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Recent advances in MXene composites research, applications and opportunities

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ABSTRACT

MXene composites have emerged as a promising class of materials due to their exceptional properties and versatility in various applications. In recent years, researchers have made significant progress in the development and characterization of MXene composites, paving the way for new opportunities in various fields, including energy storage, environmental remediation, and catalysis. The incorporation of MXenes into polymers has led to enhanced mechanical, electrical, and thermal properties. Additionally, advances in MXene synthesis and functionalization have expanded the scope of their applications. This review summarizes recent research progress in MXene composites, highlights the challenges, and discusses potential opportunities for future development.

1. Introduction

MXene as a new group of 2D materials has gained a lot of attention since being discovered in 2011 [1–3]. Through acid etching and delamination, layered 2D sheets of MXene were obtained by eliminating the A atoms from Mn + 1AXn phases. Fig. 1 shows some potential applications of MXenes in many fields such as composites, energy, electronics, optical, biomedical, environmental, electrochemical capacitors, and sensors [4–7]. Numerous investigations have shed light on the thermal uses of MXene and improved our understanding of its heat transfer properties. Interestingly, MXene with a graphene-like shape, a 2D nanosheet material synthesised using MAX phases, appears to be highly fascinating [8–11]. The number of publications is significantly increasing since 2012 as shown in Fig. 2.

2. Synthesis of mxenes

To date, more than 40 types of MXene exist and they can be more popular than other 2D materials such as graphene [9]. Hydrofluoric acid was used to selectively etch layers of transition metal carbides and carbonitrides from the MAX phases to create the first MXene generation. Ever since, a variety of synthesis techniques have been created, such as selective etching in a solution of fluoride salts, non-aqueous etchants, halogens, and molten salts, enabling the synthesis of novel MXenes with improved control on the surface chemistries [11]. Since M–A bonds are stronger than graphite layers, the usual stripping process fails to produce MXene materials, according to Zhang et al. in their study. In a nutshell, MXene can be prepared by applying the etching technique [17–19]. Fig. 3 shows the image of MAX phase treatment by hydrofluoric acid and delamination of MXene layers. Etching-assisted exfoliation is nowadays the main method for the massive production of monolayer and multilayer MXenes. Additionally, this method is employed to create MXenes for electromagnetic studies. [20–22].

Table 1 shows the properties enhancement of MXenes polymer composites obtained from available articles from 2019 to 2022. It can be observed that hydrofluoric acid, hydrochloric acid and lithium fluoride are commonly used in the processing of MXenes. Coating, film and packaging are some of the applications which can be seen in many research articles. In general, the incorporation of MXenes into the polymer can significantly increase the mechanical and electrical properties of the composites.

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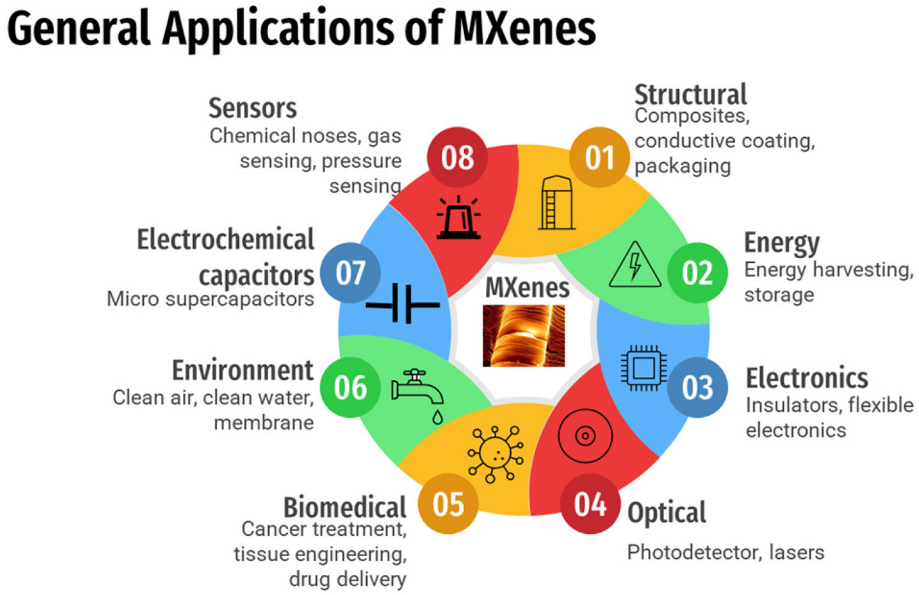

Fig. 1. General applications of MXenes [12–16].

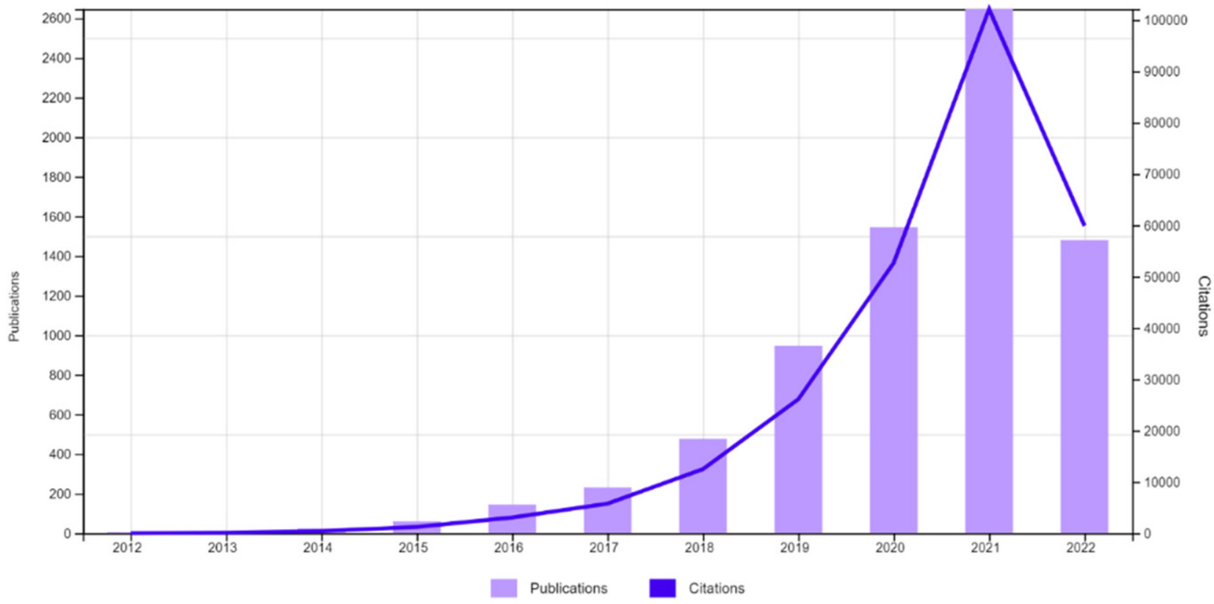

Fig. 2. Number of publications and citations from 2012 to 2022 on MXenes indexed by Web of Science (Clarivate).

3. Other important properties of MXene polymer nanocomposites

Fig. 4 shows the recent studies on tensile properties of MXene/epoxy composites from 2019 to 2022. In general, researchers agree that the presence of MXene in polymer matrix shows significant increase of mechanical properties over neat polymer [26,28–30]. From previous studies, the incorporation of MXenes increased the tensile strength up to 155% compared to neat polymer. A similar trend can be observed for tensile modulus, where MXene reinforcement can significantly improve modulus up to 102% Fig. 5. The enhancement of tensile properties is due to the microcracks bridging effect of evenly dispersed MXene particles in polymer matrix [31].

3.1. Thermal properties

According to studies, composites have better thermal characteristics than pristine epoxy. Epoxy composite with only 1.0 wt% Ti_3C_2 MXene fillers has a thermal conductivity value (0.587 $W.m^{-1}.K^{-1}$) that is 141.3% higher than neat epoxy. [12]. It was found that the composite has an improved glass transition temperature, is thermally stable, and has less thermal expansion. MXene particles could restrict the polymer chain movement thus improving storage modulus [33]. Yong Cao et al. studied the thermal properties of PVDF/MXene composites produced by solution mixing [34]. They reported that the thermal conductivity increased to 0.363 WmK-1 when a loading of 5 wt% was attained which is about 1-fold enhancement compared to a pristine poly-

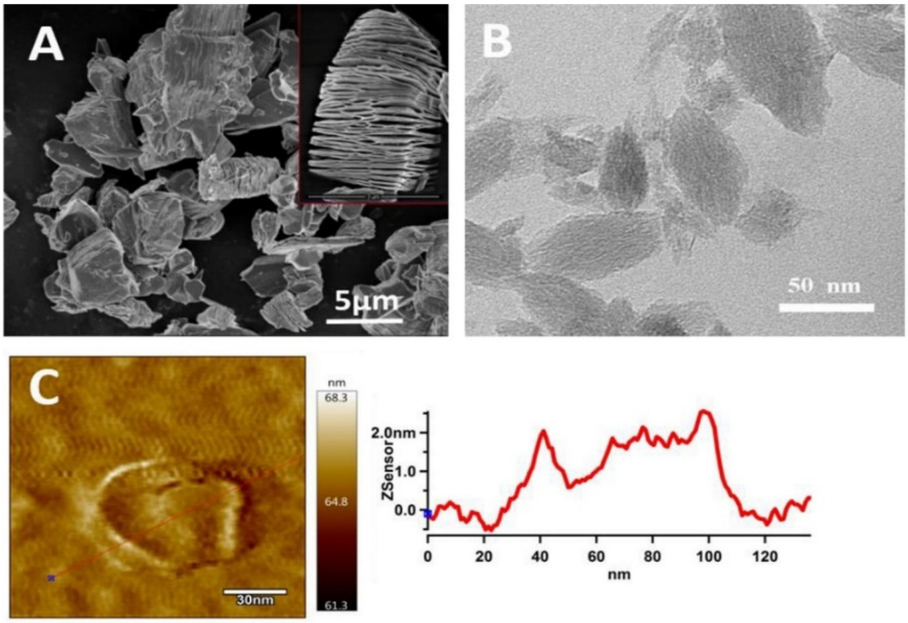

Fig. 3. SEM of MAX phase (A), TEM image (B) and AFM image with line profile of MXene paticles. . Reproduced with permission from [23]

Table 1
Properties enhancement of MXenes composites.

Ref.	Year	Polymer	Etching Solvents	Preparation	% Increase	Application	Wt%
[12]	2022	Epoxy	Hydrofluoric acid	Sonication + mechanical mix	K_{1c} and G_{1c} improved 70% and 140%	Coating	0.5 wt%
[24]	2022	PP	Hydrochloric acid	Hot pressing and vacuum drying	The final composite exhibits an EMI shielding performance of ~90 dB (8–12 GHz, thickness ~400 µm).	Electronic device protection	25 wt%
[25]	2022	PVDF	Hydrochloric acid	Sonication + planetary mixing	MXene/GNP-PVDF film reveals the outstanding electrical conductivity (7423 S/m) and excellent in-plane TC (36.9 W/mK).	Composite film	100 mg/mL
[13]	2021	Epoxy	Lithium fluoride + hydrochloric acid	Vacuum drying + sonication + mechanical mix	Flexural strength increased by 32%	Coating, supercapacitor packaging and 3D printing	0.2 wt%
[5]	2021	Epoxy	Lithium fluoride + hydrochloric acid	Hand layup + vacuum bagging	Electrical permanent resistance increased 16.25%	Sensing coating	3.3 mg/mL
[26]	2021	Epoxy	Nitric acid	Mechanical mix + ultrasonication	Flexural strength and stress intensity factor increased by 67% and 216%	Composites	1 mg/mL
[3]	2020	Epoxy	Lithium fluoride + hydrochloric acid	Mechanical mix	Limiting oxygen index value of 38% and high thermal stability	Coating	3 wt%
[27]	2020	Epoxy	Hydrogen fluoride	Stirring in DI water + cellulose	Thermal conductivity improved 3609%	Electronic packaging	30.2 wt% MXene-CF
[15]	2020	Epoxy	Hydrochloric acid	Mechanical mix + ball milling	Impact strength increased 100%, electrical conductivity improved 10 orders of magnitude higher	Composites	1.2 wt%
[23]	2019	CoPA	Hydrofluoric acid	Sonication + mechanical mix + casting	Reasonable enhancement of electrical conductivity up to 1.4 $x10^{-2}S.cm^{-1}$	Flexible electronics	5 wt%
[6]	2019	Epoxy	Hydrofluoric acid + Lithium chloride	Vacuum degass + mechanical mix	Permeability of epoxy was reduced up to 90% with a loading of 5 wt% filler	Coating	5 wt%

mer. Lee and Kim [35] demonstrated through-plane and in-plane conductivities of 1.51 and 4.28 $W.m^{-1}.K^{-1}$. Thus, proving that incorporation of MXene enhanced the thermal properties of the composites film (see Fig. 6).

3.2. Electrical conductivity

The exceptional electrical properties of MXene make it an excellent choice for electrocatalytic processes. Numerous researchers have investigated the effects of various M, X, and surface functions on the electrical properties of MXene. As MXene loading increases, electrical conductivity likewise rise [1,39]. The superior conductivity of MXenes is due to the conductive carbide core, which is affected by surface groups, particle size, defect concentration and contact resistance between flakes [40]. Fig. 6 below shows electrical conductivity of epoxy/$Ti3C_2Tx$ at different loading. It can be observed that more weight percent of MXene nanosheets significantly increased electrical conductivity.

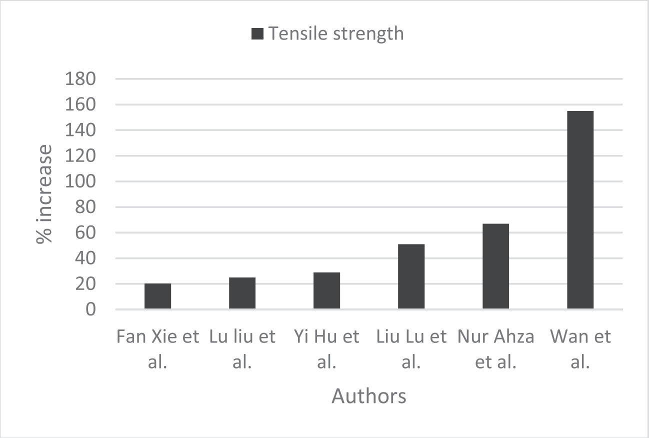

Fig. 4. Tensile strength of MXene/epoxy composites from literature review [2,4,13,14,32].

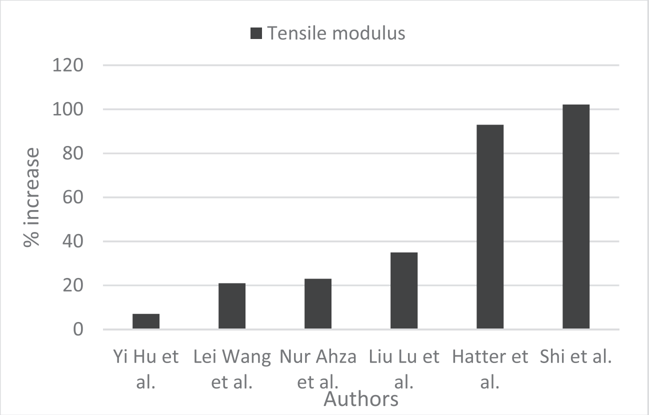

Fig. 5. Tensile modulus of MXene/epoxy composites from literature [13,31,32,36–38].

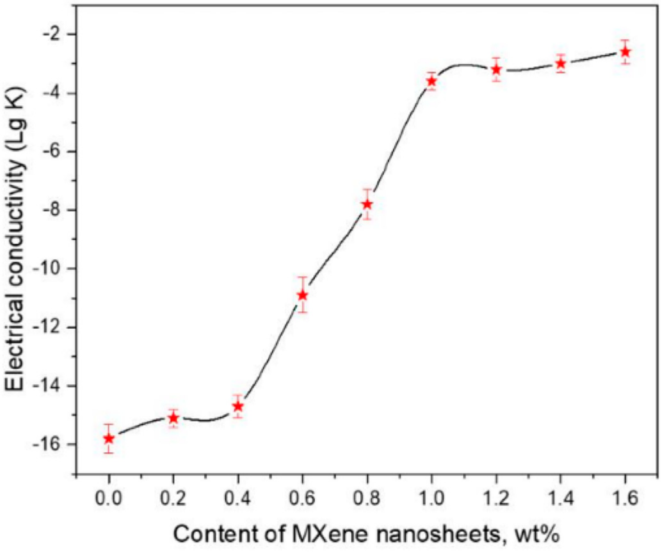

Fig. 6. Electrical conductivity of epoxy/$Ti_3C_2T_x$ at different loading. . Reproduced with permission from [15]

4. Conclusions

MXenes have substantial benefits over traditional materials in terms of competitiveness. MXenes have produced excellent or at least notable improvements over present technologies, ushering in a new paradigm. Even though MXenes have been lauded for their mechanical and electrical properties, their dispersion qualities have not been adequately examined in most publications. Computational investigation of MXenes' electronic density and orbital interaction will aid in the discovery of a new combination of basic elements. The processing, particularly the dispersion quality, is one of the critical barriers to extensive industrial substitution and expansion of commercial MXenes. It is still anticipated that researchers will overcome these obstacles, which will contribute to the advancement of nanotechnology and the commercial products associated with it for a number of years to come.

5. Future prospects and opportunities

Among the results produced by researchers, the current trend indicates an improvement in all aspects of technology such as mechanical performance of composites, energy storage capacity, electrical conductivity and thermal properties. MXene has been used in numerous scientific applications, from wastewater treatment to life-saving medicinal and biological applications, despite still being in the testing phase. High power densities have been demonstrated for this novel 2D material, but when paired with polymers, these power storage options also include flexibility and biocompatibility. Recent advances in MXene composites have focused on enhancing their performance and stability by introducing new materials and modifying their synthesis methods. Overall, the recent advances in MXene composites have shown that they have great potential for various applications, and ongoing research in this field is expected to lead to further improvements and new discoveries. Despite numerous studies that have been reported, there is no single publication which mentioned machinability properties for MXene polymer composites. The machinability properties are useful because MXene polymer composites can be applied in mobile phone and power sectors [41,42]. It is hoped that there will be more reports on the influence of the addition MXene particles on the morphology of machined surfaces, chip formation, cutting forces, and tool wear in the near future.

CRediT authorship contribution statement

M.S Saharudin: Funding acquisition, Project administration, Methodology, Writing – original draft. **A. Ayub:** Investigation. **S. Hasbi:** Investigation. **F. Muhammad-Sukki:** Investigation. **Islam Shyha:** Writing – review & editing. **Fawad Inam:** Writing – review & editing.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] X. Chen, Y. Zhao, L. Li, Y. Wang, J. Wang, J. Xiong, S. Du, P. Zhang, X. Shi, J. Yu, MXene/Polymer Nanocomposites: Preparation, Properties, and Applications, Polym. Rev. 61 (1) (2021) 80–115.

[2] F. Xie, F. Jia, L. Zhuo, Z. Lu, L. Si, J. Huang, M. Zhang, Q. Ma, Ultrathin MXene/aramid nanofiber composite paper with excellent mechanical properties for efficient electromagnetic interference shielding, Nanoscale 11 (48) (2019) 23382–23391.

[3] S. Huang, L. Wang, Y. Li, C. Liang, and J. Zhang, "Novel Ti3C2Tx MXene/epoxy intumescent fire-retardant coatings for ancient wooden architectures," Journal of Applied Polymer Science, vol. 138, no. 27, Jul. 2021, doi: 10.1002/app.50649.

[4] Y.-J. Wan, X.-M. Li, P.-L. Zhu, R. Sun, C.-P. Wong, W.-H. Liao, Lightweight, flexible MXene/polymer film with simultaneously excellent mechanical property and high-performance electromagnetic interference shielding, Compos. A Appl. Sci. Manuf. 130 (2020) 105764.

[5] K. Zukiene, G. Monastyreckis, S. Kilikevicius, M. Procházka, M. Micusik, M. Omastová, A. Aniskevich, D. Zeleniakiene, Wettability of MXene and its interfacial adhesion with epoxy resin, Mater. Chem. Phys. 257 (2021) 123820.

[6] M.S. Carey, M. Sokol, G.R. Palmese, M.W. Barsoum, Water Transport and Thermomechanical Properties of Ti3C2T z MXene Epoxy Nanocomposites, ACS Appl. Mater. Interfaces 11 (42) (Oct. 2019) 39143–39149, https://doi.org/10.1021/acsami.9b11448.

[7] G. Monastyreckis, et al., "Strain sensing coatings for large composite structures based on 2d mxene nanoparticles," Sensors, vol. 21, no. 7, 2021, doi: 10.3390/s21072378.

[8] X. Li, M. Li, Q.i. Yang, G. Liang, Z. Huang, L. Ma, D. Wang, F. Mo, B. Dong, Q. Huang, C. Zhi, In Situ Electrochemical Synthesis of MXenes without Acid/Alkali Usage in/for an Aqueous Zinc Ion Battery, Adv. Energy Mater. 10 (36) (2020) 2001791.

[9] M. Naguib, M.W. Barsoum, Y. Gogotsi, Ten Years of Progress in the Synthesis and Development of MXenes, Adv. Mater. 33 (39) (2021) 2103393.

[10] L. Verger, C. Xu, V. Natu, H.-M. Cheng, W. Ren, M.W. Barsoum, Overview of the synthesis of MXenes and other ultrathin 2D transition metal carbides and nitrides, Curr. Opin. Solid State Mater. Sci. 23 (3) (2019) 149–163.

[11] Y.i. Wei, P. Zhang, R.A. Soomro, Q. Zhu, B. Xu, Advances in the Synthesis of 2D MXenes, Adv. Mater. 33 (39) (2021) 2103148.

[12] R. Wazalwar, M. Tripathi, A.M. Raichur, Curing Behavior and Mechanical Properties of Tetra-Functional Epoxy Reinforced with Polyethyleneimine-Functionalized MXene, ACS Applied Polymer Materials 4 (4) (Apr. 2022) 2573–2584, https://doi.org/10.1021/acsapm.1c01876.

[13] L.u. Liu, G. Ying, D. Wen, K. Zhang, C. Hu, Y. Zheng, C. Zhang, X. Wang, C. Wang, Aqueous solution-processed MXene (Ti3C2Tx) for non-hydrophilic epoxy resin-based composites with enhanced mechanical and physical properties, Mater. Des. 197 (2021) 109276.

[14] L. Liu et al., Mxene (Ti3c2tx) functionalized short carbon fibers as a cross-scale mechanical reinforcement for epoxy composites, Polymers (Basel) 13 (11) (2021), https://doi.org/10.3390/polym13111825.

[15] A. Feng, T. Hou, Z. Jia, Y. Zhang, F. Zhang, G. Wu, Preparation and characterization of epoxy resin filled with Ti3C2Tx MXene nanosheets with excellent electric conductivity, Nanomaterials 10 (1) (2020), https://doi.org/10.3390/nano10010162.

[16] R. Ding, Y. Sun, J. Lee, J.-D. Nam, J. Suhr, Enhancing interfacial properties of carbon fiber reinforced epoxy composites by grafting MXene sheets (Ti2C), Compos. B Eng. 207 (2021) 108580.

[17] C. Zhang, Y. Ma, X. Zhang, S. Abdolhosseinzadeh, H. Sheng, W. Lan, A. Pakdel, J. Heier, F. Nüesch, Two-Dimensional Transition Metal Carbides and Nitrides (MXenes): Synthesis, Properties, and Electrochemical Energy Storage Applications, Energy and Environmental Materials 3 (1) (2020) 29–55.

[18] A. Iqbal, J. Hong, T.Y. Ko, C.M. Koo, "Improving oxidation stability of 2D MXenes: synthesis, storage media, and conditions", Nano Convergence 8 (1) (2021) pp, https://doi.org/10.1186/s40580-021-00259-6.

[19] E. Lee, D.-J. Kim, Review— Recent Exploration of Two-Dimensional MXenes for Gas Sensing: From a Theoretical to an Experimental View, J. Electrochem. Soc. 167 (3) (2020) pp, https://doi.org/10.1149/2.0152003jes.

[20] X. Tang, M. Zhou, "MXene-based electromagnetic wave response", JPhys Energy 3 (4) (2021) pp, https://doi.org/10.1088/2515-7655/abf8f7.

[21] X. Wu, T. Tu, Y. Dai, P. Tang, Y.u. Zhang, Z. Deng, L. Li, H.-B. Zhang, Z.-Z. Yu, Direct Ink Writing of Highly Conductive MXene Frames for Tunable Electromagnetic Interference Shielding and Electromagnetic Wave-Induced Thermochromism, Nano-Micro Letters 13 (1) (2021), https://doi.org/10.1007/s40820-021-00665-9.

[22] A. Iqbal et al., Enhanced absorption of electromagnetic waves in Ti3C2Tx MXene films with segregated polymer inclusions, Compos. Sci. Technol. 213 (2021), https://doi.org/10.1016/j.compscitech.2021.108878.

[23] A. Tanvir, P. Sobolčiak, A. Popelka, M. Mrlik, Z. Spitalsky, M. Micusik, J. Prokes, I. Krupa, Electrically conductive, transparent polymeric nanocomposites modified by 2D Ti3C2Tx (MXene), Polymers (Basel) 11 (8) (2019) 1272.

[24] T. Tang, S. Wang, Y. Jiang, Z. Xu, Y.u. Chen, T. Peng, F. Khan, J. Feng, P. Song, Y. Zhao, Flexible and flame-retarding phosphorylated MXene/polypropylene composites for efficient electromagnetic interference shielding, J. Mater. Sci. Technol. 111 (2022) 66–75.

[25] Y. Li, D. Zhang, B. Zhou, C. He, Synergistically enhancing electromagnetic interference shielding performance and thermal conductivity of polyvinylidene fluoride-based lamellar film with MXene and graphene, Compos. A 157 (2022) (2022) 106944–106952.

[26] L.u. Liu, G. Ying, Y. Zhao, Y. Li, Y. Wu, D. Wen, M. Wu, M. Wang, Q. Zhou, X. Wang, C. Wang, Attapulgite–mxene hybrids with ti3c2tx lamellae surface modified by attapulgite as a mechanical reinforcement for epoxy composites, Polymers (Basel) 13 (11) (2021) 1820.

[27] L. Guo, Z. Zhang, M. Li, R. Kang, Y. Chen, G. Song, S.-T. Han, C.-T. Lin, N. Jiang, J. Yu, Extremely high thermal conductivity of carbon fiber/epoxy with synergistic effect of MXenes by freeze-drying, Compos. Commun. 19 (2020) 134–141.

[28] D. Wang, Y. Xin, Y. Wang, X. Li, H.u. Wu, W. Zhang, D. Yao, H. Wang, Y. Zheng, Z. He, Z. Yang, X. Lei, A general way to transform Ti3C2Tx MXene into solvent-free fluids for filler phase applications, Chem. Eng. J. 409 (2021) 128082.

[29] J. Chen, S. Wang, X. Du, Advances in Epoxy/two-dimensional Nanomaterial Composites, Cailiao Daobao/Materials Reports 35 (17) (2021) pp, https://doi.org/10.11896/cldb.20070082.

[30] J. Yu, H. Chen, H. Huang, M. Zeng, J. Qin, H. Liu, M. Ji, F. Bao, C. Zhu, J. Xu, Protein-induced decoration of applying MXene directly to UHMWPE fibers and fabrics for improved adhesion properties and electronic textiles, Compos. Sci. Technol. 218 (2022) 109158.

[31] Y.i. Hu, S. Pang, G. Yang, X. Yao, C. Li, J. Jiang, Y. Li, MXene modified carbon fiber composites with improved mechanical properties based on electrophoretic deposition, Mater. Res. Bull. 150 (2022) 111761.

[32] N. A. Che Nasir, M. S. Saharudin, W. N. Wan Jusoh, and O. S. Kooi, "Effect of Nanofillers on the Mechanical Properties of Epoxy Nanocomposites," in Advanced Structured Materials, vol. 167, 2022. doi: 10.1007/978-3-030-89988-2_15.

[33] R. Kang et al., Enhanced Thermal Conductivity of Epoxy Composites Filled with 2D Transition Metal Carbides (MXenes) with Ultralow Loading, Sci. Rep. 9 (1) (2019), https://doi.org/10.1038/s41598-019-45664-4.

[34] Y. Cao, Q. Deng, Z. Liu, D. Shen, T. Wang, Q. Huang, S. Du, N. Jiang, C.-T. Lin, J. Yu, "Enhanced thermal properties of poly(vinylidene fluoride) composites with ultrathin nanosheets of MXene", *RSC*, Advances 7 (33) (2017) 20494–20501.

[35] S. Lee, J. Kim, Incorporating MXene into boron nitride/poly(vinyl alcohol) composite films to enhance thermal andmechanical properties, Polymers (Basel) 13 (3) (2021) pp, https://doi.org/10.3390/polym13030379.

[36] L. Wang, L. Chen, P. Song, C. Liang, Y. Lu, H. Qiu, Y. Zhang, J. Kong, J. Gu, Fabrication on the annealed Ti3C2Tx MXene/Epoxy nanocomposites for electromagnetic interference shielding application, Compos. B Eng. 171 (2019) 111–118.

[37] C.B. Hatter, J. Shah, B. Anasori, Y. Gogotsi, Micromechanical response of two-dimensional transition metal carbonitride (MXene) reinforced epoxy composites, Compos. B Eng. 182 (2020) 107603.

[38] Y. Shi, C. Liu, L.u. Liu, L. Fu, B. Yu, Y. Lv, F. Yang, P. Song, Strengthening, toughing and thermally stable ultra-thin MXene nanosheets/polypropylene nanocomposites via nanoconfinement, Chem. Eng. J. 378 (2019) 122267.

[39] H. Cao, M. Escamilla, M. Anas, Z. Tan, S. Gulati, J. Yun, K.D. Arole, J.L. Lutkenhaus, M. Radovic, E.B. Pentzer, M.J. Green, Synthesis and Electronic Applications of Particle-Templated Ti3C2TzMXene-Polymer Films via Pickering Emulsion Polymerization, ACS Appl. Mater. Interfaces 13 (43) (2021) 51556–51566.

[40] M.-S. Cao, Y.-Z. Cai, P. He, J.-C. Shu, W.-Q. Cao, J. Yuan, 2D MXenes: Electromagnetic property for microwave absorption and electromagnetic interference shielding, Chem. Eng. J. 359 (2019) 1265–1302.

[41] B. Le, J. Khaliq, D. Huo, X. Teng, I. Shyha, A review on nanocomposites. Part 2: Micromachining, J. Manuf. Sci. E. T. ASME 142 (10) (Oct. 2020), https://doi.org/10.1115/1.4047138.

[42] G. Fu, D. Huo, I. Shyha, K. Pancholi, B. Alzahrani, Experimental investigation on micromachining of epoxy/graphene nano platelet nanocomposites, International Journal of Advanced Manufacturing Technology 107 (7–8) (Apr. 2020) 3169–3183, https://doi.org/10.1007/s00170-020-05190-4.