

MXene-integrated smart textiles and their applica- tions

Department of Mechanical and Materials Engineering
Bachelor's thesis

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24.06.2025
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Subject: MXenes in smart textiles

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Title: MXene-integrated smart textiles and their applications

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Number of pages: 36 pages

Date: 24.06.2025

Abstract.

The amount of wearable electronics and portable energy storage is continually increasing. Consequently, interest in MXene-integrated smart textiles and their applications is rising rapidly, though it has yet to be fully mastered. Numerous challenges remain to be addressed before the technology is ready for large-scale production. This thesis reviews the various synthesis methods for MXenes, fabrication approaches for integrating MXenes into smart textiles, and the applications that MXene-integrated smart textiles can have.

There are two main approaches for synthesising MXenes. The most commonly used top-down method involves etching precursor materials known as MAX phases to synthesise MXenes. The other approach is the bottom-up method, in which MXene is synthesised by directly growing them from precursor materials in the gaseous or vapour phase. The scalability of the synthesis process presents one of the limiting issues for large-scale production due to the usage of harsh chemicals, high energy consumption, lack of precision, long synthesis times, and low production yields. However, several methods, such as low-temperature molten salt etching (LTMS), have demonstrated significant potential for large-scale production. Chemical vapour deposition (CVD) has also yielded promising results, as it can precisely control the size and symmetry of MXenes. Yet, further research is still necessary to achieve reliable and reproducible results in large quantities. CVD is the optimal choice when a precise structure of MXene is required for its application. The desired properties for specific applications involving MXene-integrated smart textiles can be fine-tuned at every step, from selecting the MXene synthesis method to utilising the fabrication approach, thereby further enhancing the desired properties such as conductivity.

While the synthesis, fabrication approaches, and applications of MXenes in smart textiles have shown remarkable progress and results in all areas, further research is still required to tackle the challenges of durability, stability, environmental concerns, efficiency, and cost that limit the large-scale production of MXene-containing smart textiles.

This thesis compares these methods regarding process conditions and product quality. We then examine various fabrication methods for MXene-integrated smart textiles and their extensive range of applications, including energy harvesting, transfer, storage, and use in various heating, sensing, and multifunctional applications. Complete multifunctional wearable smart garments that harvest energy from the human body, store it in a supercapacitor, and utilise it in applications such as joule heating or medical sensing can be produced entirely with MXene-integrated smart textiles. The applications for this type of garment continue to expand, and the properties of MXenes make them optimal for fields such as medical applications and outerwear.

Key words: MXene, synthesis, smart textiles, 2D nanomaterials.

Table of contents

1	Introduction	4
2	Two-dimensional nanomaterials in smart textiles	6
2.1	The rise of 2D nanomaterials	6
3	Synthesis of MXenes	10
3.1	Top-down approach	11
3.1.1	HF etching	12
3.1.2	Fluoride salts/ in situ HF	12
3.1.3	Electrochemical etching	13
3.1.4	Hydrothermal/alkali etching	13
3.1.5	Molten salt etching	14
3.2	Delamination	15
3.3	Bottom-up approach	16
4	Fabrication Methods for MXene Integrated Smart Textiles	18
4.1	Coating methods	19
4.2	Printing Techniques	20
4.2.1	Screen printing and stamping	20
4.2.2	Inkjet printing	20
4.2.3	Direct ink writing	21
4.3	Electrospinning	22
4.4	Wet spinning	24
4.5	Biscrolling	24
5	Applications of MXene incorporated smart textiles	25
5.1	Thermal management and EMI	26
5.2	Energy harvesting	28
5.2.1	Photovoltaic energy harvesting	28
5.2.2	Thermoelectric energy harvesting	29
5.2.3	Piezoelectric energy harvesting	29
5.2.4	Triboelectric energy harvesting	30
5.3	Energy storage	30
5.3.1	Flexible supercapacitors	30
5.4	Wireless power transfer	31
5.5	Other uses	32
6	Conclusion and future perspectives	33
	References	35

1 Introduction

The constantly growing demand for wearable electronics in modern society drives a significant surge in the development and research towards smart textiles.¹ These types of smart textiles inherit properties which cannot be achieved with traditional fabrics or yarns.^{1,2} To attain the wanted properties from the textile, they must be integrated with materials that confer abilities for sensing, heating, or any other intended application.^{1,3,4} These are not merely conventional fabrics; they are designed to actively interact with their user and environment by incorporating advanced functionalities well beyond traditional clothing roles, such as sensing, energy harvesting, storage, thermal regulation, and energy transfer.¹ Integrating functionality directly into garments offers unique benefits, including a large surface area and close proximity to the user.⁵ As the need for more energy-efficient and wearable technology increases, so does the demand for smart textiles in the global market. It is estimated that the market cap will reach approximately \$150.189 billion by 2028.^{3,6} Smart textiles have the potential to transform a wide range of industries, including healthcare monitoring, sports performance, human-computer interaction, and even military applications.^{1,7,8}

Achieving these functionalities fundamentally requires endowing traditional textile substrates with new properties, primarily electroconductivity, as well as thermoconductive capabilities, which conventional fibres inherently lack.^{1,4} Historically, various more traditional materials have been explored for integration into textiles, including metallic wires, carbon-based materials, and conductive polymers.^{2,9} While these materials enabled initial progress, they often presented significant limitations when applied to flexible and wearable fabrics.⁹ For instance, carbon-based materials could exhibit high electrical resistance; metals might suffer from poor mechanical properties, high cost, -weight, and comfort issues, while conductive polymers could face degradation over time, negatively impacting their electrical properties, stretchability, and durability.^{1,10} A central challenge has been integrating these functional materials whilst maintaining the desired properties of textiles, such as flexibility, breathability, comfort, washability, and long-term durability in real-world use.^{1,11}

For the past twenty years, interest in 2D nanomaterials has been driven by their properties, which makes them one of the best candidates for smart textiles.^{1,12} The structure of 2D nanomaterials is only one or two atoms thick, which gives them unique properties such as high thermal and electric conductivity, thanks to the large surface area and the symmetry of the structure that 2D nanomaterials inherit. Within 2D nanomaterials, MXenes have rapidly

emerged as promising candidates for smart textile applications.^{13–16} MXenes are a large and growing family of 2D transition metal carbides, nitrides, and carbonitrides.^{17,18} MXenes were first discovered in 2011, meaning this family of materials has been studied for only a little over ten years; yet, the pace of research and discovery has been exponential.^{11,19} Usually derived from their MAX phase precursors, as-synthesised MXenes have the general formula $M_{n+1}X_nT_x$, where T_x represents various surface terminations such as -O, -OH, and -F. These surface groups are critically important, significantly influencing their properties and enabling their integration with textile fibres.²⁰ MXenes offer a unique combination of properties that often outperform or complement other 2D nanomaterials in a way that is particularly beneficial for textile integration and applications.²¹ Several key advantages make them an excellent choice for smart textiles, such as mechanical flexibility, durability, and tuneable surface chemistry.^{17,22} MXenes offer exceptional tunability throughout each step of the processing path. Each step from synthesis to fabrication of MXene-integrated smart textiles is tuneable and can amplify the desired properties from MXenes to the specific application with smart textiles.^{12,17,21} This adjustability is one of the key factors that significantly enhances the usability of MXenes in smart textiles. By selecting specific MAX phase precursors, choosing synthesis methods (e.g., low-temperature molten salt etching for scalability or CVD for precise structure control), and optimising delamination, the intrinsic properties of the MXene sheets can be tailored. Subsequently, the choice and parameters of the fabrication method used to integrate MXenes into textiles (coating thickness, chosen technique, total weight percentage(wt%) of MXenes composite composition) can further amplify or adjust properties like conductivity, mechanical strength, flexibility, and stability to meet the precise requirements of the target application.^{4,11,18,23,24}

This thesis reviews advancements in MXene-integrated smart textiles, discusses various synthesis methods for MXenes, details the various fabrication approaches used to integrate them into textile substrates, and explores the promising applications enabled by MXene infused smart textiles. Despite the remarkable progress and encouraging results achieved in these areas, significant challenges remain to be addressed before large-scale production and widespread adoption of MXene integrated smart textiles can be realised. These challenges include issues related to durability, long-term stability, environmental impact, efficiency, cost-effectiveness, and seamless integration. However, ongoing research into improved synthesis methods, protective coatings, and advanced hybrid materials is actively working to overcome these limitations.

2 Two-dimensional nanomaterials in smart textiles

2.1 The rise of 2D nanomaterials

In 2004, Konstantin Novoselov and Andre Geim at the University of Manchester successfully isolated graphene in the form of a single-atom-thick layer for the first time.¹⁹ This discovery proved the theoretical existence of graphene right that Phillip. R. Wallace theorised in 1947.⁶ Another milestone in the field of 2D nanomaterials came in 2011 when Yury Gogotsi and his team at Drexel University synthesised the first MXene by hydrofluoric acid (HF) etching of a MAX phase.¹⁸ Both discoveries had profound implications for advancing the understanding and development of 2D nanomaterials. These advancements paved the way for investigating numerous 2D nanomaterials and their potential applications.²⁵ This discovery not only validated decades of theoretical predictions but also inaugurated a new era in the study of 2D nanomaterials, motivating intensive research into other nanomaterials with unique physicochemical properties.¹⁹

Smart textiles represent a class of materials that are designed not only for traditional purposes such as comfort and aesthetics but also to perform sensing, actuation, energy harvesting, -storage and -transfer.^{5,17} The integration of 2D nanomaterials into textiles is a key strategy for achieving these advanced functions, primarily due to their exceptional mechanical, electrical, and thermal properties, combined with their nanoscale thickness and high aspect ratios.⁸ Smart textiles have been studied for multiple decades and one of the most studied materials for them are 2D nanomaterials due to their ability to provide unique properties, that are beneficial for any type of smart textile.⁶ All 2D nanomaterials inherit an ultra-thin structure that provides good mechanical-, electrical- and even some semiconductor-like properties and thanks to the small structure, they can be adapted to a wide array of substrates.²⁶

Unlike traditional conductive materials such as metals or conductive polymers, 2D nanomaterials maintain flexibility and can conform to the dynamic deformations of fabrics without compromising performance.¹ For instance, graphene offers high carrier mobility and thermal conductivity, while 2D nanomaterials such as MoS₂ provide semiconducting behaviour useful in optoelectronics.¹ However, many of these materials still face limitations in terms of processability, environmental stability, or compatibility with textile substrates.²³

MXenes, in contrast, exhibit a unique combination of properties that make them particularly well-suited for textile integration. Their high electrical conductivity, surface functionalization

capabilities, and excellent mechanical durability position them as one of the most promising materials for scalable and multifunctional smart textile applications.³

MXenes are 2D nanomaterials that consist of transition metal carbides/nitrides that have garnered significant interest for smart textile use thanks to their properties.⁵ MXenes are an excellent choice for smart textiles due to their overall properties compared to other 2D nanomaterials such as graphene and MoS₂, which can be brittle, hydrophobic and hard to fabricate to smart textiles.^{12,19} There is a wide range of applications for MXenes, and the biggest reason for this is the stability of MXenes and the material's excellent properties, mechanically, electrically, and large surface area.^{9,17} One key factor is that MXenes can be immersed in polar solvents, which makes them easier to adhere to textiles and natural fibres, which is also one of the key factors why MXenes are a good choice for smart textiles.^{4,7} MXenes are usually hydrophobic, but they can have either hydrophobic or hydrophilic properties, and depending on the application, both properties can be useful.^{1,2} In case of hydrophobic properties in MXenes it can increase the materials longevity and electrical conductivity.^{4,20} On the other hand, hydrophilic properties can be beneficial, for example, in energy storage and sensors.^{4,20}

MXenes are a family of 2D transition metal carbides, nitrides, and carbonitrides, typically derived from MAX phases by selectively etching out the A elements. General formula of MXenes are $M_{n+1}X_nT_x$, where M represents early transition metals (e.g., Ti, Zr, V, Mo), n is 1, 2, or 3, X represents carbon or nitrogen, and T_x refers to surface terminations such as -OH, -O, -F, and -Cl, which are bonded to the M atoms. MAX phases serve as the precursor materials for MXenes, sharing the same M and X components, while the A layer consists of group A elements from groups 12 to 16, most commonly from groups 13 and 14.^{25,27} These surface terminations, introduced during the etching process, play a key role in defining the properties of MXenes.⁴ They contribute to the hydrophilic nature of the material and enable further surface functionalisation, which is critical for applications involving polymer matrices, biofluids, and other materials relevant to textile and biomedical fields.¹⁸ The 2D nature of MXenes results in a high aspect ratio and large surface area, both of which are beneficial for constructing conductive networks within textiles.⁴ Their high electrical conductivity makes MXenes ideal for applications such as Joule heating, sensing, and electromagnetic shielding.^{18,25} For example, Ti₃C₂T_x MXene has shown conductivities exceeding 100 S/m, outperforming many conventional materials used in wearable electronics.^{9,8} To date, over 60 distinct MXene compositions and more than 340 MAX phases have been reported, with more than half of the MXene and MAX phase discoveries made after 2018.^{23,28}

In addition to superior conductivity, MXenes offer excellent mechanical strength and flexibility, enabling them to conform to textile substrates during bending, stretching, and washing.⁷ Their layered morphology and interlayer spacing facilitate ion intercalation, making them suitable for electrochemical energy storage and thermal management applications.⁸

MXenes exhibit hydrophilic properties due to their surface terminations, a stark contrast to graphene, which is typically hydrophobic.¹³ This allows MXene flakes to disperse easily in water-based inks and simplifies processing methods such as dip-coating, spraying, or printing onto textiles.¹ Their biocompatibility, stemming from their chemical composition and relative inertness, makes them safe for wearable devices in direct contact with skin.⁵

Recent advances in smart textiles have demonstrated the versatility of MXenes across multiple applications. In Figure 1 The most prominent applications for MXene integrated smart textiles are illustrated. MXene-based textile sensors have been developed for real-time health monitoring, including strain, pressure, temperature, and electrophysiological signals.^{7,8} These sensors exhibit high sensitivity, fast response times, and excellent durability under repeated mechanical deformation.⁶ Moreover, MXene-coated textiles have shown promise in energy storage, functioning as electrodes for flexible supercapacitors and batteries.^{14,29}

In thermal management, MXenes have proven effective in both passive photothermal and active electrothermal heating.²⁵ Their high infrared absorption and Joule heating efficiency allow for on-demand thermal regulation, which is particularly beneficial in thermotherapy garments and cold-weather wearables.^{5,8} Additionally, recent studies have explored MXenes in thermoelectric applications, converting body heat into electrical energy to power small wearable electronics. Their high electrical conductivity and tunable Seebeck coefficient through surface modification make them promising candidates for textile-based thermoelectric generators.¹

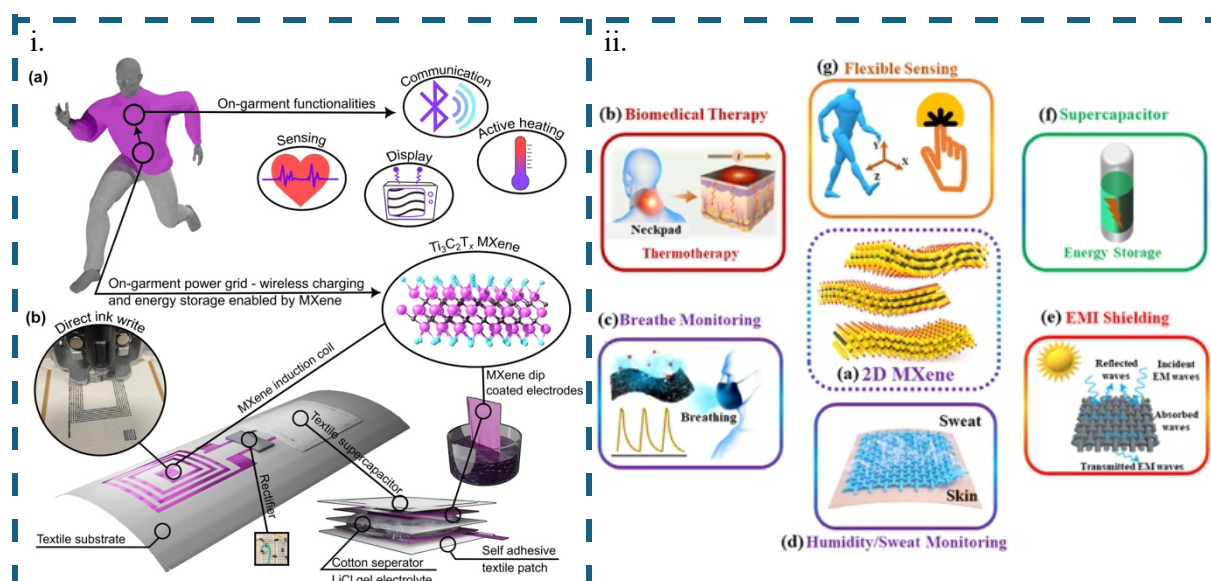


Figure 1 i. a) Illustration of possible applications for MXene integrated smart textiles. b) Illustration of an MXene-made wearable wireless power transfer coil and supercapacitor. ii. Applications for MXene smart textiles. Figure 1 from Ref ⁶, used under Commons CC-BY 4.0 license. Figure 1 ii Reprinted with permission from⁵. Copyright 2020 American Chemical Society.

Despite these promising findings, challenges remain in the widespread adoption of MXenes in commercial smart textiles.⁷ Issues such as long-term stability, synthesis scalability, and integration with diverse textile architectures still need to be addressed. However, ongoing research into protective coatings, environmentally benign synthesis methods, and hybrid materials is actively working to overcome these limitations.

MXenes represent one of the most versatile and application-rich materials among 2D nanomaterials for smart textiles. Their unique combination of processability, electrical and mechanical performance, hydrophilicity, and chemical tunability makes them well-suited for enabling next-generation wearable technologies. As fabrication methods continue to improve and integration challenges are resolved, MXene integrated textiles are expected to become important components in intelligent garments designed for healthcare, energy, and adaptive environments.

3 Synthesis of MXenes

Various synthesis methods are being developed, each affecting the structure and functional characteristics differently. Some approaches emphasise electro-/thermoconductive properties, thermoelectric, and sustainability, whereas others aim for high yield, fast processing, or tailored surface terminations. Despite their differences, all methods share a common objective: to create MXenes that exhibit preferred structural, electrical, and surface chemical properties.¹⁷

There are two different main types of synthesis that can be used to make MXenes these are Top-down approach and Bottom-up approach.

Table 1 presents a comprehensive comparison of the most prominent synthesis techniques from both main types, detailing key parameters such as advantages and disadvantages, synthesis temperature, cost, scalability, processing time, and the properties of the resulting materials.

Table 1 Properties of different synthesis methods

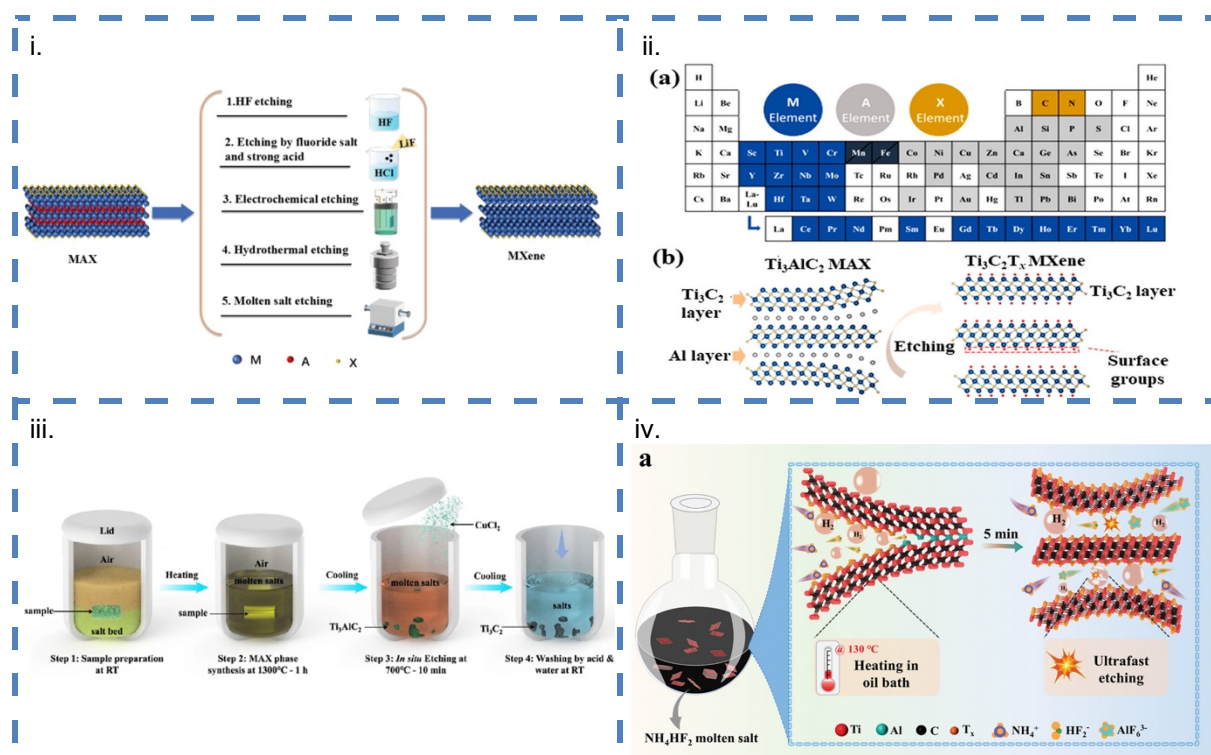
Synthesis method	Time (h)	Temperature (° C)	Scalability	Advantages	Disadvantages	Ref
HF etching	2	RT	Bad	<ul style="list-style-type: none"> • Easy setup on small scale • can produce multiple MXene variants • relatively cheap 	<ul style="list-style-type: none"> • Toxicity (use of HF) • Highly corrosive environment and working environment concerns • Over etching 	¹¹
Fluoride salts/in situ	2.3-11	RT	Ok	<ul style="list-style-type: none"> • Environmentally friendlier • Better delamination • safer alternative for HF 	<ul style="list-style-type: none"> • Impurities • Use of fluorides 	¹¹
Electrochemical	5	50	Ok	<ul style="list-style-type: none"> • Environmentally friendlier • Better control of the etching 	<ul style="list-style-type: none"> • Low efficiency • delicate process 	^{11,21}
Hydrothermal/ Alkali	24	180	Good	<ul style="list-style-type: none"> • High purity and yield • increased stability • environmentally friendlier 	<ul style="list-style-type: none"> • Oxidation during synthesis • Long synthesis time 	^{2,10,30}
Molten salt	2.3	550-800	Ok	<ul style="list-style-type: none"> • Increased conductivity • Hydrophobic properties 	<ul style="list-style-type: none"> • High energy usage • Potential use of fluorides 	^{10,11,21,23}
Low temperature molten salt	0.0833 3	130	Good	<ul style="list-style-type: none"> • Energy efficient • Hydrophobic properties 	<ul style="list-style-type: none"> • Cannot produce all MXenes • Use of fluorides 	²³
Chemical vapor deposition	2	640-975	Good	<ul style="list-style-type: none"> • Exceptional symmetry • High purity • Can produce MXenes other cant 	<ul style="list-style-type: none"> • High energy usage • Potential use of fluorides 	^{2,11,24,25}

The selection of the appropriate synthesis method is crucial, particularly for applications such as smart textiles, where the flake size, surface chemistry, conductivity, and mechanical flexibility of MXenes can significantly affect performance.⁵ All synthesis approaches mentioned in

Table 1, such as HF-based, fluoride-free, molten salt etching, or Chemical vapour deposition, can amplify distinct physical and chemical characteristics of the final product. As such, tailoring the synthesis method to the specific functional requirements of the application is a crucial step in integrating MXenes into smart textile systems

3.1 Top-down approach

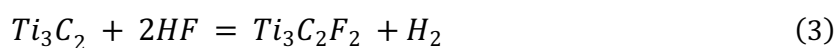
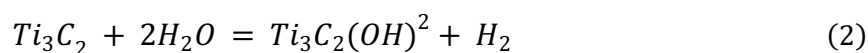
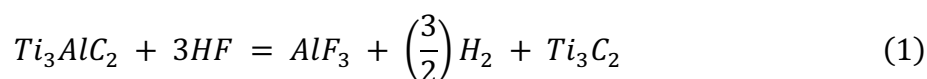
The top-down approach is the most common process for synthesizing MXenes. Top-down method produces MXenes by etching the A layer from the predecessor material MAX phase.¹¹ Depending on the differences in reactivity between the elements M and A in MAX phase, certain reagents are capable of etching A from MAX phase. Based on the type of reagent utilised and the techniques employed, these etching methods can primarily be classified into six categories: HF etching, acid and fluoride salt etching, electrochemical etching, hydrothermal etching, molten salt etching, and alkali etching. Among these, HF etching remains one of the most used yet controversial approach due to its toxicity, corrosiveness, and environmental risks.^{5,12} Due to risks with HF etching, other synthesis approaches have rapidly accelerated the exploration and development of alternative synthesis strategies aimed at mitigating these hazards while maintaining synthesis efficiency and product quality.^{2,9}



Commons CC-BY 4.0 licence, Figure 2 ii Reprinted with permission from⁵. Copyright 2020 American Chemical Society. Figure 2 iv Reprinted with permission from²³. Copyright 2020 John Wiley and Sons.

3.1.1 HF etching

The first MXene $Ti_3C_2T_x$ where synthesized in 2011 from Ti_3AlC_2 MAX-phase by hydrofluoric (HF) etching.¹⁹ and it continues to be among the most commonly employed techniques for synthesizing MXenes from their corresponding MAX phases. This method involves immersing MAX phase powders (e.g., Ti_3AlC_2) into an aqueous solution of concentrated HF, typically 5–50 wt.%, at room temperature (RT).¹⁶ The process selectively removes the A layer from the MAX structure, converting it into a 2D layered MXene material, such as $Ti_3C_2T_x$. The synthesis approach for HF etching is illustrated in equations (1) through (3). Equation (1) pertains to the etching process, equation (2) describes the hydrolysis process, and equation (3) outlines the surface fluorination process. As a result of these reactions, the MXene surface becomes terminated with a combination of $-F$, $-OH$, and $-O$ groups, forming the characteristic T_x functional groups.⁸

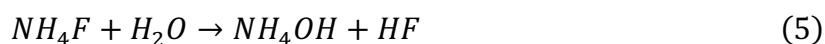


Compared to other methods, HF etching is not the most optimal synthesis method due to impurities and the risk of over etching.^{2,16} As mentioned in the Table 1 this method has high toxicity, long synthesis time, poor scalability, environmental concerns, risky working environment and cost, which can all be traced to the usage of HF its use often results in partial oxidation of the MXene surface and formation of structural defects such as pores or carbon vacancies.^{2,10} Additionally, multilayered MXenes produced via HF etching usually require further delamination to obtain single layer MXene flakes.¹⁰

3.1.2 Fluoride salts/ in situ HF

Risks with HF can be minimized by using fluoride salts that form HF in situ (equation 4), thus removing the handling step of HF from fluoride salt etching, and the chemicals that are used are relatively cheap.^{1,10,19} This approach needs a strong acid like HCl to react with a fluoride salt (e.g., LiF, NaF, KF, NH_4F , or CaF_2).^{2,5} The MXene synthesized with fluoride salt etching

gives similar results as direct HF etching, due to the synthesis processes with fluoride salt etching and HF etching being the same reaction as shown in equation (1) through equation (3) after the fluoride salt breaks down to HF in situ, which is shown in equation (4) and equation (5).^{8,10}



One of the notable benefits of in situ HF etching is the simultaneous intercalation of cations like Li^+ or NH_4^+ into the MXene interlayers during the reaction, which increases the interlayer spacing and improves delamination efficiency.^{10,11} This often leads to larger single flakes and improved dispersion stability in solution.²¹ This method is safer and produces fewer structural defects, but it still faces the same problems that necessitate similar safety precautions in waste treatment as traditional HF etching. Moreover, another downside is the etching times, which can be significantly longer compared to other approaches (2–48h).^{16,23}

3.1.3 Electrochemical etching

Electrochemical etching has emerged as a promising, fluoride-free strategy for synthesizing MXenes from their MAX phase precursors.¹¹ This method employs a controlled electrochemical cell for etching.¹¹ It offers improved environmental safety, the potential for selective surface terminations, and a scalable, energy-efficient synthesis route.²¹ The process typically involves a three-electrode electrochemical setup, where the MAX phase acts as the working electrode (anode), a platinum or graphite sheet serves as the counter electrode (cathode), and a reference electrode (e.g., Ag or AgCl) is used to monitor potential.^{10,11,21} The electrolyte is usually a chloride salt solution, such as NaCl, KCl, or NH_4Cl , chosen for its ionic conductivity and ability to complex with the A layer cations.^{19,21} During anodic polarization, the A atoms in the MAX phase are oxidized and dissolved into the electrolyte, while the M–X layers remain intact.^{10,21} One key advantage of electrochemical etching is the ability to control the lateral flake size, as it does not use strong acids.¹⁶

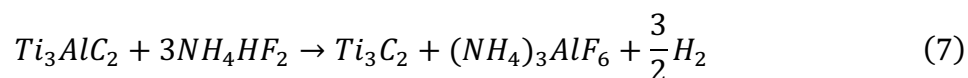
3.1.4 Hydrothermal/alkali etching

Hydrothermal/alkali etching is another fluoride free synthesis method. In a hydrothermal autoclave, MAX phase is treated with a concentrated alkali solution such as NaOH or KOH, typically at 180–270 °C for several hours.^{5,16} For instance Ti_3AlC_2 can be etched at 270 °C in 27.5 M NaOH. Under these conditions, Al is oxidized to $Al(OH)_4^-$ which dissolves, and after cooling

and washing, a Ti_3C_2 material remains.^{11,18} Hydrothermal etching tends to yield multilayer MXene with $-O/-OH$ terminations. Intercalation steps (e.g., with quaternary ammonium salts) are often required post-etch to fully delaminate the MXene.^{10,18,19} Alkali etching requires high temperature and highly concentrated base, which can also attack the MXene layers or cause oxidation.¹⁰ Indeed, a significant issue is that MXene (especially carbide MXenes like Ti_3C_2) can oxidize to TiO_2 in hot alkaline conditions, thus, careful control of temperature/time is needed.²² Additionally, residual hydroxides may adsorb on MXene surfaces, affecting purity.¹¹ Mo_2C MXenes have demonstrated improved tolerance to alkali etching (because Mo_2Ga_2C can be etched in NaOH to Mo_2C without severe oxidation).^{11,30} Alkali etching produces fluoride free MXenes, it has not yet become a widespread method due to the harsh conditions and potential for incomplete reactions.^{11,30} It is an area of ongoing research to identify conditions or catalysts that could lower the temperature required.¹¹

3.1.5 Molten salt etching

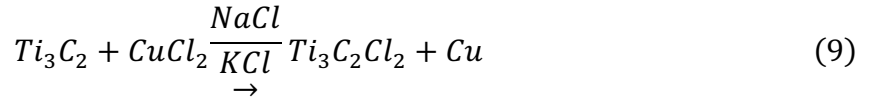
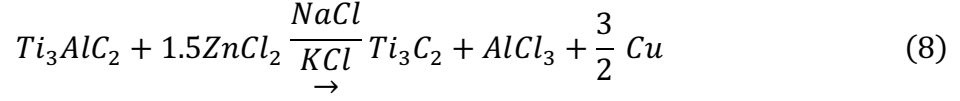
One of the most promising synthesis methods for large-scale production is low temperature molten salt (LTMS) etching, thanks to it being able to produce large amounts of MXenes in baths and only needing $130^\circ C$ and 5 minutes for the synthesis.²³ LTMS is illustrated in Figure 2. A wide array of MXenes can be synthesized with LTMS etching, which is also one of the major advantages.²³ In equation (7) MXene Ti_3C_2 is synthesized with LTMS etching from MAX phase by using NH_4HF_2 as the primary etchant.²³



The downsides of LTMS etching include the use of HF, the formation of $(NH_4)_3AlF_6$ a by-product requires thorough washing steps to remove impurities.²³ Additionally, NH_4^+ ions can intercalate into the MXene layers during the process, which might affect the final properties and may not be desirable for all applications.¹¹ Surface Termination Control: While LTMS etching consistently yields oxygen and fluorine terminations, the precise control over the ratio and type of these functional groups might be limited compared to methods using specific molten salts for targeted terminations.^{4,23}

Traditional molten salt etching approach can be a fluorine-free alternative to HF based etching approaches for MXene synthesis.³¹ This approach exploits redox-active molten salt systems to

selectively remove the A element from MAX phases and simultaneously functionalize the surface of the resulting MXene with halogen terminations scalable industrial production, making it highly attractive in the context of advanced MXene fabrication.^{11,16,31}



Molten salt etching provides precise control over selective surface terminations with elements such as –Cl, –Br, –S, –Te, or –O, depending on the halide or chalcogenide precursor employed.^{16,31} For example, etching in the presence of Li₂Te or Li₂S results in Te- or S-terminated MXenes, respectively. These tailored terminations significantly affect the MXenes electronic, catalytic, and hydrophilic properties, enabling application-specific tuning.^{11,18,31} Structurally, MXenes produced via molten salt etching often exhibit increased interlayer spacing compared to their other top-down approaches.¹⁶ This is attributed to the thermal expansion and lattice relaxation induced during the high-temperature synthesis process, as well as the size of halogen surface groups. Increased d-spacing facilitates ion intercalation and diffusion, which enhances performance in applications such as supercapacitors, batteries, and catalysis.^{11,13,18}

In terms of material quality, molten salt methods frequently yield MXene flakes with good structure and fewer defects.^{8,23} This is particularly relevant for electronic applications, where high electrical conductivity and low defect density are essential. Chlorine-terminated Ti₃C₂Cl₂, for example, has shown remarkable conductivity and chemical stability compared to –F or –OH-terminated variants.^{9,21} process (Figure 2) typically requires elevated temperatures (often 550–750 °C), which introduces concerns regarding energy consumption, equipment durability, and potential MAX phase decomposition.^{5,11,21} Moreover, salt recovery and purification remain technical bottlenecks, especially in industrial-scale processes. Incomplete removal of by-products such as residual metal particles (e.g., Zn, Cu) may necessitate additional post-processing steps using mild acids or oxidizers.^{10,16,31}

3.2 Delamination

MXenes, usually synthesized using top-down approaches, must be delaminated to get single-layer MXene flakes from the multilayered structures they usually produce.^{5,32} Sonication is the

most widely used method due to it being a fast, reliable and cost-effective approach.¹⁰ In Figure 3 is illustrated how sonication works by using ultrasonic soundwaves, which cause cavitation between the MXene flakes, thus separating the layers into individual single-layer flakes by overcoming the internal Van Der Waals forces.⁵

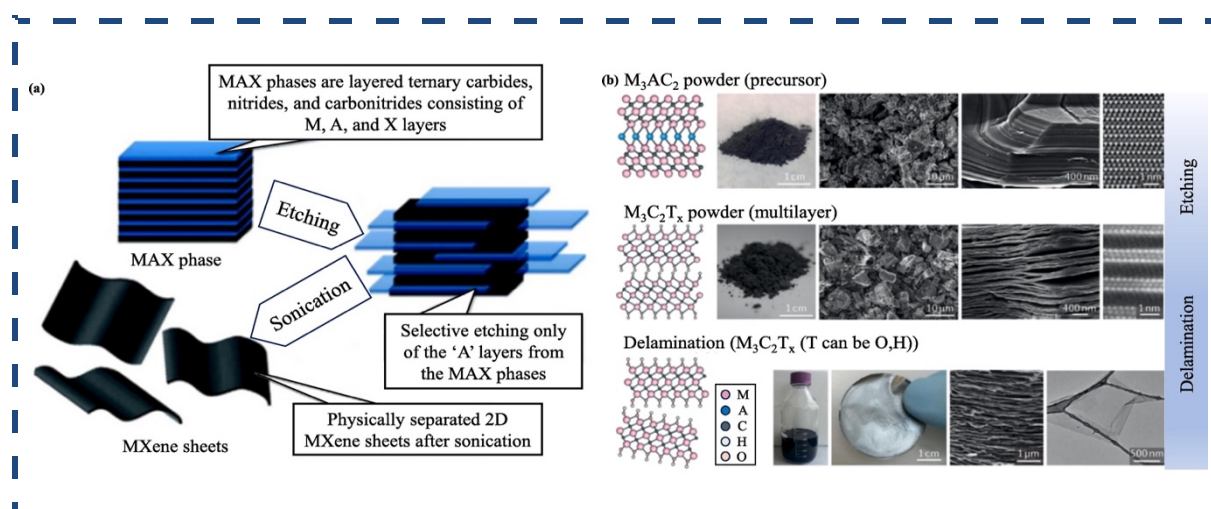


Figure 3 a) Illustration of top-down etching and delamination of MXenes with sonication. b) illustrations of the etching sonication, and pictures of the stages. Ref¹⁶ Figure 3 used under Commons CC-BY 4.0 licence

The vibration produced with ultrasound must be high enough to overcome the Van der Waals forces between the flakes. This can be achieved with a frequency between 20-40 kHz.¹⁰ Synthesis approaches, such as fluoride salt and molten salt etching, can produce LiCl and other molecules between the layers, which can help the delamination process by separating the MXene flakes in situ.^{11,23} Delamination of MXenes have also been demonstrated by immersing MXene powder into a polar organic solvent and mechanical shaking.^{4,12} Fluoride salt etching, molten salt etching, LTMS etching, and CVD have all shown results indicating in situ delamination of MXene flakes, but further research is still needed to produce more reliable delamination. Sonication is the most promising delamination approach for large-scale production.^{5,23}

3.3 Bottom-up approach

In the bottom-up approach, there is no MAX phase that the MXene would be etched out of; instead, the entire desired MXene is synthesized from self-assembled atoms that form the desired 2D nanostructure.¹⁸ The bottom-up approach produces more symmetrical and stable MXenes than most top-down methods.²⁴ Usually, bottom-up approaches are more controllable, and the produced 2D nanostructures have fewer defects and impurities than the more popular top-down approach, thanks to most of the bottom-up approaches not having as much space or

reactions to form impurities.¹¹ Chemical vapor deposition is one of the most widely used methods for producing various 2D nanomaterials, thanks to its ability to produce intricate and precise structures repeatably.⁶ CVD can synthesize MXenes that can't be produced with top-down approaches such as Ti_2CCl_2 and Ti_2NCl_2 .²⁴ Other challenging MXenes like Zr_2CCl_2 and Zr_2CBr_2 have also been synthesized with CVD.²⁴ CVD uniquely enables the growth of vertically aligned, carpet-like structures, orienting MXene sheets perpendicular to the substrate, which is difficult with top-down methods. This morphology is promising for applications requiring accessible surfaces, such as ion intercalation.²⁴

CVD presents certain limitations. The production outcome can depend on the substrate size.¹⁴ The generation of CVD-grown MXenes is influenced by complex reaction dynamics rather than simple templated growth, and controlling the flow rate of gaseous reagents significantly impacts morphology.¹¹ While offering high MXene quality without defects, synthesizing large-area single-layer nanomaterial films remains challenging.¹⁰ Despite these drawbacks, CVD gives potential results for MXene synthesis. The synthesis of Ti_2NCl_2 MXene, which is challenging to achieve via traditional etching due to its lower stability with HF etching, has been demonstrated using CVD.¹¹ The scalability of CVD for large-scale applications is supported by its established use in producing large-area 2d materials, such as graphene, where roll-to-roll processes have yielded large batches (e.g., 0.7 m x 500 m) and significant annual production capacities (e.g., 20,000 m²).⁶ While applying these scaling successes directly to all MXene CVD processes requires further research, the foundation for large-scale production appears feasible.

4 Fabrication Methods for MXene Integrated Smart Textiles

The primary purpose of every fabrication method mentioned is to incorporate MXenes into smart textiles, but choosing the proper fabrication method for MXene integrated smart textile is the most crucial part of the production right after the synthesis due to it being able to amplify or adjust the wanted properties of MXenes such as physical structure, conductivity, stability, mechanical -, hydrophilic - and hydrophobic properties, which all can be adjusted to meet the needed properties for each application.^{4,5,7} Each fabrication technique offers distinct advantages and challenges concerning scalability, uniformity, and the properties of the MXene-textile. Optimizing these methods is crucial for developing practical smart textile applications.^{1,3,13} Table 2 lists all mentioned fabrication methods and the properties they inherit.

Table 2. Properties of the fabrication approaches

Fabrication approach	Scalability	Price	Amplified properties from method	Conductivity	Advantages	disadvantages	wt%	ref
Dip/spray coating	Good	Low	<ul style="list-style-type: none"> Conductivity can be tuned with increasing layers Increased mechanical properties Hydrophilicity 	670 S/cm	<ul style="list-style-type: none"> Repeatable Reliable results Simple production equipment Can be used with many fabrics/fibers 	<ul style="list-style-type: none"> uneven thickness, rough surface, slow due to multiple coating cycles, weak stability 	77	^{7,17}
Screen printing	Good	Low	<ul style="list-style-type: none"> increased conductivity flexibility Tuneable conductivity 	15100 S/cm	<ul style="list-style-type: none"> fast, easily repeatable Simple setup Fast 	<ul style="list-style-type: none"> use of large quantities of ink Lack of preciseness 	70	^{3,17,29}
Electro-spinning	bad	Low	<ul style="list-style-type: none"> hydrophobic/hydrophilic increased stability mechanical properties 	1195 S/cm	<ul style="list-style-type: none"> Fast Good conductivity even with low wt% Fine fibers 	<ul style="list-style-type: none"> uneven dispersion, high energy consumption 	90	⁷
Wet spinning	Good	Low	<ul style="list-style-type: none"> Similar properties gained with electro-spinning High conductivity 	7750 S/cm	<ul style="list-style-type: none"> easily repeatable, even dispersion of MXenes, 	<ul style="list-style-type: none"> slow proses, high precision is needed, 	88	⁷
Biscrolling	Bad	High	<ul style="list-style-type: none"> increased mechanical strength Electrochemical properties Increased stability 	270 S/m	<ul style="list-style-type: none"> even disruption of MXene, high wt%, 	<ul style="list-style-type: none"> short yarn length, potential health risks, limited host materials, 	98	^{2,7}
Direct ink writing	Good	High	<ul style="list-style-type: none"> increased conductivity Mechanical properties 	5323 S/cm	<ul style="list-style-type: none"> High resolution patterns, simple setup 	<ul style="list-style-type: none"> Don't work with all textiles slow process 	5	^{1,2,29}
Inkjet printing	Good	Low	<ul style="list-style-type: none"> Hydrophilicity Mechanical properties High-resolution patterns 	6900 S/cm	<ul style="list-style-type: none"> sustainable Fast and simple setup 	<ul style="list-style-type: none"> Clogging Low wt% 	10-30	^{21,26,33}
Stamping	Good	Low	<ul style="list-style-type: none"> Increased conductivity 	-	<ul style="list-style-type: none"> Fast and simple sustainable 	<ul style="list-style-type: none"> Lack of persistence 	24	^{16,17}

4.1 Coating methods

All coating approaches are good for large-scale production, but they have limited uses due to a lack of precision, because the MXene immersed solution cannot form complex patterns or shapes. In both dip- and spray coating MXene solution, which contains solvent, MXene flakes, and binding material.

Both Dip – and spray coating approaches are illustrated in Figure 3. In Table 2, dip coating is a good choice for large-area fabrics; however, the dispersion of MXenes is not as precise as with other methods. With dip coating, the fabric is immersed in the MXene solution and remains in the solution to ensure an even immersion of the MXene substrate.^{1,13} After the fabric is removed, excess liquid is drained, and the solvent is evaporated, typically via air drying or in a low-temperature oven (below 80°C to prevent substrate burning or MXene oxidation).^{4,5} The coating procedure can be repeated multiple times to achieve the desired MXene concentration on the substrate, thereby enhancing the desired properties.¹ Dip coating is particularly well-suited for large-area fabrics. For instance, pristine cellulose yarns have been coated with $Ti_3C_2T_x$ MXene, achieving a high MXene loading of 77wt%.¹³ This method has shown good MXene adhesion to cotton yarns, maintaining conductivity even after extensive washing. Similarly, cotton, linen, bamboo, silver-coated nylon, polyamide, PET, and carbon-based fabrics have been successfully coated using dip coating.^{4,5,8} Furthermore, dip coating has also been employed to layer other materials with MXenes, such as silver nanowires and polydopamine, to functionalise textiles for electrothermal applications.⁸ Layer-by-layer (LBL) assembly using sequential dip coating in solutions like PEI (polyethyleneimine) and MXene has been utilised to create conductive and stable coatings on cotton fabrics, enhancing properties such as EMI shielding and photothermal activity.¹³

The downsides of dip coating are a lack of precision and uniformity.⁴ The smoothness or roughness of the textile surface, as well as the uniformity of the applied conductive layers, can be inconsistent, resulting in variations in electrical resistance.¹⁷ Controlling the thickness of the coated layers can be challenging due to factors such as surface morphology, textile substrate tension, and processing parameters such as immersion time, temperature, withdrawal speed, and the concentration and composition of MXene dispersion.¹

With spray coating aerosolized MXene solution is sprayed onto textiles, allowing for controlled deposition by adjusting the nozzle size, pressure, and distance. This method is suitable for large-area applications.^{4,6} Spray coating can produce more evenly coated textiles compared to dip coating; however, the size and uniformity of the droplets are crucial for achieving a homogeneous surface.¹³ This technique is also suitable for large-area applications.

Coating methods provide a cost-effective and easily scalable approach to fabricating MXene-integrated smart textiles.¹ These methods can coat a wide range of yarns, fabrics, and fibres. However, all coating approaches have limited applications due to a lack of precision, due to MXene immersed solution is unable to form complex patterns or shapes.³

4.2 Printing Techniques

4.2.1 Screen printing and stamping

Another common fabrication method is screen printing, where MXene ink is pushed through a patterned screen stencil with a squeegee onto the textile substrate, illustrated in Figure 4. A wide array of synthetic and natural textiles can be used, but with screen printing, the surface or substrate must be even and held flat to ensure proper binding. Often, a polymer binder is added to the ink to improve adhesion. After printing, the fabric is dried at RT, leaving the printed MXene pattern. Screen printing is attractive for mass production as it can rapidly produce repeated patterns, such as printing circuits onto a roll of fabric, while still providing the desired properties with the minor downsides mentioned in Table 2.

Stamping is not the most advanced technique. It is easily repeatable due to having a solid mould of the desired pattern or structure. Stamping is inexpensive because of its simple process and quick fabrication time. Additionally, it is easily scalable and suitable for large-scale production, and it can be used with almost all types of textiles. The disadvantages of stamping are the same than with screen printing, including a lack of persistency.

4.2.2 Inkjet printing

One of the most popular and promising approaches is inkjet printing.³³ In this method, MXene ink is loaded into an inkjet print head, which deposits tiny droplets in a desired pattern based on digital designs.^{6,33} The process is non-contact and maskless, meaning it does not require a physical stencil like screen printing, and the print head does not touch the substrate. The pattern is controlled digitally via digital design, allowing for easy customisation and ease of large-scale

manufacturing, as there is no need to change the entire fabrication assembly.^{6,17} By adjusting the MXene flake size and ink rheology, inkjet printing can achieve finer resolution patterns than other printing methods.^{17,29} MXene-based inks for inkjet printing must possess specific rheological properties to ensure successful printing, including good dispersion of MXene nanosheets in the solvent, low viscosity, reliable jetting without clogging the nozzle, the ability to consistently form droplets and appropriate surface tension to effectively wet the textile substrate.⁶ Inkjet printing is a cost-effective and scalable approach suitable for industrial-scale production.³³ The process is fast and efficient, minimizing material waste.^{4,17} The precision of inkjet printing allows for high-resolution patterning and the creation of intricate designs, enabling high conductivity, as shown in Table 2 the integration of multiple functionalities into a single textile.^{4,9,23,33} Inkjet printing is compatible with various textile substrates.²⁹

However, inkjet printing onto textiles also presents certain challenges. Formulating MXene inks with the precise low viscosity, surface tension, and stable dispersion required for reliable jetting can be difficult.^{14,17} Achieving uniform deposition and pattern fidelity on the inherently rough and porous surfaces of textiles poses challenges.⁶ While an interface layer can potentially smooth the textile surface, this might compromise the fabric's native elasticity and feel.^{17,33} The technical specifications and capabilities of the printing equipment influence the overall quality and complexity of the printed structures.^{3,17} Additionally, despite advancements in developing stable MXene inks, MXene smart textiles can still tend to aggregate, and oxidation remains a concern that must be carefully managed through ink formulation and processing strategies.^{4,13}

4.2.3 Direct ink writing

Direct Ink Writing (DIW) enables the fabrication of high-resolution structures with enhanced conductivity, mechanical strength, and stability.^{3,10} DIW extrudes MXene ink through a nozzle onto textile substrates using patterns from the programmed digital design.¹ For successful DIW fabrication, MXene ink formulation requires high viscosity at low shear rates, significant shear thinning at high shear rates, and a gel-like structure under low strain.²⁹ These properties are needed for the MXene ink to flow readily through the printing needle under high shear forces experienced during extrusion, while enabling the deposited material to retain its printed geometry on the textile surface without spreading under low shear conditions.²⁹ After printing, the textile is dried at RT.

One key advantage of DIW in MXene-integrated smart textiles is the ability to produce intricate patterns that enable specific properties mentioned in Table 2, such as electronic functionalities within the textile structure.¹⁴ DIW is generally slower than alternative approaches such as screen printing or inkjet printing.²⁹ Moreover, achieving consistent deposition quality can be challenging, particularly on textiles with inherent surface roughness or complex textures, potentially leading to printing defects such as short or open traces in the conductive paths.²⁹ Despite these limitations, DIW is ideal for fast prototyping. Design modifications can be implemented quickly and easily simply by altering software parameters, unlike screen printing or stamping, which require the production of physical screens or moulds.¹⁷

Screen printing and stamping are generally favoured for high-speed, large-scale production of repeated patterns.²⁶ DIW is ideal for printing high-viscosity inks, building thicker layers, and creating complex structures, offering rapid prototyping through software adjustments like inkjet printing, but it is typically a slower deposition process than inkjet printing.^{3,33} Inkjet printing, with its digital control, high resolution, and compatibility with low-viscosity inks, is particularly well-suited for creating complex, high-resolution patterns and for rapid prototyping on textiles, where material precision is key.^{6,17} In all these techniques, ensuring the MXene adheres through drying.²⁹ Even so, the electrical performance is impressive. MXene printed patterns maintain conductivity even when the fabric is bent or crumpled, due to the flake network's flexibility.¹⁷ Patterns of MXenes fabricated with printing approaches can be used for sensors, heating elements, and wireless power transfer (WPT) coil printing.^{7,8,29}

4.3 Electrospinning

One of the most popular methods for fabricating MXene or other 2D nanomaterials incorporated yarns is electrospinning.⁷ The process for electrospinning illustrated in Figure 4 consists of a syringe filled with a polymer solution containing dispersed MXene flakes, a positively charged needle tip connected to the syringe, a high-voltage power supply, and a metallic grounded plate, cylinder, or a ground bath.⁷ In Figure 4 electrospinning setup is depicted, the syringe needle tip is positively charged with a high voltage, which causes a strong electric field between the needle and the ground, that makes MXene fibers dispersed within the polymer solution to overcome the surface tension causing a polymer jet to eject from the positively charged needle tip toward the negatively charged metallic plate, cylinder or bath.^{1,4} 90 wt% of MXene can be achieved by using the bath electrospinning method, which uses a liquid ground bath as opposed to a traditional plate or cylinder.² Electrospinning produce extremely thin

continuous fibers, that can be spun to yarns that can have many advantages due to the use of polymers combined with MXenes, which increases the desired properties of MXenes, such as hydrophobicity, which leads to greater electrical conductivity, efficiency, stability, and overall mechanical properties of the yarn.² MXene integrated yarn fabricated by electrospinning is versatile and can be used in a wide range of applications.⁷

One of the most significant downsides of electrospinning is the uneven thickness and dispersion of MXenes in the yarn. MXenes have high electrical conductivity, which can cause them to cluster within the polymer solution, leading to an uneven distribution of MXenes dispensed from the needle tip.⁴ Additionally, the high conductivity of MXenes can result in needle blockages and short circuits during fabrication.^{17,22,32} The difficulties with getting high wt% of MXenes in the yarn is not the biggest problem, due to even 1wt% MXene-containing yarn fabricated with electrospinning having good electrical conductivity thanks to the increased hydrophobicity.²⁰

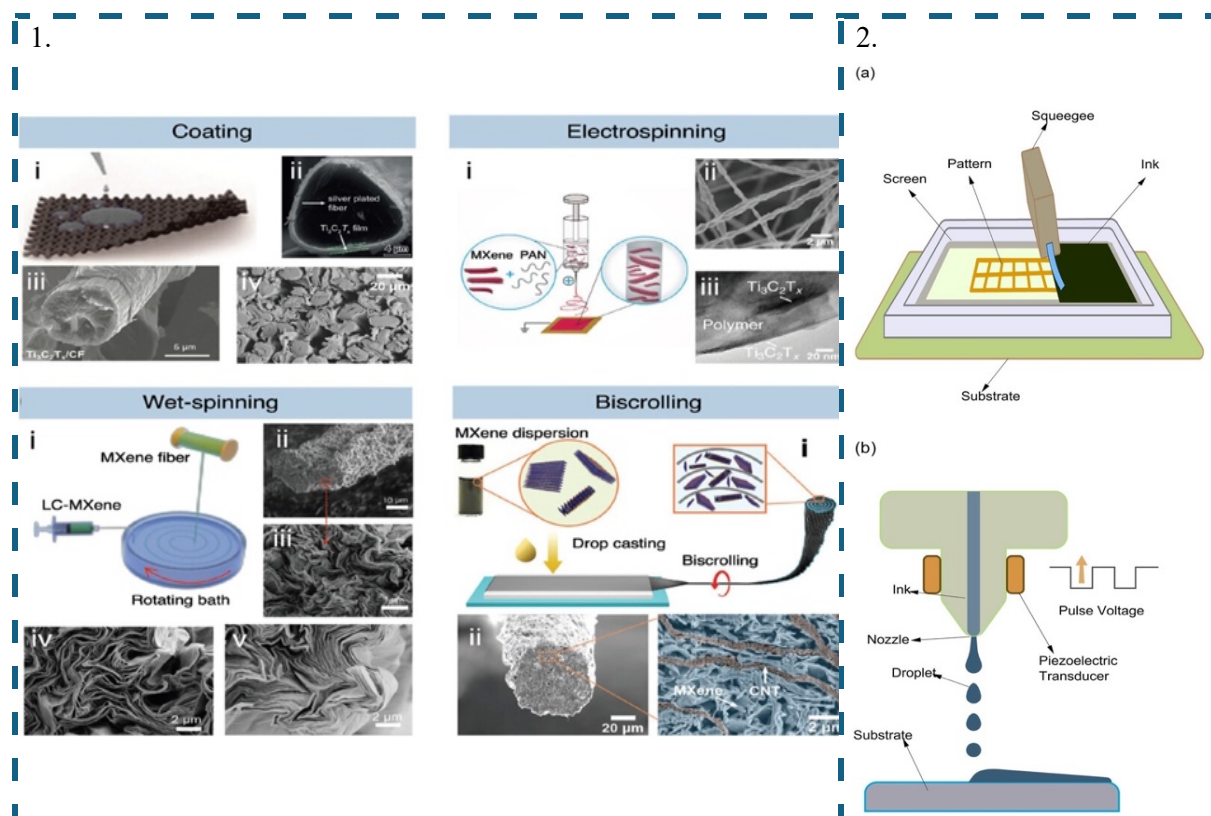


Figure 4. 1. Illustrations of fabrication methods: coating, electrospinning, wet-spinning, and Biscrolling and the resulting yarns/fabrics. 2. (a) Illustration of screen-printing setup (b) Illustration of inkjet printing. Ref⁶ Figure 4 used under Commons CC-BY 4.0 licence

4.4 Wet spinning

Wet spinning can continuously produce yarns with a wide array of 2D nanomaterials, amplifying the interest in using them for the fabrication of MXene integrated smart textiles.¹ To produce MXene containing yarn with wet spinning, MXene containing spinning solution is extruded through a needle into a coagulation bath, transforming the spinning solution into a fibre, which is then collected onto a spool.^{2,7} Figure 4 illustrates the wet spinning setup. One significant advantage of employing wet spinning to integrate MXene into textiles is its remarkable dispersibility in various polar solvents.^{4,7,32} This property enables the integration of MXene with a diverse range of spinnable materials, including polycaprolactone (PCL), polyurethane (PU), and graphene oxide (GO).⁴ The incorporation of these materials significantly enhances the processability of MXene for producing continuous fibres, making wet spinning easily scalable. However, producing high wt% MXene fibres through wet spinning is challenging due to the weak internal contact forces between the MXene sheets.² For the process to be effective, the MXene flakes need to be precisely shaped and sized.^{2,10} It has still been achieved by producing 100 wt% MXene yarn, which exhibits exceptional properties such as high conductivity, as mentioned in Table 2.⁵

4.5 Biscrolling

Biscrolling, illustrated in Figure 4, is an unconventional fabrication method that can produce yarn from 2D nanomaterials that generally cannot be spun into yarn by themselves.⁷ One of the 2D nanomaterials that cannot be spun to yarn by themselves are MXenes due to the weak internal bonds between the flakes, but with Biscrolling, they can be embedded with carbon nanotube (CNT) sheet and by spinning them together in a vertical way, producing helical structured yarn that has through the whole structure even dispersion of MXenes.⁷ Before spinning, the CNT sheet must be coated with a layer of MXene, and for this, any of the liquid phase coating or in situ growth coating can be used. Yarn produced with this method can consist of 98 wt% in MXenes, thanks to not having any other auxiliary material present.³² Table 2 shows properties of biscrolling yarn such as extraordinary mechanical and electrical properties thanks to the helical structure and even dispersion of MXenes in the structure.⁴

Downsides of this method are the limited length that can be produced, high production cost due to multiple steps in the process, use of CNT, that can inherit health risks and environmental concerns.

5 Applications of MXene incorporated smart textiles

The incorporation of MXenes in smart textiles facilitates a wide range of applications that have previously been unattainable with conventional materials due to their properties such as high electrical conductivity, hydrophilicity, chemical stability, mechanical properties, large surface area, tuneable surface reactants, low price and ease of integration functionalities positions MXene integrated smart textiles for impact across numerous fields.^{1,2} Table 3 highlights the most discussed applications currently. As shown in Figure 5, complete smart textile systems can be built with MXenes that provide the power from energy harvesting unit or WPT receiver coil fabricated from MXene ink by printing, storing it in flexible supercapacitor and using the power for the wanted application such as sensing or heating.^{5,9,29}

Table 3 Applications of MXene integrated smart textiles

Application	Synthesis	Fabrication	Outcomes	Ref
Joule heater	All approaches	Wet spinning Electrospinning All coating methods	<ul style="list-style-type: none"> 65.9°C at 2.0 V 	32
Wireless power transfer receiver coil	All top-down methods	Inkjet printing DIW	<ul style="list-style-type: none"> efficiency of 10% 	26,29
Breath sensor	All fluoride-free approaches	Inkjet printing All coating methods	<ul style="list-style-type: none"> cost-effective, reliable lasting 1000 cycles 	9,32
EMI shield	All coating methods	All approaches	<ul style="list-style-type: none"> up to 108 dB 	7,8,10,32
Flexible supercapacitor	All methods	All approaches	<ul style="list-style-type: none"> up to 50000 lifecycle 3188 mF/cm² 	5,7,14,17,29
Strain/pressure sensor	All approaches	All coating methods Electrospinning Wet spinning DIW Inkjet printing	<ul style="list-style-type: none"> Response in milliseconds High accuracy 	9,2,5,3
Wearable antibacterial textile	All fluoride-free approaches	Coating Methods Electrospinning	<ul style="list-style-type: none"> up to 99% antibacterial 	4
Energy harvesting textiles	all approaches	All approaches	<ul style="list-style-type: none"> Peak output of 1087.6 mWm² 	2,6,9,34

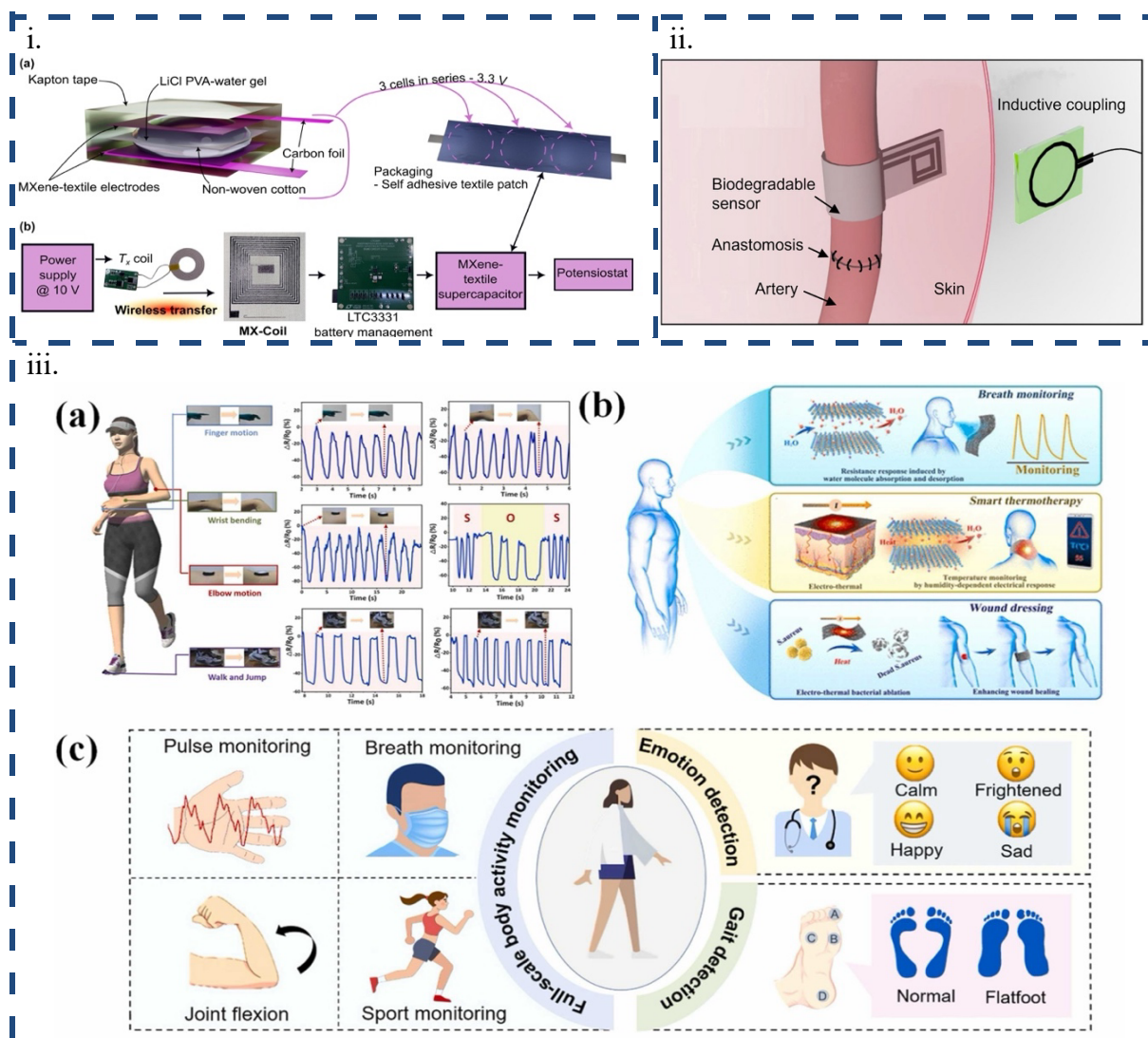


Figure 5 i. MXene flexible supercapacitor and WPT receiver coil ii. WPT coil made with MXenes demonstration of transferring energy to an internal medical device iii. (a) MXene pressure sensor measuring human motion(b), MXene smart textile medical applications (c), Possible fields for multifunctional sensing in smart textiles. Figure 5. I. From Ref ⁶, used under Commons CC-BY 4.0 license. ii. Reprinted with permission from Ref ²⁶ Copyright 2023 Elsevier. iii. Reprinted with permission from Ref ³ Copyright 2025 Elsevier.

5.1 Thermal management and EMI

Thermal management and electromagnetic interference (EMI) shielding are two of the most talked-about applications for MXene-integrated smart textiles. ^{7,32} These applications are often discussed in conjunction due to similarities in the approaches to incorporating MXenes into textile structures and the functional requirements, such as needing the active material to cover substantial areas of the fabric for effective performance. ¹³ There are active and passive thermal regulation approaches, and thanks to the properties of MXenes, they both can be used in the same smart textile platform. ¹

In active thermal management, a heating source is always present, allowing the temperature to be raised back to the desired levels.⁸ MXenes can be used as Joule heaters and piezoelectric heaters.^{5,8} MXenes have demonstrated exceptional performance in joule heating applications shown in Figure 5, with their mechanical durability, low power consumption, and efficient heat production.^{8,10} Joule heating occurs when an electric current flows through a material with electrical resistance, converting electrical energy into heat.^{8,21} As shown in Table 2, MXenes exhibit excellent electrical conductivity, making them highly suitable for efficient Joule heating, for example, wet spinning with MXenes achieving 7750 S/cm.^{1,5} The electrical performance, including conductivity, can be maintained even under mechanical deformation.¹³ For human-centric applications, MXene-based textiles have shown promising results at low voltages and temperatures relevant for personal comfort or thermotherapy.^{4,8} For instance, MXene integrated textiles have been displayed to have strong electrothermal activity by generating temperatures of 28–116 °C at 1–8 V.^{8,13,25}

Passive thermal management relies solely on the user's body heat and the ambient environment to maintain temperature stability.¹ This typically involves techniques to minimize heat loss from the body.⁸ Textiles play a vital role in trapping body heat. MXenes, due to their good electrical and thermal conductivity, can serve as a passive heating component by absorbing and retaining heat from the body or the environment.⁸ When incorporated into textiles, they can help store and radiate heat back towards the wearer, contributing to temperature regulation.⁸ In passive heating, MXene strong photothermal conversion and heat retention properties help regulate body temperature by harnessing ambient energy.^{13,22} Under simulated sunlight MXene integrated smart textile raised its surface temperature by 15 °C in 30 minutes, illustrating how MXene layers absorb and convert solar radiation to warmth.^{3,16,25} MXenes high thermal/electrical conductivity also enables efficient distribution of the wearer's body heat, preventing local cold spots and maintaining comfort.^{1,10}

In addition to thermal management, EMI shielding with MXene-integrated smart textiles has shown promising results, as listed in Table 3, having demonstrated multiple times by repeatedly achieving shielding capabilities of up to 90 dB at a 1.3 mm layer thickness.^{2,5,7} Even higher performance, of up to 108 dB, can be achieved when using silver nanowires with MXenes.^{5,18} Electromagnetic interference (EMI) shielding is essential for protecting electronics and users from unwanted radiation, primarily by reflecting or absorbing electromagnetic waves.^{1,4,21} As indicated in Table 3, properties such as high electrical conductivity are crucial for achieving effective reflection and adsorption.⁵ MXenes excel due to their conductivity and 2D structure,

facilitating reflection and absorption.^{5,8,10,13} Examples include PPy/MXene on PET textiles that display high dB values, and MXene/AgNW composites showing enhanced performance.^{7,8,10,18} Multifunctional smart clothing has been demonstrated where EMI shielding and Joule heating are combined.^{1,9} For instance, a MXene-integrated synthetic leather exhibited ~ 30 dB EMI shielding while providing Joule heating for cold protection and even flame retardancy for aerospace garments.¹⁰

In summary, MXenes equip textiles with an exceptional blend of thermal management (heating and heat dissipation) and EMI shielding, improving wearer comfort and safety in environments ranging from daily urban life to extreme conditions.^{7,18}

5.2 Energy harvesting

With the smart textile applications, one of the most interest gained applications is energy harvesting.⁶ There are several types of energy harvesting in smart textiles and the most promising and talked about ones are photovoltaic-, thermoelectric-, piezoelectric- and triboelectric energy harvesting types, due to their ability to be adapted and used in wearable smart textiles. Mentioned energy harvesting methods are illustrated in Figure 6.

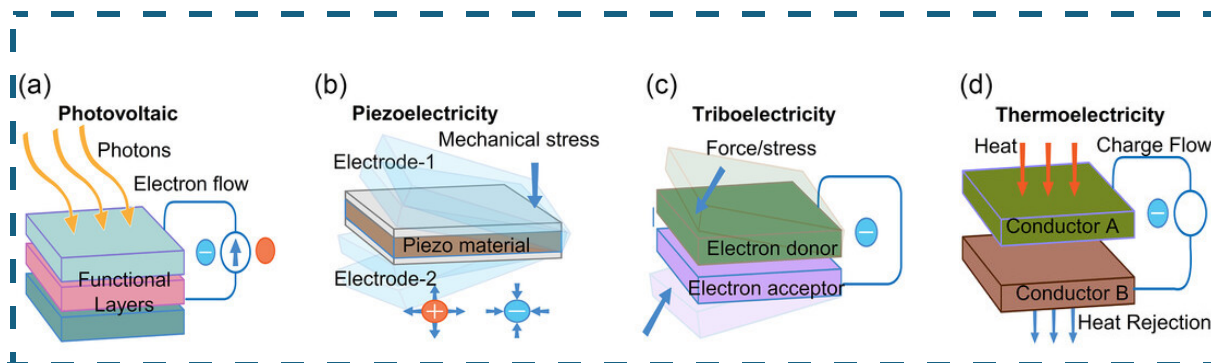


Figure 6 Illustrations of different types of energy harvesting (a) Photovoltaic energy harvesting (b) Piezoelectric energy harvesting (c) triboelectric energy harvesting (d) Thermoelectric energy harvesting From Ref⁶, Figure 6 used under Commons CC-BY 4.0 license.

The properties of MXenes, such as high conductivity, surface reactant tunability, and especially flexibility, make them a good choice for energy harvesting compared to other 2D nanomaterials, such as Mo_2C , which lacks the mechanical properties, such as flexibility, needed in wearable smart textiles.^{5,7,13,17}

5.2.1 Photovoltaic energy harvesting

Photovoltaic devices demonstrate significant potential because they can be fabricated using screen printing, inkjet printing, and other straightforward, repeatable fabrication approaches.

^{6,18} Photovoltaic energy harvesting converts solar energy directly to electricity, making it a versatile energy source for multiple textiles. However, the need for sunlight limits their use because they only work with constant light. ²⁹ Currents of 1–25 mA/cm² have been reported. ²⁹ High efficiency (17.2%) large-area flexible chalcogenide solar cells have the potential to be used in cellulose-based fabrics. ¹⁴ MXenes used as the main material for the photovoltaic energy harvesting has not been studied properly yet, thus further studies are needed to produce working and efficient photovoltaic energy harvesting textile.¹

The downsides of the photovoltaic approach are linked to stability, the difficulties of keeping the coating evenly distributed, and low output voltage.⁶

5.2.2 Thermoelectric energy harvesting

Thermoelectric (TE) energy harvesting works by utilising the heat from the human body and the ambient temperature to produce electricity from the temperature differences with the Seebeck effect. ¹⁶ Even with TE nanogenerators made with MXenes have lower energy output compared to other harvesting approaches they have shown great results in providing constant power output, which could be potentially used for powering small electronics such as medical devices or wearable sensors with low power usage or for partially charging partially wearable energy storage such as supercapacitors. ⁶ Energy output from all MXene made flexible TE nanogenerator constructed with 20 p-n units fabricated from n-type Mo₂Ti₂C₂T_x and p-type Nb₂CT_x using Ti₂C₂T_x as a contact electrode gave at RT outputs as high as 35.3 mV and 33.9 nW.¹⁶

5.2.3 Piezoelectric energy harvesting

Piezoelectric energy harvesting capitalizes on the mechanical energy from human motion. ^{3,6} Incorporating MXene into piezoelectric nanogenerators (PENGs) has enhanced their sensitivity to mechanical pressure, converting biomechanical energy into electricity. ^{6,13} PENG devices where MXene serves as the primary active material responsible for the piezoelectric effect, or where its enhancement is directly quantified with output results, remain under development. Therefore, while promising, tangible results are not yet available. ⁶ Other 2D nanomaterials in PENGs have demonstrated encouraging outcomes. ⁶ For example, a flexible PENG integrated into shoes using MoS₂ monolayers and hollow MoS₂ nanoflakes achieved a maximum output voltage of 18 V and a power density of 1.62 mW/m² during walking. ^{1,6} Although MXenes show potential in enhancing piezoelectric materials and contributing to mechanical energy harvesting textiles, further research into MXene-based PENGs is essential.^{9,21}

5.2.4 Triboelectric energy harvesting

Triboelectric energy harvesting converts mechanical energy from human body movement into electricity through electrostatic induction by deforming the energy harvesting unit. Triboelectric nanogenerators TENGs constructed through knitting and double-sided coating fabrication processes involving MXene composites provide significant voltage outputs.² TENG systems typically generate low currents; their versatility and adaptability make them suitable for wearable applications.¹³ Peng et al. created triboelectric generators from biomimetic hierarchical graphene materials which were effective for enhancing both mechanical resilience and energy-conversion efficiency.¹ A TENG based on MXenes has given an promising results, achieving a peak output of 1087.6 mWm^{-2} and demonstrating the capacity to power up to 360 LEDs simultaneously.⁶ Jiang et al. integrated a TENG into an agricultural textile, coating elastic fibres with MXene ink, growing silver nanoparticles (AgNPs), and then coating with PDMS, resulting in a TENG yarn with a diameter $400 \mu\text{m}$ with excellent electrical output characteristics of 7.7 V .⁹ This TENG yarn could be integrated into agricultural textiles for protection.⁹ Salauddin et al. used fabric-assisted micropatterning on an MXene/silica gel nanocomposite surface for self-powered sensors and wearable electronic devices, demonstrating the potential for commercial-scale production of high-performance textile-assisted DSC-TENGs.^{1,9} Graphene textile-based TENGs, developed through spinning, dip coating, multiaxial winding, and machine knitting, showed outstanding properties like high flexibility and achieved a peak output of $3.6 \mu\text{W}$, A textile-based TENG incorporating BP wrapped with hydrophobic cellulose oleoyl ester nanoparticles produced a significant output voltage of up to 880 V , with a current density of $1.1 \mu\text{A cm}^{-2}$.^{3,6}

5.3 Energy storage

5.3.1 Flexible supercapacitors

Supercapacitors are gaining increasing interest due to their rapid charging times, higher energy density per area, flexibility, and environmental sustainability compared to conventional batteries. The demand for portable energy solutions has grown steadily alongside smart wearable electronics, and supercapacitors made with MXenes have demonstrated highly promising results, such as the ability to retain over 90% capacitance even after 10000 discharge cycles. Under ideal conditions, supercapacitors made with MXenes in Swagelok cell form can achieve lifecycles of up to 500000.^{5,27} All the properties concerning longevity make superconductors a

superior choice compared to conventional batteries.⁴ The capacity of supercapacitors is usually measured as either a real or volumetric capacitance. Areal capacitances as high as 3188 mF/cm² have been demonstrated with MXene supercapacitors fabricated with Biscrolling.⁴ With textile supercapacitors, it is crucial to have a large surface area combined with a relatively small volume. For this reason, MXenes are an excellent choice for the electrodes due to their large surface area to volume ratio, attributed to their inherent nanostructure. The large surface area and hydrophilic properties enhance the amount of electrolyte solution that can interact with the MXene electrode surface, thereby increasing the active area, promoting ion transport, and consequently enhancing electrochemical charge storage and capacitance.^{17,20,21,23} MXene supercapacitors can be fabricated using a variety of textile substrates such as cotton, silk, carbon-based fabrics, nylon, PET, and cellulose.^{4,5,14} All fabrication methods listed in Table 2 can be utilised to create MXene electrodes for supercapacitors.¹⁴ The choice of fabrication approach depends on whether the MXene electrodes are wanted in sheet or yarn form.^{2,5} As noted in Table 3, flexible supercapacitors can be produced using all fabrication methods with satisfactory results; however, not all of them are ready for large-scale production due to challenges with scalability, ink rheology, and stability.^{10,13} For instance, printing methods show promising outcomes for creating the electrodes for the supercapacitor, but further research is necessary to address issues related to stability and the wt% of MXenes on the electrode.^{4,5}

Supercapacitors with MXene electrodes are promising, yet research remains essential to resolve the challenges associated with the restacking of MXene flakes during use and maintaining stable electrode contacts in packaging to ensure reliability and longevity.²⁹

5.4 Wireless power transfer

MXenes are an excellent choice for applications in wireless charging and other wireless power transfer (WPT) methods in smart textiles due to their flexibility, electrical properties, and breathability.¹ WPT coils can be printed directly onto textile substrates using the direct ink writing (DIW) method and MXene ink.²⁹ WPT coils printed with DIW using MXene ink have proven to be stable, maintaining 92% of their original output power after 250 bending cycles.²⁹ During bending, the coils retained 75% efficiency at a bend diameter of 6 cm, allowing them to be positioned in various locations on the human body.^{1,29} Furthermore, the coils maintained 99% efficiency of the original energy output after a simulated washing cycle at 60°C and 360 RPM.²⁹ The flexible WPT coil significantly enhances user comfort, as traditional charging ports limit comfort and are more prone to breaking than the soft, flexible WPT coil.^{1,6,9} While

WPT coils can be fabricated using various methods, the most cost-effective and efficient approach is to employ direct ink printing.^{7,29} In the future, the wireless power transfer coil could potentially be multifunctional, accommodating applications such as heating and EMI shielding with minimal modifications.^{5,10,29} WPT coils have shown considerable promise in medical applications, and owing to the low toxicity and antibacterial properties of MXenes, they could be utilised to charge the medical device within the patient, potentially used in the device situated inside the patient (Figure 4).^{3,5,9}

5.5 Miscellaneous uses

As shown in Table 3, MXenes can be utilized for a wide range of applications. The most prominent include various sensing applications, such as in medical uses and health monitoring.¹ Another significant use case is in strain and pressure sensors in smart textiles. These sensors depend on the piezoresistive effect, whereby the electrical resistance of a conductive material changes with mechanical deformation, such as stretching or bending.⁹ They can detect strains from minor to substantial deformations and measure pressures up to 160 kPa, including low-pressure sensitivity for subtle forces like a light heart rate.^{7,9} Both sensor types function with millisecond response and recovery times, effectively monitoring human movement, such as finger bending and joint activity, while maintaining stable performance over thousands of cycles.²²

Properties such as antibacterial activity, high conductivity, hydrophilicity, low weight, flexibility, and low toxicity make MXenes an excellent choice for medical applications.⁴ The medical applications of MXene-integrated smart textiles are numerous, covering a wide array of human functions from mood monitoring to more precise medical sensing, including breath and heart rate, pulse, and pressure monitoring.¹³ MXene textile sensors can also sense temperature changes in specific areas of the body, which can assist in locating inflamed regions and thereby aiding in the diagnosis of arthritis and inflammation.^{9,13} For instance, MXene-integrated smart textiles can identify inflamed areas through heat monitoring, apply heat using joule heating, preventing further inflammation, and monitor the movement of the inflamed region to further prevent future injury thanks to its antibacterial properties and breathability.^{4,13}

6 Conclusion and future perspectives

To reach the \$150 billion market cap, issues in large-scale production must be dealt with.^{3,6} These are the scalability of the synthesis part of MXenes, efficient and scalable fabrication, and overall environmental concerns.¹⁹ The synthesis results of MXenes using top-down approach LTMS etching, and alternatively the bottom-up approach CVD show promising results with the potential to produce large amounts of MXenes reliably and in a relatively fast time frame.^{14,21,23} The most significant problems with synthesis that must be met are the use of HF, impurities formed during synthesis, uneven flake size/symmetry and the energy consumption.^{2,4,25} LTMS etching is the most promising for large-scale applications, thanks to the 5-minute synthesis time, low temperature of 130 °C and proven ability to produce large batches with a relatively simple setup.^{11,23} CVD shows promising results for large-scale synthesis for applications that need more specific MXene flake symmetry and structure.^{14,21,24} Both have still downsides, such as CVD needing high temperature and pressure during the synthesis and for LTMS producing small amount of HF during the synthesis, making the waste handling more dangerous.^{3,14,23,24}

Each fabrication technique presents unique advantages and challenges; therefore, the choice is crucial, as it can amplify or adjust the desired properties of MXenes.^{1,14,17}

Coating methods are cost-effective and can coat a wide range of fabrics and yarns, with the capability to tune conductivity by increasing layers.^{1,4,7} Dip coating has achieved a high MXene loading of 77 wt% on cellulose yarns.⁵ However, forming complex patterns and controlling layer thickness remain challenging.⁴

Printing techniques offer great precision. Screen printing and stamping are fast, repeatable, and scalable for mass production of repeated patterns, although they lack fine precision.^{3,6,17} Inkjet printing is highly promising due to its minimal material waste, non-contact and digitally controlled nature, allowing cost-effective customization and high-resolution patterning.^{17,33} DIW produces high-resolution patterns with enhanced conductivity and mechanical properties, making it ideal for rapid prototyping.^{1,29}

Electrospinning can create extremely thin, continuous fibers, achieving up to 90 wt% MXene content.⁷ Electrospinning can enhance the yarn's hydrophobicity, electrical conductivity, and mechanical properties.^{5,7} However, there are challenges with uneven dispersion due to MXene clustering and potential needle blockages.^{4,5} Wet spinning can continuously produce yarns with even dispersibility of MXenes.¹ 100 wt% MXene yarn with a conductivity of 7750 S/cm has

been made with wet spinning.⁵ However, maintaining weak internal contact forces between MXene sheets and requiring precise flake shaping remain challenges for high wt% production.⁴ Biscrolling can produce yarns with up to 98 wt% MXenes, resulting in exceptional mechanical and electrical properties.^{3,7} Downsides include limited yarn length, high production costs, and potential health risks associated with CNTs.⁷

A wide range of applications for MXene-integrated smart textiles has shown promising results, such as in thermal management, demonstrating the capability to repeatedly produce temperatures ranging from 28-116 °C at 1-8 V through Joule heating, even under mechanical deformation.^{8,16} WPT coils printed with DIW maintained 92% of their original 10% output after 250 bending cycles.^{26,29} Flexible supercapacitors produced with MXene electrodes have exhibited exceptional performance, with life cycles of up to 500000 and the ability to withstand mechanical deformation and washing.^{5,26} While energy harvesting applications such as photovoltaic, thermoelectric, piezoelectric, and triboelectric nanogenerators using MXenes remain under active development, they show significant potential for powering small wearable electronics or charging supercapacitors by converting various forms of ambient energy and human motion into electricity.^{1,6} Various textile sensors made with MXenes have demonstrated millisecond response times and the ability to detect pressure from heart rate to pressures as high as 160 kPa, maintaining stable performance for thousands of cycles.^{3,7,9}

Multifunctional MXene-integrated smart textiles have shown great promise. With further research, one smart textile can be used as a WPT receiver coil, joule heater, EMI shield, and even medical sensing with power, which could be harvested from human movement with an MXene-made energy harvester and stored in a flexible supercapacitor with MXene electrodes.^{1,7,15,29}

In conclusion, MXene-integrated smart textiles represent the cutting edge of next-generation smart textiles, thanks to their exceptional properties and outcomes across various applications. However, further research is necessary to address the challenges associated with the synthesis, fabrication, and overall stability of MXene-integrated smart textiles in order to fully unleash the potential and promote the widespread commercialization of this technology.

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