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REVIEW

MXene Fiber-based Wearable Textiles in Sensing and Energy Storage Applications

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Abstract

Currently, flexibly wearable electronics greatly facilitate our life that can collect non-electrical signals such as physiological signals or body motions and then translate them into electrical signals such as current, voltage or resistance. With the development of next-generation wearable devices, functional and intelligent textile with softness, wearability and durability has attracted widespread attention, especially for fiber-based materials that are easy to modify. MXene, as an emerging two-dimensional (2D) material with excellent electrical conductivity, biocompatibility and hydrophilicity, enables accurate sensing and energy storing of fiber-based textiles. In this review, we focus on MXene fiber-based textiles that applied in sensing and energy-storing fields. At first, we summarized the typical fiber-based functional textiles as a brief introduction. Next, to better understand the important role of MXene in fiber-based textiles, synthesis, structure and properties of MXene were reviewed. Moreover, the fabrication methods for MXene fiber-based textiles including electrospinning, wet-spinning, biscrolling, three-dimensional (3D) Printing and coating are the fundamental strategies. At last, the applications of MXene fiber-based textiles in energy storing, sensing and other fields were demonstrated, enabling more advanced and multifunctional textiles, and would be playing an important role in future wearable electronics.

Keywords Fiber · Smart textiles · MXene · Sensing · Energy storing

1 Introduction

Nowadays, highly stretchable electronics with excellent mechanical stability are widely applied in wearable fields, such as electron skin [1, 2]. In general, wearable devices need excellent skin-friendly comfort, abrasive resistance and avirulence, and ordinary fabrics that we wear daily have these above basic properties. As a result, giving common textiles intelligent features such as sensation, heating, energy storing and antibacterial property [3] is an important strategy. To achieve the above purpose, combining high-performance advanced materials such graphene [4], black phosphorus [5], metal-organic frameworks (MOFs) [6], covalent organic frameworks (COFs) [7], Graphidyne [8], carbon nanotubes [9] and MXene [10] with textiles is a conventional solution. In a broad sense, 2D layered nanomaterials usually have a longitudinal thickness less than 5 nm and a lateral dimension of about several hundred nanometers or even micrometers [11]. The novel 2D nanomaterials can be used for supercapacitors, batteries, actuators and sensors [12] because of these superior microstructures. Graphene [13], and have been discovered due to its excellent mechanical and electrical properties, so they have been widely used in various research fields.

Compared with them, MXene not only has excellent graphene-like properties but also has metal-like conductivity and high energy density [14]. Due to the few layers, small vertical size and large horizontal size, MXene has a larger specific surface area than other dimensional materials, and the large interlayer distance makes electrons confined between layers because of weak van der Waals force. As a result, the conductivity is more significant [15]. Due to the relatively dispersed connections between layers, MXene is easier to graft active functional groups on the surface of the atomic layer [16], which makes a difference in regulating the physical and chemical properties. To date, it is gradually applied in energy storing, hydrogen storage, electromagnetic shielding (EMI), sensors, and will make more contributions in the future.

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Moreover, the rise of emerging textile technologies such as electrospinning and wet-spinning methods make finer fibers and yarns possible, improving flexibility, wearability and durability, and providing us the best skin-friendly touch, leading to fabricating more and more advanced textiles. For instance, electrospinning and non-woven processing technologies create finer fibers, yarns and softer fabrics, which is more conducive to the combination with the interface of nanomaterials, enabling wearing comfort and integrating advanced information technologies. [17, 18]

Based on this, we review the recent progress of flexible MXene fiber-based textiles that was divided into four parts. As shown in Fig. 1, firstly, fiber-based functional textiles were demonstrated from fabrication to applications. The second part is the current synthesis methods and basic characterization of MXene and some samples of typical fiber-based textiles. The third part is the fabrication methods of MXene textiles from fiber, yarn, to fabric, which includes five advanced technologies that are electrospinning, [19] wet-spinning, [20–22] biscrolling, [23] 3D printing [24] and coating [25]. The fourth part is the applications of MXene fiber-based textiles, including energy storing, sensing and other applications. At last, the future of MXene fiber-based textiles were discussed. It is important to make full use of the advantages of MXene and textiles to create the next generation of intelligent fibers, yarns, and fabrics with fine sensation, self-powered capability and self-actuation, which have the potential in electric skin and robotic devices.

2 Fiber-based Multifunctional Textiles

Compared with the currently wearable electronics, textile-based devices have unique advantages, such as softness, wear resistance, comfort, and antibacterial property. However, fiber-based wearable devices often exhibit more excellent electrochemical and physical properties than textile-based devices, because the fabrication processes and steps from fiber (yarn) to fabric are controllable, [26, 27] especially providing the feasibility of introducing MXene and other intelligent materials. As shown in Fig. 2a a commercial polyester yarn was coated by Ni metal and reduced graphene oxide (rGO) as an electrically conductive layer and then coated the polyvinyl alcohol (PVA)/H_3PO_4 layer for

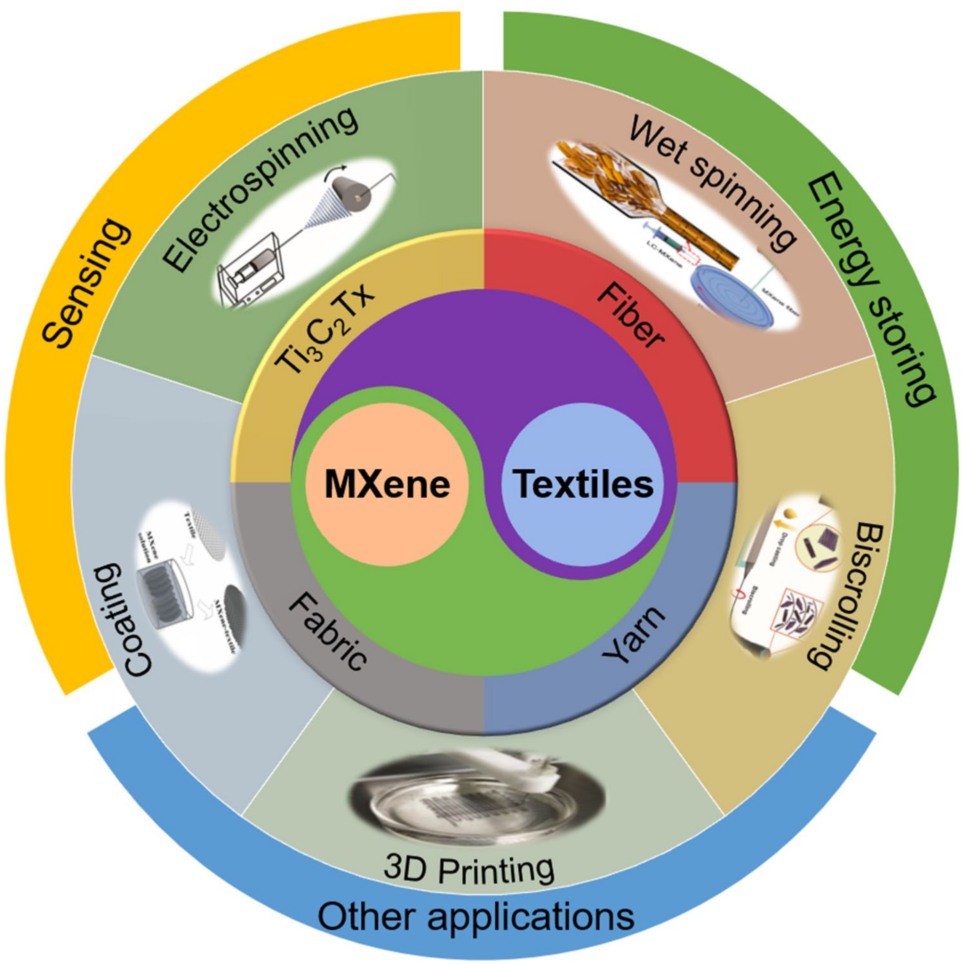

Fig. 1 MXene fiber-based wearable textiles for energy storing and sensing, and the insets are the fabrication methods: electrospinning, [19] Copyright 2019, The Royal Society of Chemistry. Wet-spinning, [20] Copyright 2020, American Chemical Society. Biscrolling, [23] Copyright 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. 3D printing, [24] Copyright 2019, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Coating, [25] Copyright 2019, The Royal Society of Chemistry

Fig. 2 Fiber-based wearable textiles. **a** A self-charging power jacket integrating the supercapacitor yarns as energy-storing fabrics, the TENG cloth as energy-harvesting fabrics, and wearable electronics (e.g., button sensors). [28] Copyright 2015, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. **b** A graphene-based fiber for sensing tensile strain, bending, and torsion. [29] Copyright 2015, WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **c** Hierarchically buckled sheath-core fibers for superelastic electronics, sensors, and muscles. [30] Copyright 2015, American Association for the Advancement of Science (AAAS). **d** 3D double-faced interlock biomotion energy harvesting fabric for tactile sensors. [31] Copyright 2019, Elsevier Ltd. **e** A spider-web-inspired elastomer-filled graphene woven fabric used to wearable strain sensors. [32] Copyright 2018, American Chemical Society. **f** Carbonized plain weave cotton fabric for strain sensor. [33] Copyright 2016, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. **g** Weft-knitted fabric for a highly stretchable and low-voltage wearable heater. [34] Copyright 2017, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

fabricating yarn supercapacitor. Then, the prepared supercapacitor yarn was woven into a polyester jacket with a triboelectric nanogenerator (TENG) area. [28] In this way, the jacket as a wearable electronic device has energy-storing and energy-harvesting dual capabilities by integrating functional yarns and cloths.

Compared with yarn or fabric, fiber with multifunctional properties easier achieve accurate targets whether in energy storing or sensing due to the smaller scale combined with nanomaterials. The functional fiber-based electronics are shown in Fig. 2b, c. Herein, the smart fibers are composed of the helical and highly elastic core as well as graphene oxide (GO)/carbon nanotubes (CNT) sheath via a dip-coating method, enabling highly sensitive strain sensors and muscles. [29, 30] By combining with carbon nanomaterials, the sheath-core fibers exhibit precise strain, bending and torsion, showing better flexibility under large strains than other related textile forms (yarn and fabric). At the yarn level, it gives more potential in the application. As shown in Fig. 2d a commercial four-ply twisted polyamide yarn coating with silver and silicon rubber and another commercial three-ply twisted cotton yarn were knitted as a 3D double-faced interlock fabric. [31] This yarn-based textile exhibit energy harvesting and sensing performance, enabling human motion detection and smart prosthetics.

At the fabric level, every fiber as an element together enhances the mechanical properties of fabric, as well as improving wearability. For example, a graphene-coated woven fabric in Fig. 2e was filled by elastomer to fabricate a wearable strain sensor, exhibiting a high gauge factor at 282 under 20% strain. [32] In this work, every modified fiber is a wire and is part of a spider web-like fabric equivalent circuit, enabling more complex strain behaviors and detecting large and small body motion signals. Another fabric wearable strain sensor is made from carbonized cotton fabric that encapsulated by Ecoflex silicon rubber in Fig. 2f. The fibers were shrunk (49.2% and 84.7% in the surface area and the weight) and fined after the carbonization process, enabling the detection of ultralow stain, 0.02%. [33] In addition to strain sensors, wearable heaters, as an important branch in intelligent textiles, are also one of the research points. As shown in Fig. 2g a conductive weft-knitted fabric with good stretchable (70% strain) and Joule heating performance (100 °C under 3 V voltage) was prepared by a similar carbonization method. [34] In this work, more conductive contact points between adjacent fibers were produced due to the carbonization and the structure of the weft-knitted fabric, having the potential in wearable heater and thermal therapy.

In addition to TENG, sensors and heaters, fiber-based wearable textiles also can be used as transistors [35], antennas [36], and electric connectors [37] after combining with some conductive materials. [38] As a key factor for fabricating fiber-based wearable electronics, highly conductive, flexible and easily modifiable smart materials are essential for upgrading traditional textiles. Meanwhile, carbon-based materials exhibit excellent electrochemical and mechanical properties such as graphene [39], CNT [40] and MXene [10], playing a fundamental role in energy storing and sensing. Moreover, 2D layered material, MXene, has large layer spacing and rich terminal groups that are more suitable for the fabrication of supercapacitors, wearable heaters and precise sensors.

3 Synthesis of MXene

As one of the nanomaterials, MXene is tunable on the micromorphology and can be easily combined with textiles because of its excellent hydrophilicity than other materials. and the current textile technologies also make MXene firmly attached to fibers, yarns and fabrics. In this section, we will elaborate MXene itself from synthesis, and characterization to basic properties.

At present, there are more than 70 known MAX phases, corresponding to a variety of MXenes [41], which were derived from dozens of intercalated ions (lithium, sodium and potassium are the most common). [42] However, only a small amount of MXenes ($Ti_3C_2T_x$ is the earliest [10]) can be synthesized and developed, and the theoretically feasible MXene still needs further investigation. For the synthesis of MXene, there is three main ways: hydrofluoric (HF) acid-direct etching, *in-situ* HF indirect etching and fluoride-free synthesis method, which all have advantages and shortcomings for getting the ultimately exfoliated and pure MXene. [43]

HF acid-direct etching is the original method that was synthesized the first MXene of the world, and it is also the most extensive way to remove the A-element from MAX phases although HF acid is an extremely hazardous reagent for the human body [44]. Figure 3a presents some of MXenes, $Ti_3C_2T_x$ [45], $Hf_3C_2T_z$ [46], Mo_2TiC_2, and $Mo_2Ti_2C_3$ [47], that were synthesized by HF acid-direct etching method, showing layered nanostructures, electronic and ion channels, and reactively functional groups (for example, F, O, and OH). [45] On the basis of synthesizing different types of MXene by using HF acid-direct etching, the chemical reactions that occurred during the etching process to remove A-element maybe reasonably described by the following equations [48] (for example, Aluminum element as the A-element):

$$M_{n+1}AlX_n + 3HF \rightarrow M_{n+1}X_n + AlF_3 + \frac{3}{2}H_2 \quad (1)$$

$$M_{n+1}X_n + 2H_2O \rightarrow M_{n+1}X_n(OH)_2 + H_2 \quad (2)$$

$$M_{n+1}X_n + 2HF \rightarrow M_{n+1}X_nF_2 + H_2 \quad (3)$$

where *M* represents the transition metals and *X* represents the C or N element, respectively. Certainly, the concentration and reaction temperature of the HF aqueous system are crucial for synthesizing different structural parameters. [43, 49, 50] For example, Mohamed Alhabeb et al. put three

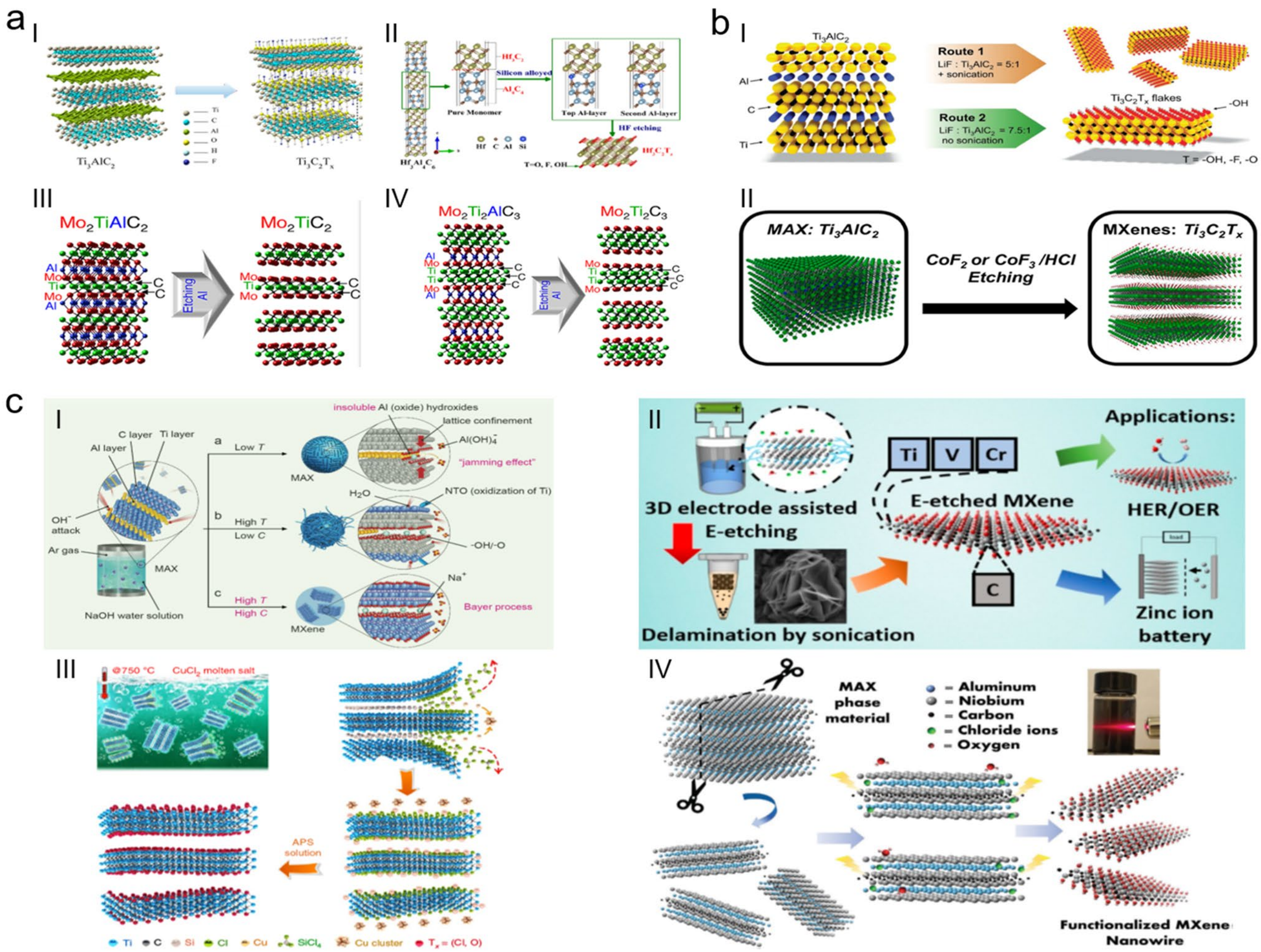

Fig. 3 Schematic illustration of the synthesis process of MXene by HF acid-direct etching protocol, *in-situ*. HF-indirect etching protocol and fluorine-free synthesis method. **a** HF acid-direct etching protocol. (I) $Ti_3C_2T_x$. [45] Copyright 2019, American Chemical Society. (II) $Hf_3C_2T_z$. [46] Copyright 2017, American Chemical Society. (III) Mo_2TiC_2. and (IV) $Mo_2Ti_2C_3$. [47] Copyright 2015, American Chemical Society. **b** *In-situ*. HF-indirect etching protocol. (I) Different ratios of LiF and Ti_3AlC_2 (5:1 to 7.5:1) are used in situ HF to synthesize MXene. [61] Copyright 2016, WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. (II) CoF_2/CoF_3 joins HCl as etchants forming in situ HF to design heterostructure. [65] Copyright 2019, American Chemical Society. **c** Fluorine-free synthesis method. (I) The reaction between Ti_3AlC_2 and NaOH aqueous solution under different conditions. [75] Copyright 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (II) A universal strategy based on a thermal-assisted electrochemical etching route is developed to synthesize MXene (Ti_2CT_x, Cr_2CT_x, and V_2CT_x). [76] Copyright 2019, American Chemical Society. (III) Reaction process demonstration that Ti_3SiC_2 etched in $CuCl_2$ Lewis molten salt at 750 ℃ and further washed in ammonium persulfate (APS) solution. [77] Copyright 2020, CC BY 4.0.. (IV) Synthesis process of the Nb_2CT_x Nanowires via hydrolysis and HF-free E-etching method and Tyndall effect. [78] Copyright 2020, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

concentrations of HF acid (5 wt.%, 10 wt.% and 30 wt.%) into Ti_3AlC_2 powder at room temperature for 24, 18 and 5 h respectively to study the micromorphologies and crystal structures among different reaction conditions. [51, 52] Subsequently, the intercalation and delamination of HF-etched MXene were explored by Na^+, K^+, NH_4^+, Mg^{2+}, and Al.$^{3+}$, dimethyl sulfoxide (DMSO), N,N-dimethylformamide (DMF), etc.. [52, 53]

In-situ HF indirect etching is conducted by fluoride salts including bifluoride (for example, NH_4HF_2) [54, 55] and common fluoride salts (for example, LiF) [56], that can produce about 5% HF acid mediately. Herein, we list several approaches to obtain $Ti_3C_2T_x$ with different etchants and ratios in Fig. 3b [57–59]. In the choice of fluoride salts, LiF is the most common, which can indirectly remove the Al atomic layer and then directly insert Li^+ into the gap. [60–63] In addition, other cationic fluoride salts such as FeF_3 [64], CoF_2 and CoF_3 [65] also have similar functions.

Both the HF acid-direct etching method and *in-situ* HF indirect etching method inevitably produce F-MXene, which is not conducive to hydrophilicity and environmental friendliness. More importantly, most of the A elements present acidic, and the HF-related methods are only suitable for etching the MAX phases that contain acidic-related elements. Interestingly, the fluorine-free method can be etched in alkaline environments.

Fluoride-free synthesis method is an emerging protocol that is safer for the human body than the HF-related method, enabling the hydrophilicity of MXene and easier to intercalate by other cations such as Li^+, NH_4^+, Na^+, $K.^+$, etc. [66] Herein, we sort out several ways by fluorine-free synthesis method in Fig. 3c. As an emerging method, fluoride-free synthesis method can protect the atomic structure of the surface and maintain the continuity of electronic transmission channels that are conducive to the stability of conductivity and mechanical properties. To some extent, the fluorine-free synthesis method expands the range of MAX phase precursors, explores the types of MXene, increases MXene yields, and has been applied in many fields. [67, 68]

The synthesis of MXene is almost covered by the above methods. [69, 70] Among them, most of MXene were synthesized by etching MAX phases in a certain concentration of HF aqueous system [71, 72] or *in-situ* HF (generally LiF) system. Besides, the stable dispersion of MXene in liquid-phased systems and its long-term storage are equally important for further applications. For instance, Kathleen Maleski et al. studied the dispersions of titanium carbide MXene in organic solvents including DMF, N-methyl-2-pyrrolidone (NMP), DMSO, propylene carbonate and ethanol to verify the decentralization of MXene and further expand the layer spacing by introducing the organic macromolecules. [73] On the other hand, oxidative stability is also a vital aspect for large-scale preparation or industrialization, because MXene has active terminal groups and bare atomic layers that easily combined with other functional groups. Therefore, many works have been devoted to improving oxidative stability. For example, Zhang et al. improved the stability of $Ti_3C_2T_x$ by storing it in a hermetic Ar atmosphere at 5 °C, which is an effective way for storing the finally delaminated MXene [74].

Large layer spacing, metal-like crystalline and rich surface terminations endow MXene excellent electrical and thermal conductivity, magnetism and optical absorption, enabling wide applications that were summarized in Table 1. In addition, embedding MXene into fiber, yarn and fabric is a nice strategy to make textiles smart. In the following section, MXene fiber-based textiles will be discussed from fabrication to application, and in this review, we hope to provide some references for others.

4 Fabrication Methods of MXene Fiber-based Textiles

MXene with high-performed hydrophilicity because of surface terminations such as OH and O is easier attached on the surface of fibers, so there are many strategies to fabricate MXene fiber-based textiles. In this section, we summarized two methods for the fabrication of MXene fibers, electrospinning and wet-spinning; One method for the fabrication of MXene yarns, biscrolling; Two methods for the fabrication of MXene fabrics, 3D printing and coating. As shown in Fig. 4a, b a facile method to obtain fibers is blending a ratio of polymer solution and MXene dispersion, and then extruding the mixture via electrospinning [19] or wet-spinning [20]. It should be noted that the diameter of electrospun fibers is about a few hundred nanometers, and a lightweight nanofiber film is usually used as a wearable device, while the diameter of wet-spinning fibers is micrometers, and a single fiber can be used as a wearable device. To obtain yarns, twisting is a key factor. Wang et al. created biscrolled yarns called biscrolling by drop-casting MXene dispersion on the CNT sheets in Fig. 4c [23]. This approach needs host materials (usually CNT) and guest materials such as MXene, and the yarn diameter can be controlled by adjusting the twisting speed. Similar to the wet-spinning method, one biscrolling yarn also can be used as an independent wearable device. To obtain fabrics, there are two methods, one is the preparing fibers to assemble into fabrics by 3D continuous printing in

Table 1 Fundamental applications of MXene

Type of MXene	Application	Typical strategy	Ref
$Ti_3C_2T_x$	EMI shielding	Ultralight aerogel with EMI shielding of 75 dB and low reflection < 1 dB	[79]
$Ti_3C_2T_x$	Antibacterial activity	Against both *Escherichia coli (E. coli)* and *Bacillus subtilis (B. subtilis)*	[80]
$Ti_3C_2T_x$	Ion sieving	Controllable thicknesses of $Ti_3C_2T_x$ membranes with ultrafast water flux of 37.4 L/(Bar·h·m^2)	[81]
$Ti_3C_2T_x$	Gas separation	H_2 permeability > 2200 Barrer and H_2/CO_2 selectivity > 160	[82]
NbC_2, TaC_2, MoC_2	Electrocatalysts	Water splitting for oxygen reduction reaction (ORR), hydrogen evolution reaction (HER) and oxygen evolution reaction (OER)	[83]
$Ti_3C_2T_x$	Intraocular lens (IOL) design	A sheet resistance ranging from 0.2–1.0 kΩ sq^{-1} with 50–80% transmittance	[84]
$Ti_3C_2T_x$	Electrochromic device	A visible absorption peak shift from 770 to 670 nm and a 12% reversible change in transmittance with a switching rate of < 1 s	[85]

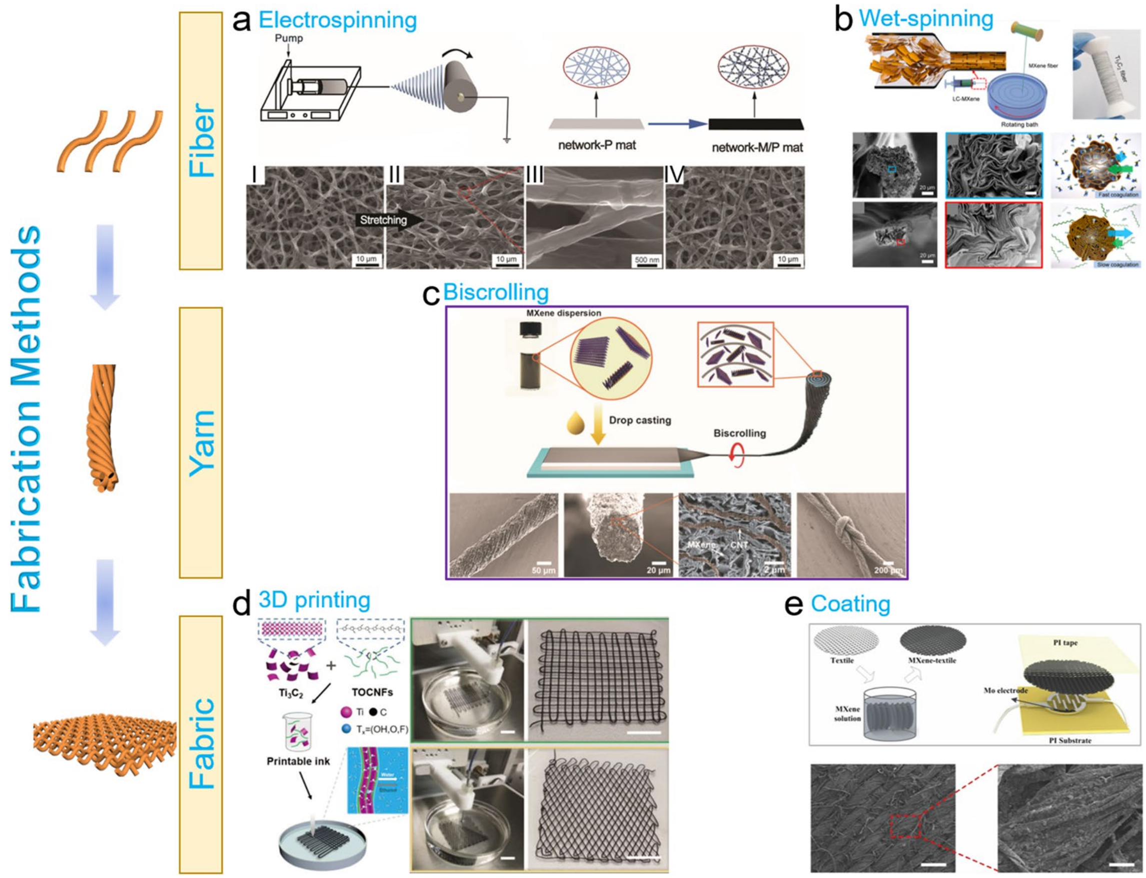

Fig. 4 Fabrication methods for MXene fiber-based textiles from fiber, yarn to fabric. **a** Electrospinning network-structured MXene/polyurethane mat. [19] Copyright 2019, The Royal Society of Chemistry. **b** Wet-spinning of liquid crystals MXene fibers [20] Copyright 2020, American Chemical Society. **c** Biscrolling fabrication of MXene/CNT hybrid yarns. [23] Copyright 2018, WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **d** 3D printing smart textiles. [24] Copyright 2019, WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **e** Coating MXene fabrics [25] Copyright 2019, The Royal Society of Chemistry

Fig. 4d. [24] By blending 3D printing ink and MXene, the mixture can be directly printed into fiber and then formed fabrics by adjusting the position of the nozzle. Another facile method is shown in Fig. 4e that coating a pristine fabric into MXene dispersion. [25] The coating method does not require a spinning solution but directly attaches MXene to fabrics, so it is suitable for hydrophilic fabrics such as cotton cloth.

As a summary, electrospinning, wet-spinning, biscrolling and 3D printing approaches can effectively control the diameter and length of fibers or yarns, while the coating is simpler and more suitable for prepared textiles. These five methods basically cover the fabrication strategies of MXene fiber-based textiles, which were summarized in Table 2, and have wide applications in filtration, adsorption, thermal therapy, energy storage and multifunctional sensing. However, the physical performance of MXene fiber-based textiles would be affected because of the poor oxidative stability of MXene nanosheets, but the practical applications of MXene fibers, yarns and textiles still meet requirements due to the interfacial binding of MXene to textiles and the protection of textiles by the above-skilled preparation methods. For example, wet-spinning effectively avoids direct contact between MXene and air through the combination of MXene and polymer, improving the durability of produced fibers.

5 Applications of MXene Fiber-based Wearable Textiles

Recent decades, the appearance of wearable devices has brought great convenience to our daily life, and realize health monitoring, social communication and audio-visual function via data outputting and exchanging, promoting the progress of science and society. In addition, soft fibers, yarns and fabrics as the most basic candidate have gradually replaced traditional rigid devices and attracted more attention to fabricate the next generation wearable devices, and would play an important role in the near future. In this background, combing fiber-based textiles with MXene is a facile strategy for fabricating flexible, stretchable, and

Table 2 Fabrication methods of MXene fiber-based wearable textiles

Key material	Textile	Fabrication method	Application	Ref
$Ti_3C_2T_x$	Fiber	Electrospinning	Strain sensing	[19]
$Ti_3C_2T_x$/PVA	Fiber	Electrospinning	TENG	[86]
$Ti_3C_2T_x$	Fiber	Electrospinning	Chemical sensing	[87]
$Ti_3C_2T_x$/polyacrylonitrile (PAN)	Fiber	Electrospinning	Air purification	[88]
$Ti_3C_2T_x$/chitosan	Fiber	Electrospinning	Wound healing	[89]
$Ti_3C_2T_x$	Fiber	Wet-spinning	Promising energy storage and heating	[20]
$Ti_3C_2T_x$	Fiber	Wet-spinning	Electrical wiring and signal transmission	[21]
$Ti_3C_2T_x$	Fiber	Wet-spinning	Electrical wiring and signal transmission	[22]
$Ti_3C_2T_x$/GO	Fiber	Wet-spinning	Supercapacitor	[90]
$Ti_3C_2T_x$/GO	Fiber	Wet-spinning	Supercapacitor	[91]
$Ti_3C_2T_x$/GO	Fiber	Wet-spinning	NH_3 gas sensing	[92]
$Ti_3C_2T_x$/polyurethane (PU)	Fiber	Wet-spinning	Strain sensing	[93]
$Ti_3C_2T_x$/silver nanowire (AgNW)/water-borne polyurethane (WPU)	Fiber	Coating	Strain sensing	[94]
$Ti_3C_2T_x$/CNT	Fiber	Scrolling	Supercapacitor	[95]
$Ti_3C_2T_x$/CNT	Yarn	Biscrolling	Supercapacitor	[23]
$Ti_3C_2T_x$/silver nanoparticles (AgNPs)	Yarn	Coating	TENG	[96]
$Ti_3C_2T_x$	Yarn	Coating	Electrode and pressure sensing	[97]
$Ti_3C_2T_x$	Yarn	Coating	Energy storage	[98]
$Ti_3C_2T_x$	Yarn	Coating	Heater	[99]
$Ti_3C_2T_x$/polyester (PET)	Yarn	Electrospinning	Electrode	[62]
$Ti_3C_2T_x$	Fabric	3D printing	Heating and strain sensing	[24]
$Ti_3C_2T_x$	Fabric	Coating	Pressure sensing	[25]
$Ti_3C_2T_x$/RuO_2	Fabric	Coating	Supercapacitor	[100]
$Ti_3C_2T_x$/CNT	Fabric	Coating	Energy storage	[101]
$Ti_3C_2T_x$/polypyrrole (PPy)	Fabric	Coating	Electrode	[102]
$Ti_3C_2T_x$	Fabric	Coating	EMI shielding, Joule heating and strain sensing	[103]

multifunctional wearable devices, showing surprising advantages in supercapacitors, electrodes, heaters and sensors. For example, MXene fiber-based textiles with both energy harvesting and sensing capabilities are shown in Fig. 5. The MXene-coated cellulose-based yarns were knitted into the fabric, which can be used for energy storage, harvesting and pressure sensing (Fig. 5a), [97] while the nanofiber film of PVA/MXene was assembled with silk fibroin nanofiber film that was fabricated by electrospinning manufacturing, and this PVA/MXene nanofiber film can be used for TENG as well as human motion detection (Fig. 5b) [86]. To date, MXene fiber-based wearable textiles have achieved versatility and they are applied in many fundamental fields. In this section, we will discuss MXene fiber-based wearable textiles in energy storing, sensing and other related applications.

5.1 Energy Storing

Energy storing has been a focused topic since the twenty-first century, and exploring cleanable, durable, and efficient energy sources is an important target. Comparison with other 2D materials, MXene has been verified to have a large charge storage capacity. In 2013, Lukatskaya et al. proved that titanium carbide MXene is a potential supercapacitor raw material [53]. Then, Ghidiu et al. expanded the volume-specific capacitance of MXene to 900F/cm, as a result of the redox reaction on layered surface groups. [3, 60, 104–106] As a result, MXene has the advantage to prepare energy devices due to its reversible electrochemical energy storing system, high-power density and excellent cycle stability [107–109]. When combine with textiles, MXene-based devices can be more flexible and get high-performed electrochemical properties. Herein, the energy-storing application was summarized in two parts: (1) Fiber and yarn, and (2) Fabric, which depended on the ease of fabrication and the different forms of the final textiles.

Fiber and yarn energy devices are more tunable than fabric devices due to their complexity of fabrication processes (for example, electrospinning and wet-spinning can adjust the fineness of fibers, and Biscrolling is more helpful for combining fibers with different functions into yarns, and 3D printing or coating is used for fabric surface

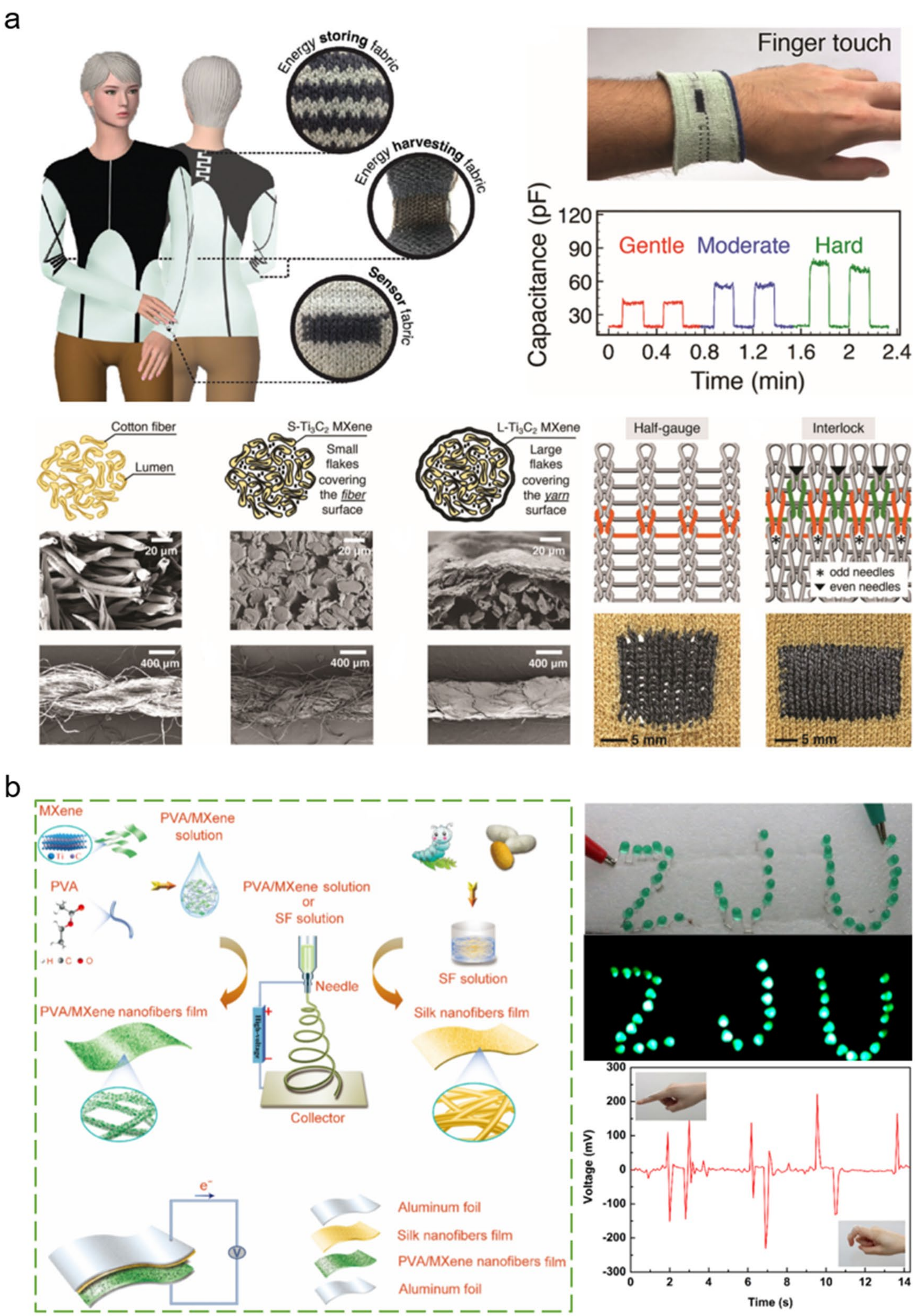

Fig. 5 MXene fiber-based textiles with both energy storing/harvesting and sensing capabilities. **a** MXene-coated cellulose-based yarns by knitting. [97] Copyright 2019, WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **b** All-electrospun flexible nanofibers film used for TENG and sensor. [86] Copyright 2019, Elsevier Ltd.

modification) and the superposition of multiple energy storage materials (such as MXene/CNT). By adapting the electrospinning method, electroactive MXene nanofibers were tangled on a PET yarn to form a yarn-shaped supercapacitor in Fig. 6a, and this work provided a nice strategy for fabricating composite yarn electrodes. [62] Combining with other electroactive materials is another strategy to enhance the energy-storing properties. As shown in Fig. 6b-d, the hybrid fibers of MXene/GO or MXene/CNT were fabricated by wet-spinning or scrolling, and these flexible fibers serve as supercapacitors with superior electrical conductivity and high volumetric capacitance. [90–92, 95] In addition, two Biscrolling yarns containing MXene (as an anode) and RuO_2 (as a cathode), respectively, were woven into a fabric, which can be used as an energy textile to power some devices as shown in Fig. 6e. [23] Moreover, the functions of yarns as the ordered arrays of fibers are increasingly diversified. For example, Jiang et al. reported a robust TENG yarn by coating 3 layers: MXene, AgNPs and polydimethylsiloxane (PDMS) in Fig. 6f, which generated 7.7 V voltage under the yarn length of 3 cm, enabling raindrop energy harvesting for agrotextiles. [96] These fiber & yarn supercapacitors are more flexible and can be conveniently embedded in fabrics for precise wearability.

Fabric energy devices take on more wearable tasks. As shown in Fig. 6g, 2-ply of MXene-coated cotton yarns as electrodes was knitted into a pristine fabric that can be used as a supercapacitor with high energy storing capability (the capacitance was 707 mF cm^{-2} at 2 mV s^{-1} in 1 M H_3PO_4 gel electrolyte). [98] This work adopted MXene-coated yarns to knit into fabric and also illustrated the knitted structure also helps enhancing the electrochemical and mechanical performance. Another pseudocapacitive fabric supercapacitor was asymmetric that assembled by coating MXene ink on a carbon fabric and growing RuO_2 particles on the back of the carbon fabric, which is shown in Fig. 6h. This asymmetric supercapacitor got a high energy density of 37 μW h cm^{-2} at a power density of 40 mW cm^{-2} and had a stable charge–discharge cycles over 20,000. [100] Moreover, highly conductive Mxene-modified textiles that fabricated by the coating method have the feasibility of supercapacitor electrodes. As shown in Fig. 6i, j, an electrospun film and a commercial

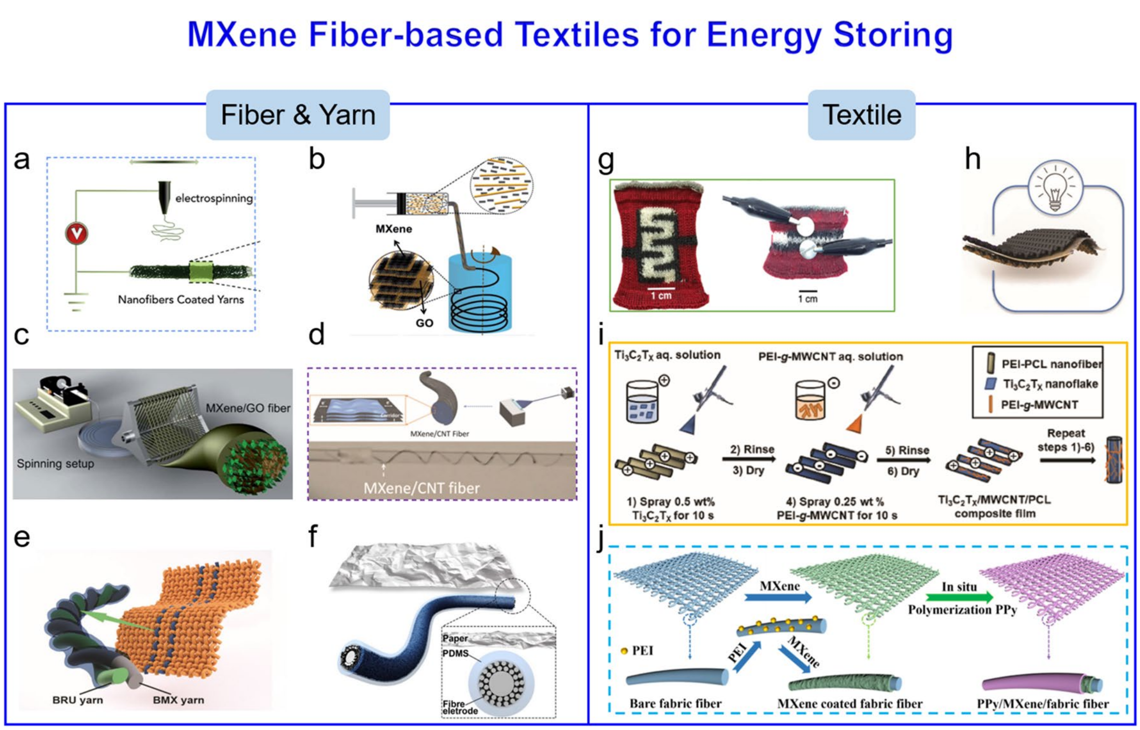

Fig. 6 MXene-fiber-based textiles for energy storing. **a** Polyester@MXene nanofibers coated yarns by electrospinning technology served as supercapacitors [62] Copyright 2018, Elsevier B.V. **b** MXene/GO fiber served as supercapacitors. [91] Copyright 2017, The Royal Society of Chemistry. **c** MXene/GO fiber supercapacitors fabricated by wet-spinning. [90] Copyright 2017, The Royal Society of Chemistry. **d** MXene/CNT fiber-shaped supercapacitors. [95] Copyright 2018, WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **e** Biscrolled MXene/CNT yarn for supercapacitors. [23] Copyright 2018, WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **f** AgNPs/MXene TENG yarn with high stretchability and self-powered performance. [96] Copyright 2020, Elsevier Ltd. **g** 3D knitted energy storing textiles using MXene-coated yarns. [98] Copyright 2020 Elsevier Ltd. **h** MXene-RuO_2 carbon fabric supercapacitors. [100] Copyright 2018, WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **i** MXene/CNT nanofiber film as a supercapacitor electrode. [101] Copyright 2018, The Royal Society of Chemistry. **j** PPy/MXene fiber-based fabric as a supercapacitor electrode. [102] Copyright 2020, Elsevier B.V

fabric were coated by MXene/CNT or MXene/PPy for obtaining a large capacitance and high-rate properties. [101, 102] MXene fiber-based textiles have demonstrated a strong energy storage capability, and, it is relatively easy to prepare textile-based wearable devices such as supercapacitors, electrodes, and nano-triboelectric generators by combining with the existing textile technology.

5.2 Sensing

Wearable electronic sensing devices are considered to be one of the key progress for personal management [110]. With the development of materials and technology, many types of sensors are fabricated such as tactile sensor, image sensor arrays, biochemical sensor, temperature sensor, and optical sensor. However, traditional sensors with a small strain range and low gauge factors (GF) are commonly made with rigid metals or semiconductors, which greatly limits their applications. [111] As a result, flexible and soft substrates are increasing as a new generation such as PET, PDMS, epoxy resign and fabric. [112–114] Here, skin-friendly textiles combined with MXene to fabricate wearable sensors are focused, which helps to monitor the human body in real time. [29, 115] In this section, the sensors of MXene fiber-based textiles were selected in three aspects: strain sensing, piezoresistive sensing and chemical sensing.

For strain sensing, the mechanism is the change of geometry (length/width or both) when attacked by external tensions, which in turn causes the change in the number of continuous contact points under a dynamic strain. [113, 116–119] Most MXene fiber-based strain sensors are elastic. For example, polyurethane-based MXene fibers with more than 100% strain were prepared by coating or wet-spinning method according to Fig. 7a, b, and these highly elastic fibers exhibited excellent sensitivity, fast response time and long lifetime, showing the potentials in body motion monitoring. [93, 94] Although not as elastic as MXene fibers, the MXene-coated cotton fabric in Fig. 7c also has a strain-sensing capability. The electrical conductivity of this fabric was only 5 Ω sq^{-1}, achieving pulse and voice recognition, and it also can be used as for EMI shielding and Joule heating. [103]

Piezoresistive sensing is subjected to external pressures, and a large impact on the carrier density would be occurred even a very small change. [120–123] Because of the unique multilayer structure of MXene in Fig. 7d, the distances between two neighboring interlayers can be compressed under an external pressure, resulting in theshrinkage of lattices. [124] Moreover, full-range human activities were recorded by this cotton MXene fabric, and pressure distribution also can be detected by 4 × 4-pixel arrays. In summary, the working mechanism of the strain sensor and piezoresistive sensor are similar that both based on geometric deformation under external stress. In addition, these two sensors can detect human motions from body postures (for example, arm bending monitoring) to physiological signals (for example, pulse monitoring), and the introduction of wireless transmission technology would be more crucial for future wearable devices. [125–127]

On the other hand, chemical sensing is more application-oriented and widely used in toxic vapor identification and air quality monitoring by adsorbing small gas molecules. [128, 129] Because of the MXene layered structure and the high porosity of fiber-based textiles, MXene textiles present a high gas adsorption rate. For example, in Fig. 7e a 3D MXene fiber framework with volatile organic chemical (VOC) sensing to acetone, methanol and ethanol was fabricated by using electrospinning technology, exhibiting ultralow sensing limit of 50 ppb to above VOC vapors and a good reversibility even after 1000 bending cycles. [87] The sensing capability of chemical sensor relied on the conductivity and layered nanochannels of MXene, and the nanopores of the 3D fiber framework contributed to adsorbing and recognizing VOC vapors. Another work reported the wet-spinning MXene/graphene hybrid fibers for NH_3 sensing. As shown in Fig. 7f, the MXene/graphene hybrid fibers exhibited dynamic NH_3 concentration response even under bending deformation. [92] The chemical sensing of MXene fiber-based textiles is playing an important role in gas detection and VOC adsorption, helping improve the quality of our daily life. However, there are not many related works for MXene fiber-based chemical sensors, so it needs to be further studied in the field of chemical sensing.

5.3 Other Applications

When MXene combines with textiles, the advantages in various fields are more obvious, including wearability, aesthetics, energy self-harvesting, etc., which are superior to rigid wearable devices. Herein, we list four fundamental applications based on MXene functional textiles, that are, EMI shielding, air purification, antibacterial activity and electric heating, as shown in Fig. 8. For EMI shielding, the MXene/cellulose nanofiber composite paper with a nacre-like lamellar structure showed an excellent EMI shielding efficiency of 2647 dB cm^2 $g.^{-1}$ at the paper thickness of 47 µm. [130] For air purification, the MXene/PAN nanofiber film that was fabricated by electrospinning exhibited the PM 2.5 removal efficiency of ~99.7% with a pressure drop of ~42 Pa, which can improve air quality in some extent. [88] For the Antibacterial activity, the biocompatible MXene/chitosan composite electrospun nanofibers inhibited 95% of Gram-negative *Escherichia coli* (*E.coli*) and 62% of Gram-positive *Staphylococcus aureus* (*S. aureus*), promising for wound repair. [89] For the electric heating, the coated MXene/PET threads were sewed into a cotton glove for fabricating wearable and

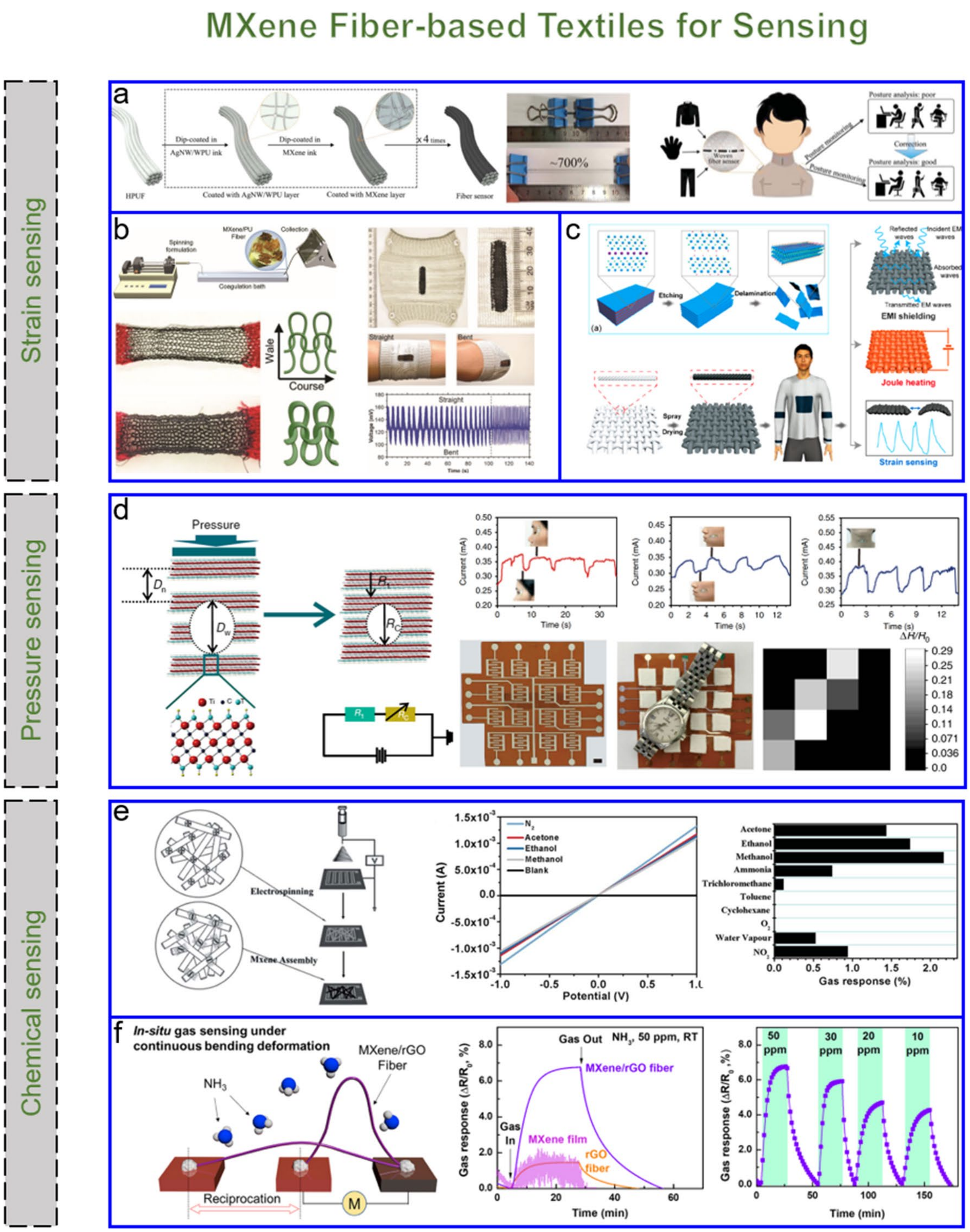

Fig. 7 MXene fiber-based wearable sensors. **a** AgNW/WPU-MXene fiber strain sensor for wearable monitoring and healthcare. [94] Copyright 2019, The Royal Society of Chemistry. **b** Coaxial fibers-based knitting fabrics with strain sensitivity. [93] Copyright 2020, WILEY–VCH Verlag GmbH & Co. KGaA, Weinheim. **c** MXene-decorated interwoven cotton fabric served as a strain sensor [103] Copyright 2020, American Chemical Society. **d** Flexible piezoresistive cotton fabric sensor. [124] Copyright 2017, CC BY 4.0. **e** 3D MXene framework by electrospinning for chemical sensing. [87] Copyright 2018, The Royal Society of Chemistry. **f** MXene/graphene hybrid fibers for NH_3 sensing. [92] Copyright 2020, American Chemical Society

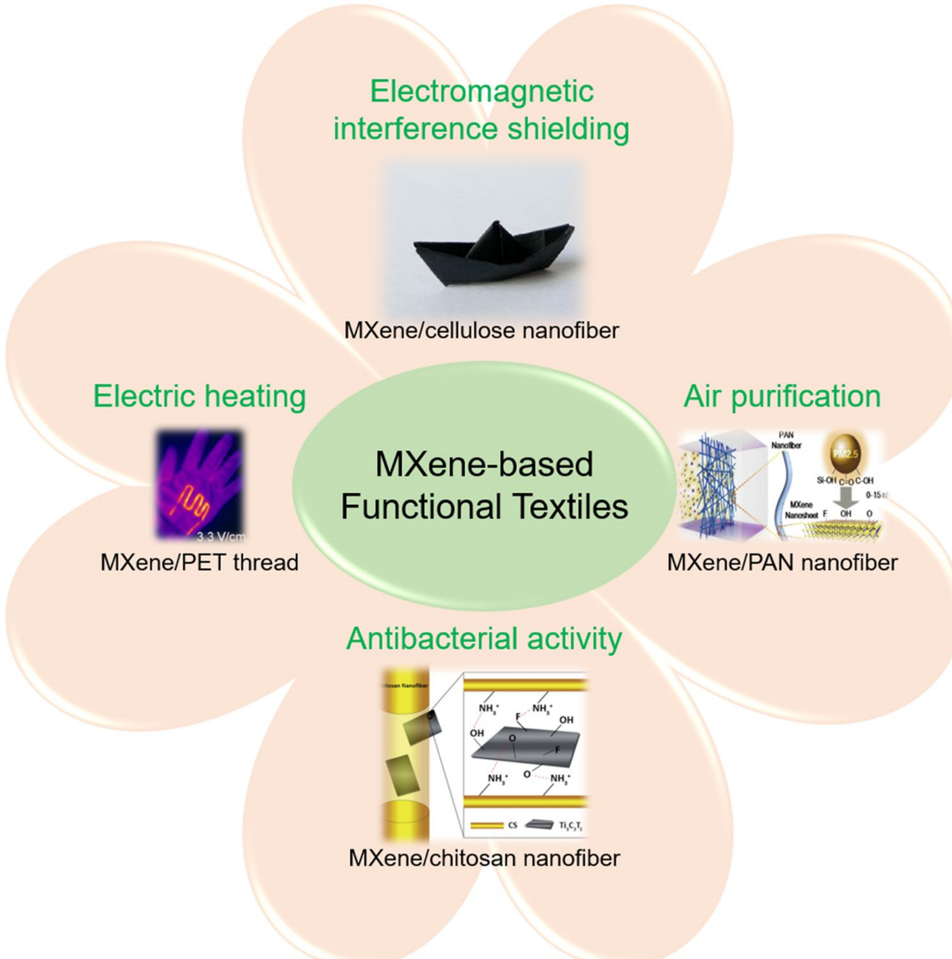

Fig. 8 MXene-based functional textiles applied in EMI shielding [130] Copyright 2018, American Chemical Society. Air purification [88] Copyright 2019, Elsevier B.V., Antibacterial activity [89] Copyright 2018, The Royal Society of Chemistry, and electric heating [99] Copyright 2019, American Chemical Society

shape-adaptable heaters, and the electrothermal response time of this heater was only dozens of seconds, providing a good fabrication strategy for thermotherapy and personal thermal management. [99] Up to date, the applications of MXene fiber-based textiles have become more diverse due to their structural and material designability, deserving deeply explored and innovation [131]

6 Conclusion and Outlook

Skin-friendly, environmentally friendly, and comfortable fiber-based materials make smart textiles to be necessary for the next generation of wearable devices. In recent years, many works studied the electrochemical and mechanical properties of MXene textiles. In this review, the synthesis, fabrication, and applications of MXene fiber-based wearable textiles are demonstrated. Different synthesis methods affect the layered structure and terminal surface groups of MXene, and the intercalation makes the final MXene more tunable, determining the basic properties such as conductivity. As an emerging 2D material, characterization and theoretical calculations play an important role in exploring the crystal structures, configurations and functional groups. Moreover, combining MXene with traditional textiles is a strategy for fabricating the next generation of wearable devices. After introducing fibers, yarns, and fabrics, the fabrication methods of MXene fiber-based textiles become diverse, which were summarized in five strategies: electrospinning and wet-spinning for MXene fibers, biscrolling for MXene yarns, 3D printing and coating for MXene fabrics. These facile fabrication strategies enable MXene fiber-based wearable textiles versatile in energy storing, sensing, EMI shielding, air purification, Antibacterial activity and electric heating.

MXene fiber-based textiles have made great progress in recent decades. However, the key technologies for combining MXene and textiles is not perfect, especially for microscopic interface binding, which directly affects the terminal performance of MXene fiber-based devices. As a result, improving the interface adhesion between MXene and textiles needs to be further studied. From the current development trend, MXene-based wearable textiles have great potentials in flexible and wearable electronics. Therefore, establishing full knowledge of MXene fiber-based textiles is necessary to promote the transformation of traditional textiles to smart textiles for practical wearable applications.

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Declarations

Conflict of Interest There are no conflicts to declare.

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