one-step co-electrodeposition method for electrochemical energy storage. *Electrochimica Acta*, 318, 820–827, 2019. <https://doi.org/10.1016/j.electacta.2019.06.045>
- Liang, K., Matsumoto, R. A., Zhao, W., Osti, N. C., Popov, I., Thapaliya, B. P., Fleischmann, S., Misra, S., Prenger, K., Tyagi, M., et al. Engineering the interlayer spacing by pre-intercalation for high-performance supercapacitor MXene electrodes in room temperature ionic liquid. *Advanced Functional Materials*, 31(33), 2104007, 2021.
- Lim, K. R. G., Shekhirev, M., Wyatt, B. C., Anasori, B., Gogotsi, Y., & Seh, Z. W. Fundamentals of MXene synthesis. *Nature Synthesis*, 1(8), 601–614, 2022. <https://doi.org/10.1038/s44160-022-00104-6>
- Ma, L., Zhao, T., Xu, F., You, T., & Zhang, X. A dual utilization strategy of lignosulfonate for MXene asymmetric supercapacitor with high area energy density. *Chemical Engineering Journal*, 405, 2021. <https://doi.org/10.1016/j.cej.2020.126694>
- Mandal, S., Mendhe, A. B., Rakhade, H. M., Barse, N. S., Roy, M., Rosaiah, P., Park, T., Lee, H.-S., Mendhe, A. C., & Kim, D. Recent advancement and design in supercapacitor hybrid electrode materials: Bridging the gap between energy and power density. *Chemical Engineering Journal Advances*, 21, 100690, 2025. <https://doi.org/10.1016/j.cej.2024.100690>
- Nahirmiaki, S., Ray, A., & Saruhan, B. Challenges and future prospects of MXene-based materials for energy storage applications. *Batteries*, 9(2), 2023. <https://doi.org/10.3390/batteries9020126>
- Ougherb, C., Ouahrani, T., Badawi, M., & Morales-García, Á. Effect of the sulfur termination on the properties of Hf_2CO_2 MXene. *Physical Chemistry Chemical Physics*, 24(12), 7243–7252, 2022. <https://doi.org/10.1039/D2CP00288D>
- Sha, D., Lu, C., He, W., Ding, J., Zhang, H., Bao, Z., Cao, X., Fan, J., Dou, Y., Pan, L., & Sun, Z. Surface selenization strategy for V_2CT_x MXene toward superior Zn-ion storage. *ACS Nano*, 16(2), 2711–2720, 2022. <https://doi.org/10.1021/acsnano.1c09639>
- Shayesteh Zeraati, A., Mirkhani, S. A., Sun, P., Naguib, M., Braun, P. V., & Sundararaj, U. Improved synthesis of $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes resulting in exceptional electrical conductivity, high synthesis yield, and enhanced capacitance. *Nanoscale*, 13(6), 3572–3580, 2021. <https://doi.org/10.1039/D0NR06671K>

- Tomy, M., Ambika Rajappan, A., V. M., V., & Thankappan Suryabai, X. Emergence of novel 2D materials for high-performance supercapacitor electrode applications: A brief review. *Energy & Fuels*, 35(24), 19881–19900, 2021. <https://doi.org/10.1021/acs.energyfuels.1c02743>
- Wen, D., Ying, G., Liu, L., Li, Y., Sun, C., Hu, C., Zhao, Y., Ji, Z., Zhang, J., & Wang, X. Direct inkjet printing of flexible MXene/graphene composite films for supercapacitor electrodes. *Journal of Alloys and Compounds*, 900, 163436, 2022. <https://doi.org/10.1016/j.jallcom.2021.163436>
- Wu, W., Wei, D., Zhu, J., Niu, D., Wang, F., Wang, L., Yang, L., Yang, P., & Wang, C. Enhanced electrochemical performances of organ-like Ti_3C_2 MXenes/polypyrrole composites as supercapacitor electrode materials. *Ceramics International*, 45(6), 7328–7337, 2019. <https://doi.org/10.1016/j.ceramint.2019.01.016>
- Xu, C., Wang, L., Liu, Z., Chen, L., Guo, J., Kang, N., Ma, X.-L., Cheng, H.-M., & Ren, W. Large-area high-quality 2D ultrathin Mo_2C superconducting crystals. *Nature Materials*, 14(11), 1135–1141, 2015. <https://doi.org/10.1038/nmat4374>
- Xu, H., Zheng, D., Liu, F., Li, W., & Lin, J. Synthesis of an MXene/polyaniline composite with excellent electrochemical properties. *Journal of Materials Chemistry A*, 8(12), 5853–5858, 2020. <https://doi.org/10.1039/d0ta00572j>
- Yang, J., Bao, W., Jaumaux, P., Zhang, S., Wang, C., & Wang, G. MXene-based composites: Synthesis and applications in rechargeable batteries and supercapacitors. *Advanced Materials Interfaces*, 6(8), 2019. <https://doi.org/10.1002/admi.201802004>
- Yu, L., Lu, L., Zhou, X., & Xu, L. Current understanding of the wettability of MXenes. *Advanced Materials Interfaces*, 10(2), 2201818, 2023.
- Zhan, X., Si, C., Zhou, J., & Sun, Z. MXene and MXene-based composites: Synthesis, properties and environment-related applications. *Nanoscale Horizons*, 5(2), 235–258, 2020.