Sahil Jangra[1,], Bhushan Kumar[2], Jaishree Sharma[1], Subhankar Das[2], Manjeet Singh Goyat[1, 3]*

[1]Cluster of Applied Sciences, School of Advanced Engineering, UPES, Dehradun, India, [2]Cluster of Mechanical Engineering, School of Advanced Engineering, UPES, Dehradun, India, [3]Mads Clausen Institute, NanoSYD, University of Southern Denmark (SDU), Denmark

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MXenes: Synthesis, properties, and applications in advanced energy storage technologies

ABSTRACT

MXenes have emerged as highly promising materials in the field of advanced energy storage technologies, owing to their distinctive properties and versatile applications. This review offers a comprehensive analysis of MXenes, focusing on their synthesis methods, fundamental properties, and applications in rechargeable batteries and supercapacitors. In response to increasing global energy demands, MXenes present compelling solutions due to their exceptional electrical and electrochemical characteristics. These include high conductivity, large surface area, hydrophilicity, and a unique two-dimensional structure comprising metal carbides, nitrides, and carbonitrides. Additionally, this review incorporates a detailed bibliometric analysis using computational tools such as VOSviewer, which examines the global landscape of MXene research spanning from 2012 to 2024. This analysis identifies collaborative trends among different countries, institutions, authors, and journals, highlighting leading research areas. Overall, this review underscores the significant potential of MXenes in advancing energy storage technologies. It provides insights into future research directions and practical applications that could effectively meet the growing energy demands driven by electric vehicles and portable electronics.
Keywords: *MXene, 2D materials, energy storage, supercapacitor, bibliometric analysis*

1. INTRODUCTION

The reliance on fossil fuels for energy production presents significant challenges to the global economy and environment [1]. The depletion of these resources and the effects of climate change are pressing issues for modern society. To meet the growing energy demand sustainably, it is essential to develop efficient and affordable energy production and storage technologies. Unlike geothermal energy, which is limited to specific locations, tidal and wave energy sources offer more consistent and abundant resources due to their steady flow [2.3]. However, the collection and transmission of this energy remain major obstacles. Renewable sources like wind and solar energy are often inconsistent, making energy storage crucial for capturing and utilizing excess power. Researchers are therefore focusing on developing advanced energy storage systems with high capacity and superior cyclic performance. Supercapacitors and high-density batteries are expected to be pivotal in powering portable electronics such as smartphones, tablets, laptops, and hybrid vehicles [4,5]. Recently, two-dimensional (2D) materials have garnered significant research interest due to their exceptional electrical properties compared to bulk materials [6]. While graphene has been extensively studied for its mechanical stability and high conductivity, other 2D materials like transition metal dichalcogenides (TMDs), hexagonal boron nitride, and metal oxides are also being investigated for their potential in flexible electronics and energy storage applications [7-10].

MXenes, a novel class of 2D materials composed of early transition metal carbides and/or nitrides, were first identified about a decade ago at Drexel University [11-13]. Fig. 1(a) shows the periodic table with MAX phases and MXene compositions [14]. These materials are notable for their versatile properties, including metal-like conductivity, high mechanical strength, and hydrophilicity, which stem from their surface-terminated functional. MXenes are produced by chemically etching the A element from their 3D MAX phase precursors as depicted in Fig. 1(b), where M-X bonds are much stronger than M-A

*Corresponding author's: Sahil Jangra
E-mail: sahilphy0407@gmail.com
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bonds. Fig. 1(c) displays the three atomic structures of MXenes—M_2X, M_3X_2, and M_4X_3—demonstrating their potential for a wide range of applications. Their distinctive properties underscore their significant potential across various fields [14-18].

A bibliometric assessment of such promising 2D materials serves as a reference for identifying their uniqueness and potential for future developments and can act as a guiding resource in the evolution of research on trending materials [19]. Bibliometric studies employ statistical techniques to evaluate sources including books, papers, and other publications. Bibliometric software was used to analyse individual performance and visualise publications using information such as titles, dates, authors, addresses, and references. VOSviewer software has potential to create and visualise organisations, nations, authors, keywords, journals; including bibliographic coupling, co-citation, and co-authorship relationships.

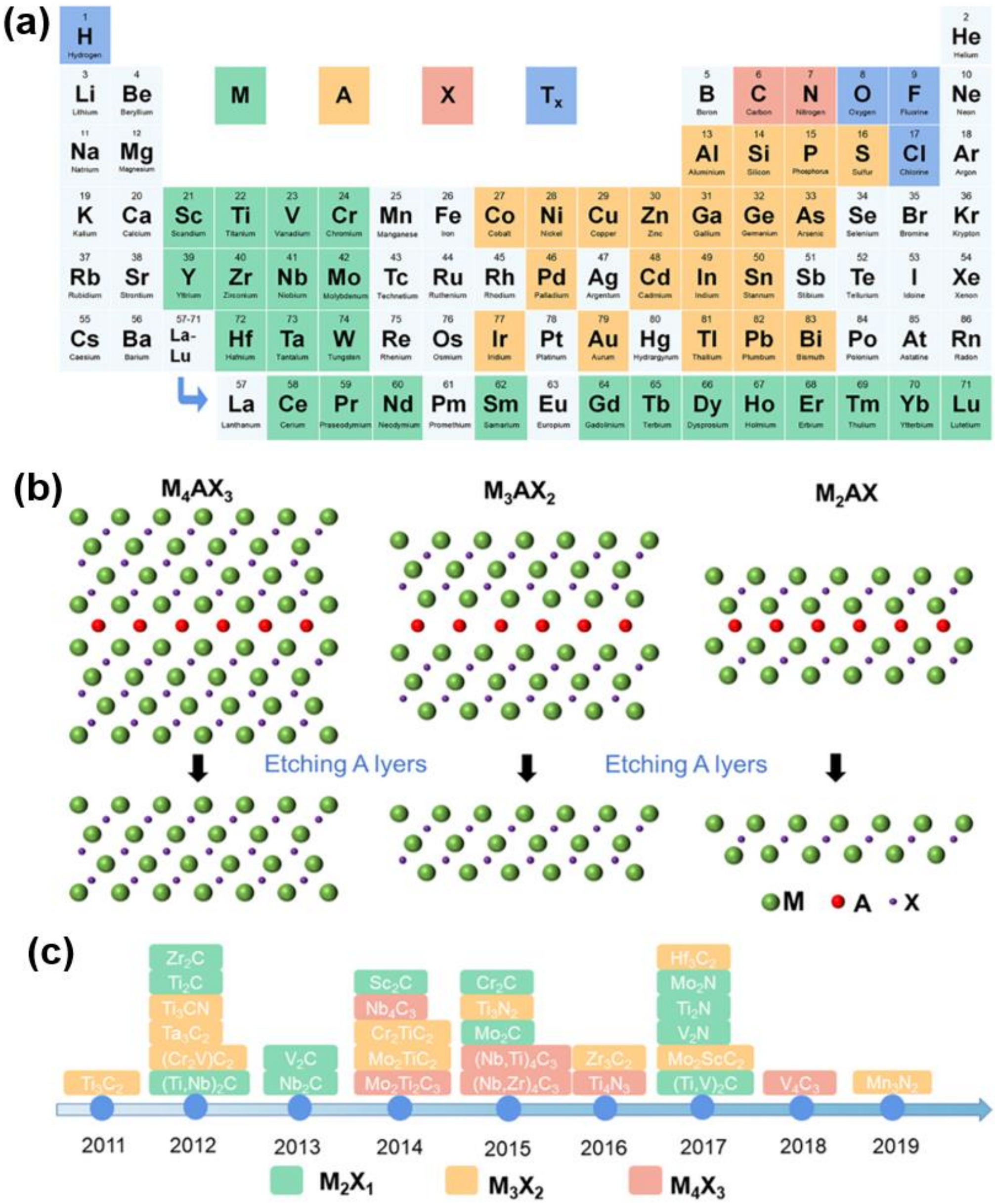

Fig. 1. (a) Periodic table showing MAX phases and MXene compositions. (b) Schematic of etching MAX phases to produce three types of MXenes: M_2X, M_3X_2, and M_4X_3. (c) Timeline of advancements in MXene synthesis. (a-c) (Reprinted with permission from Ref. [14]. Biosensors, © 2023 MDPI).

Despite significant progress in MXene-based energy storage research, a comprehensive scientometric study has been lacking. To fill this gap, this review utilizes VOSviewer software to perform an in-depth scientometric analysis of the field. The analysis examines data from diverse sources—such as countries, organizations, and authors—to uncover key research trends and focus areas. The review provides a thorough overview of MXenes, including their synthesis, properties, and applications in supercapacitors and rechargeable batteries. With their exceptional electrical and physical properties, such as high conductivity and large surface area, MXenes offer promising solutions for addressing the increasing global energy needs. The bibliometric analysis spans research from 2012 to 2024, revealing collaboration patterns and leading research themes. This review highlights MXenes' potential to advance energy storage technologies and suggests future research directions and practical applications to support the development of electric vehicles and portable electronics.

2. SYNTHESIS OF MXENES

MXenes are generally derived from their parent MAX phases, which have the formula $M_{n+1}AX_n$ (where M is an early transition metal, A is an A-group element, and X is either carbon or nitrogen) [20]. The main synthesis methods for MXenes includes:

2.1. Hydrofluoric acid (HF) etching

The most common technique involves treating the MAX phase with hydrofluoric acid (HF) to selectively remove the A layer. The MAX structure has interconnected "A" layers. MXenes are produced by etching Al from the MAX phases, which are typically easy to handle and store (Fig. 2(a-c)). For instance, etching Ti_3AlC_2 with HF results in $Ti_3C_2T_x$ MXene. To perform HF etching, the MAX phase is added to a hydrofluoric acid solution and continuously stirred. The resulting suspension is then repeatedly washed with deionized water until the black supernatant remains stable after centrifugation (Fig. (2d)). Finally, the sediment is dissolved in deionized water and sonicated for an hour [21]. SEM images reveal the structure of Ti_3AlC_2 (MAX) powder Fig.(2e) and the multilayered morphology of $Ti_3C_2T_x$ after etching Fig. (2f). Additionally, MXene flakes derived from a colloidal solution of MILD-$Ti_3C_2T_x$ are also shown in Fig. (2g). A recent study found that low HF concentration leaves A-layer atoms unetched, while high HF concentration destroys or dissolves the MAX phase. Due to the toxicity and corrosiveness of HF, researchers are exploring alternative MXene synthesis methods [22].

2.2. In-situ HF etching

To eliminate the need for direct handling of HF, a combination of a fluoride salt (such as LiF) and hydrochloric acid (HCl) is used to generate HF in situ. This method enhances safety and provides better control over the etching process. Fig. 2(h) illustrates the synthesis of Ti_3CNT_x MXene, which was achieved by selectively etching the Ti_3AlCN MAX phase using a HCl and LiF etching process. Following the etching process, the aluminum layers were successfully removed, resulting in a multilayered, accordion-like Ti_3CNT_x structure, as shown in the SEM image (Fig.2i) [23]. In earlier research, a one-step etching and intercalation method was employed, utilizing MXene's affinity for cations. Ti_3AlC_2 was gradually added to HCl mixed with LiF and stirred at 40°C for 45 hours. The precipitate was washed, centrifuged to increase its pH, yielding a monolayer of MXene. This clay paste can be molded for electrodes and supercapacitors [24]. Additionally, HCl and KF were used to etch the MAX phase of Ti_2AlN, allowing K^+ and H_2O to intercalate the Ti_2N nanosheets, resulting in well-spaced and uniform Ti_2N MXene. This one-step process is simpler, gentler, and safer for obtaining monolayer MXenes [25].

2.3. Molten Salt Method

In this method, the MAX phase is etched with molten salts such as $ZnCl_2$ at elevated temperatures. This approach produces MXenes with fewer defects and enhanced crystallinity. The process is highly efficient, typically finishing within half an hour. However, the need for high temperatures can be a disadvantage [26]. Recently, large batches of $Ti_3C_2T_x$ MXene (20 g and 60 g) were synthesized from its MAX phase using a Lewis acid molten $CuCl_2$/NaCl/KCl mixture at 700°C in a muffle furnace under acn air atmosphere [27].

2.4. Electrochemical Etching

This approach uses an electric current in a fluoride-containing electrolyte to precisely control the etching process. Recently, electrochemical etching has emerged as a key method for producing MXene from the MAX phase by selectively removing nanolaminate contents like carbide-derived carbon (CDC) and carbon/sulfur. In Ti_3AlC_2, applying a constant potential allows chloride ions (Cl^-) to bind with Al, breaking Ti–Al bonds and forming $AlCl_3$, which opens grain boundaries for Cl^- penetration and other species intercalation. However, protective CDC layers limit large-scale production. Using intercalants like tetramethyl ammonium ion can help, but their toxicity is a concern. To address this, thermally assisted electrochemical etching has been proposed [28]. This method is used to synthesize MXenes such as Ti_2CT_x, Cr_2CT_x, and V_2CT_x in HCl electrolyte, offering an environmentally friendly approach [29].

2.5. Chemical Vapor Deposition (CVD)

Chemical Vapor Deposition (CVD) is a novel technique for synthesizing MXenes, offering precise control over their composition and thickness. This involves introducing volatile precursors into a reaction chamber, where they decompose or react on a substrate to form MXene structures [30]. CVD produces high-quality, uniform MXene films with excellent crystallinity and minimal defects. The properties of MXenes can be finely tuned by adjusting parameters like temperature, pressure, and precursor flow rates, making CVD ideal for developing advanced MXenes for electronics and energy storage. Recently, α-Mo_2C was prepared by CVD from methane over a bi-layer copper foil substrate on molybdenum foil. CVD is effective for fabricating monolayer carbides and transition metal nitrides, producing MXenes with greater crystallinity than those made by etching. It also allows for the creation of MXene heterostructures and various stoichiometries [31]. The template method is another approach for preparing MXenes, yielding larger quantities. For instance, N-doped Mo_2C sheets were prepared using MoO_2 as a template, achieving perfect crystallinity and morphology by calcining MoO_2 at 700°C with dicyandiamide, introducing C and N atoms to form N-doped Mo_2C sheets [32].

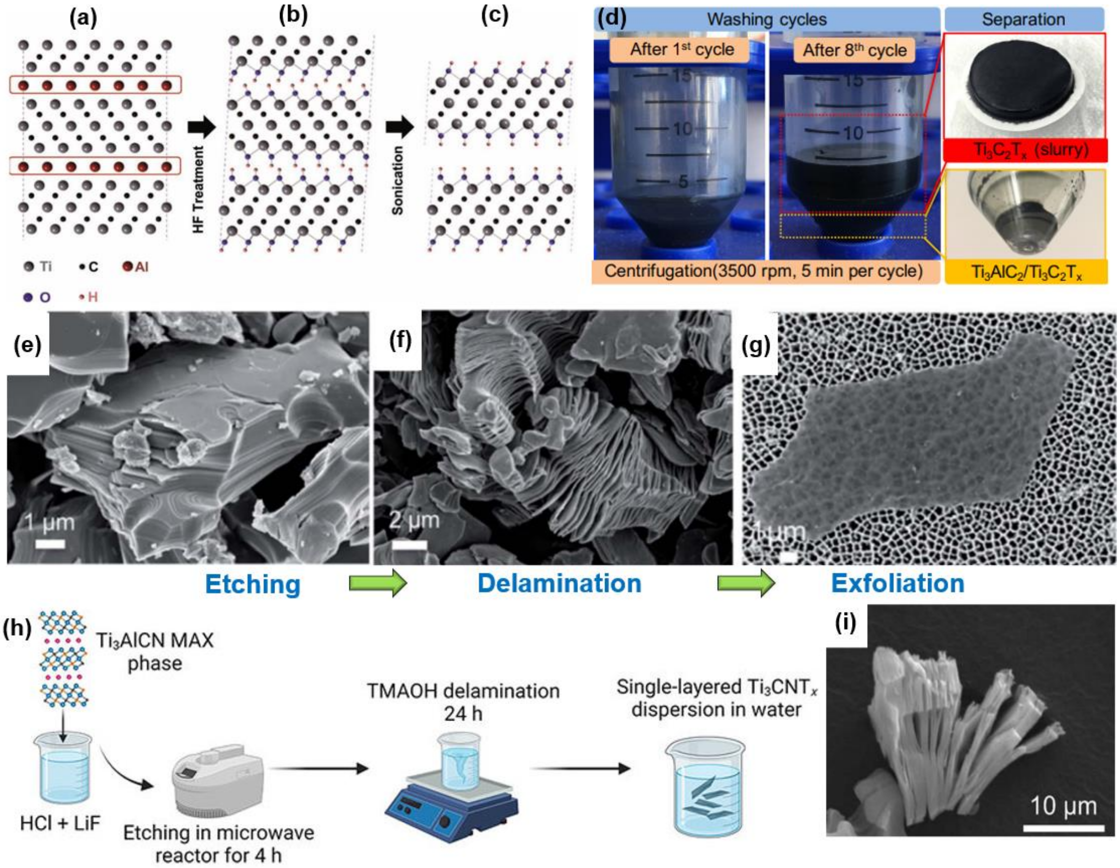

Fig. 2. Exfoliation of Ti_3AlC_2: a) Ti_3AlC_2 structure, b) OH replacing Al after HF reaction, c) Nanosheets separating after sonication. (a-c) (Reprinted with permission from Ref. [70] Advanced materials, Copyright © 2011, Wiley-VCH); (d) MILD-$Ti_3C_2T_x$ powder post first and eighth wash cycles; SEM images show (a) Ti_3AlC_2 (MAX) powder with a compact layered structure and (b) multilayered $Ti_3C_2T_x$; (g) MXene flakes obtained from a colloidal solution of MILD- $Ti_3C_2T_x$. (d-g) (Reprinted with permission from Ref .[71] Chemistry of Materials, © 2017 American Chemical Society); (h) Ti_3CNT_x MXene synthesis diagram (i) Accordion-like Ti_3CNT_x layers. (h-i) (Reprinted with permission from Ref. [23]. Applied Materials & Interfaces, © 2023 American Chemical Society).

3. PROPERTIES

MXenes are two-dimensional materials known for their exceptional properties, making them highly versatile for various applications. They exhibit metallic-level electrical conductivity, high mechanical strength, flexibility, and excellent thermal conductivity. Their hydrophilic surfaces can be functionalized with different chemical groups, enhancing their adaptability. These attributes make MXenes ideal for energy storage devices, sensors, electromagnetic interference shielding, and catalysis. Fig. 3(a) illustrates a summary of MXene properties [33].

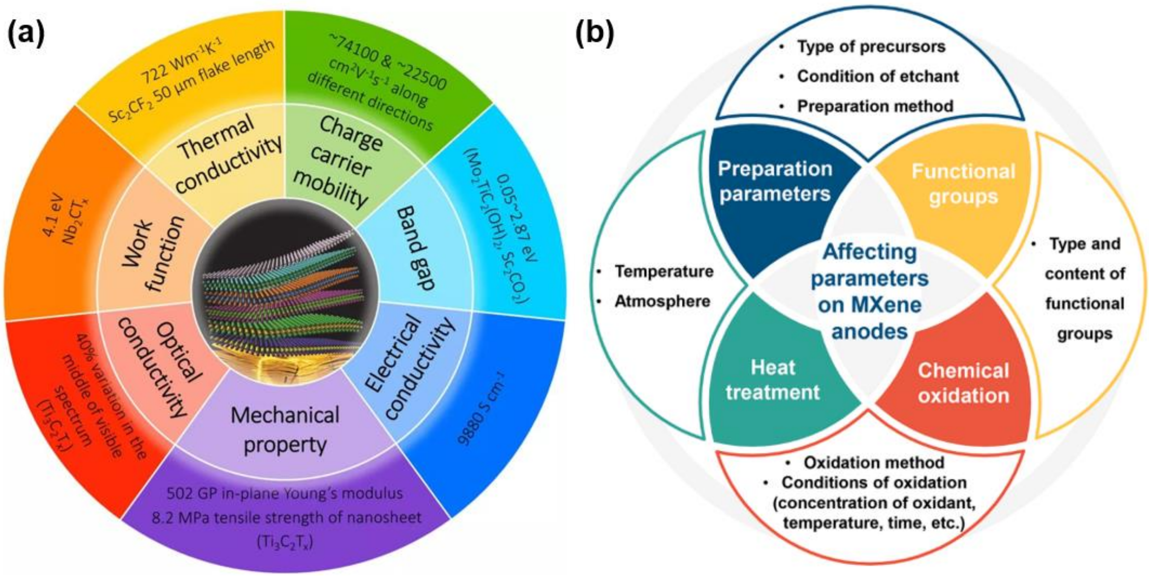

Fig. 3. Overview of MXene properties (Reprinted with permission from Ref. [33]; (a) Energy & Environmental materials, Copyright © 2019, Wiley-VCH) (b) Overview of the factors influencing the electrochemical performance of MXene anodes. (b) (Reprinted with permission from Ref. [52]. Journal of Energy Storage, Copyright © 2022, Elsevier).

3.1. Surface termination

Density functional theory (DFT) indicates that MXenes are completely terminated with functional groups, with strong negative energy reflecting a robust bond to transition metals. MXenes produced by etching MAX phases in fluoride-containing acids feature –OH, –F, and –O– groups. Research also found significant energy for –Cl and –S groups. Fluoride-free synthesis of Ti_3C_2 was achieved via anodic corrosion of Ti_3AlC_2. Functional groups can attach in three ways: on top of metals, in hollow sites on top, and in hollow sites within stacked X layers. Bond lengths for Ti–H, Ti–O, and Ti–F are 0.97, 1.9, and 2.1 Å, respectively, with –O– termination showing the highest adsorption energy of 7.7 eV. Synthesizing MXenes without terminations remains challenging despite various methods. Techniques like X-ray photoelectron spectroscopy, NMR, Raman spectroscopy, surface acoustic probing, and neutron scattering are used to examine MXene surface terminations.

3.2. Conductivity of MXene

MXenes exhibit exceptional electrical conductivity, surpassing all synthetic 2D materials and being about ten times higher than reduced graphene oxide (rGO). Their conductivity, ranging from 1 to 15,000 S cm^{-1}, can be tailored by adjusting synthesis methods, post-etching conditions, ultrasonication, storage environments, and surface chemistry [34]. Understanding these factors is essential for producing high-conductivity MXene materials. MXenes' electrical conductivity can be improved by modifying their surface functional groups or elemental composition [35]. The electrical conductivity of functional group-terminated MXenes $Ti_3C_2T_x$ exhibit metal-like properties and electrical conductivities as large as 4600 S cm^{-1} [36].

3.3. Optical properties of MXenes

Excellent candidates for optical devices include 2D materials and their heterostructures. Additionally, they offer a great platform to improve light-matter interactions due to their efficient integration with nanophotonic structures and inherent polaritonic resonances [37]. First-principles density functional theory has been used in the study of optical properties of Ti_3C_2 MXene. The outcomes demonstrate the significant impact of surface functionalization affecting the optical characteristics of MXene [38]. By varying the types and ratios of surface functional groups, MXenes' optical characteristics can be changed. The thickness, size, and modification process of MXenes all have a significant impact on the amount of UV-Visible light they absorb. Light transmittance of 5 nm $Ti_3C_2T_x$ MXene films achieved 91.2% in the 300–500 nm range; as the thickness of film increase to 70 nm, light transmittance decreased to 43.8% [39]. Other applications have been proven using MXenes' optical properties, including effective light to heat conversion, surface enhance Raman scattering

(SERS) [40], plasmonic broadband absorber, and photonic diodes [41]. The optical properties of other MXenes have not yet been researched; however, titanium carbide, $Ti_3C_2T_x$, has been the MXene that has been explored the most in the majority of these investigations.

3.4. Magnetic Properties of MXenes

MXenes exhibit a wide range of chemical and structural variations, making them highly promising for intrinsic 2D magnetism. The d-orbitals of transition metals in MXenes can occupy bonding (σ) or antibonding (σ*) states formed by M-X and M-T bonds. Typically, bonding states are filled and antibonding states remain empty, assuming minimal oxidation. The magnetic behavior is attributed to electrons in the nonbonding d-orbitals [42]. Khazaei et al. [43] were the first to predict ferromagnetic ground states in pure Cr_2C and Cr_2N MXenes, which are particularly valuable for spintronics applications. While covalent M-X and M-T bonds generally lead to nonmagnetic ground states due to their strength, some studies have discovered intrinsic magnetism in both unfunctionalized and functionalized MXenes, including Ti_2C and Ti_2N [44]. MXenes are promising candidates for 2D magnetic materials that can operate in ambient conditions, offering significant magnetic anisotropy, intrinsic and controllable magnetic ordering, and thermal stability. Despite advancements in predicting the magnetic properties of MXenes, there remain many intriguing challenges and opportunities in this field [45].

4. ENERGY STORAGE APPLICATION

MXenes, a family of two-dimensional transition metal carbides and nitrides, have attracted significant attention recently due to their exceptional electrical conductivity, high surface area, and customizable chemical properties [46–48]. These unique attributes make MXenes highly suitable for various energy storage applications, including supercapacitors and batteries [49]. Compared to other materials like graphene, metal oxides, and conducting polymers, MXenes exhibit superior ion intercalation and diffusion capabilities, essential for high-performance energy storage [50]. Their ability to intercalate various ions, combined with excellent mechanical flexibility and chemical stability, facilitates the development of high-performance, durable energy storage devices [51]. Moreover, the versatile surface chemistry of MXenes allows for functionalization, further enhancing their electrochemical properties. Fig. 3(b) illustrates various factors affecting the electrochemical performance of MXene anodes [52]. As research advances, MXenes are poised to revolutionize energy storage, providing sustainable and efficient solutions for future energy needs.

4.1. Supercapacitor

Supercapacitors offer high power output, rapid charging, and long cycle life [53]. They are mainly classified into Electrochemical Double-Layer Capacitors (EDLCs), which store energy through ion accumulation, and pseudocapacitors, which rely on reversible Faradaic reactions [54]. MXenes, known for their mechanical flexibility, high energy density, and excellent electrochemical performance, have become popular electrode materials [55]. Research on MXenes has surged, especially in 2021, with a focus on MXene-based composites such as conductive polymers, metal oxides, and carbon nanostructures. About 34-38% of these studies aim to improve cycle life, energy density, and oxidation resistance while addressing MXene stacking issues [56].

The energy storage performance of MXene-based materials is influenced by various factors [55]. One key factor for supercapacitors is the sheet size of MXenes synthesized through the etching process. Larger MXene sheets are generally suitable as electrode materials; however, their longer etching times lead to lower capacitance values, typically between 10-20 Fg^{-1} [57]. Smaller MXene sheets improve supercapacitor performance by providing more electrochemically active sites during charge-discharge cycles. However, the smaller size increases the risk of oxidation at the sheet edges [28]. A recent study explored how the size of Ti_3C_2 MXene flakes affects supercapacitor performance. The flakes, produced via sonication and density gradient centrifugation, had lateral sizes from 0.1 to 5 µm. By employing centrifugation, they produced MXene sheets with various lateral sizes into monodisperse fractions. The best capacitance value, 290 Fg^{-1} at 2 mV/s, was achieved with MXene flakes approximately 1 µm in size, demonstrating that lateral size significantly impacts performance [57].

The performance of supercapacitors depends on the electrolyte used. Electrolytes can be aqueous, organic, ionic, or solid [58]. Each type affects the potential window and overall performance. In acidic environments, MXene-based materials exhibit higher pseudocapacitance, leading to greater volumetric capacitance. Sulfate-based electrolytes like Na_2SO_4 and K_2SO_4 promote EDLC behavior, though they are less suitable for practical devices. Gel electrolytes such as PVA/Na_2SO_4 are often used but can suppress the voltage window and reduce electrochemical performance [59,60]. Organic electrolytes, which dissolve well in solvents like acetonitrile, can improve the potential window but are costly, toxic, and flammable. Ionic electrolytes, such as EMI-TFSI, enhance supercapacitor performance by interacting with pores and adjusting interlayer spacing. Studies have shown that MXene interlayer spacing decreases under positive potential and increases under negative potential, influenced by the intercalation and deintercalation of ions [28,61]. A recent study showed clay-like $Ti_3C_2T_x$ MXene supercapacitor electrodes in H_2SO_4 achieved 245 Fg^{-1} at 2 mV/s and retained capacitance after 10,000 cycles at 10 A/g [62].

MXenes' rich chemistry and surface functionalization boost electrochemical activity but worsen self-discharge in supercapacitors. Researchers are focusing on MXene-based composites to enhance performance [34]. Enhancing capacitance and rate performance in flexible supercapacitors' carbon-based electrodes is vital. $Ti_3C_2T_x$ MXene/CNF electrodes were made via electrospinning and carbonization Fig. 4(a-d). Fig. 4(e) shows medium-sized MXene/CNF with a porous, network-like structure formed by nanoscalefibers. $Ti_3C_2T_x$ MXene/CNF electrodes achieved 90 Fg^{-1} at 300 mV/s, 2.3 times larger than pure PAN-derived CNF. Fig. 4(f) also showed 98% retention after 10,000 cycles and excellent flexibility. These MXene/CNF electrodes hold promise for flexible electronics [63].

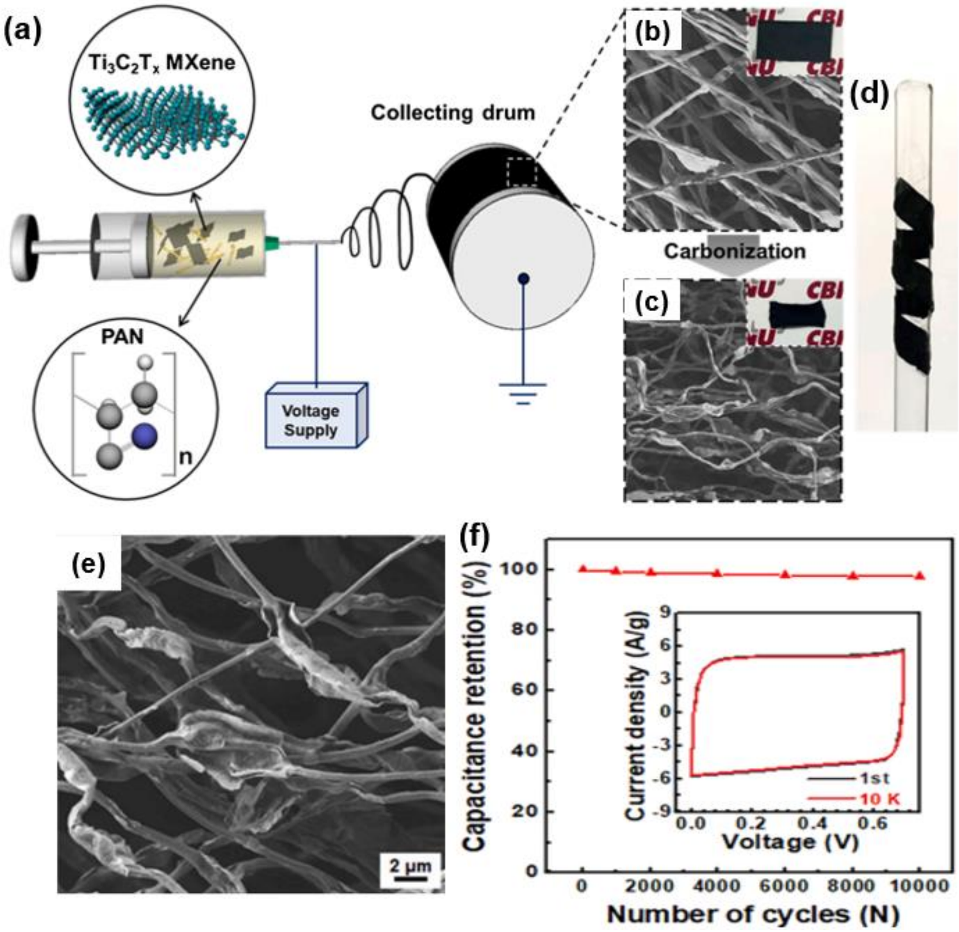

Fig. 4. (a) Electrospinning schematic, (b) and (c) show nanofibers post-spinning and carbonization with TEM insets, (d) flexible electrode wrapped around a glass rod; (e) Morphology of electrospun medium-sized $Ti_3C_2T_x$ MXene/carbon nanofibers; (f) Cyclic stability. (a-f) (Reprinted with permission from Ref. [63]. Applied surface science, Copyright © 2021, Elsevier).

Metal oxides are of great interest for their pseudocapacitive behavior and high performance. Nanocrystalline ε-MnO_2 whiskers were synthesized on MXene surfaces to create nanocomposite electrodes for aqueous pseudocapacitors Fig. 5(a). A specific capacitance of 212 Fg^{-1} was achieved for the composite (Fig. 5b). These ε-MnO_2/MXenes upercapacitors showed ~88% capacitance retention after 10,000 cycles (Fig. (5c)), leveraging MnO_2's high capacitance and MXenes' conductivity and stability [64].

Furthermore, though conjugated polymers like polyaniline and polypyrrole are used in flexible supercapacitors for their high pseudocapacitance and flexibility, their structural instability limits practicality. A new approach combines PDT with MXene ($Ti_3C_2T_x$) to form a freestanding hybrid film, enhancing cycling performance (Fig. 5d). This hybrid layer shows a dense, granular structure on $Ti_3C_2T_x$-FTO (Fig. 5e). The supercapacitor exhibits good charge-discharge symmetry (Fig. 5f) and flexibility, with 10,000 cycles of 0–90° bending (Fig. 5g). PDT enhances charge transport and stability through strong bonds with $Ti_3C_2T_x$ [65].

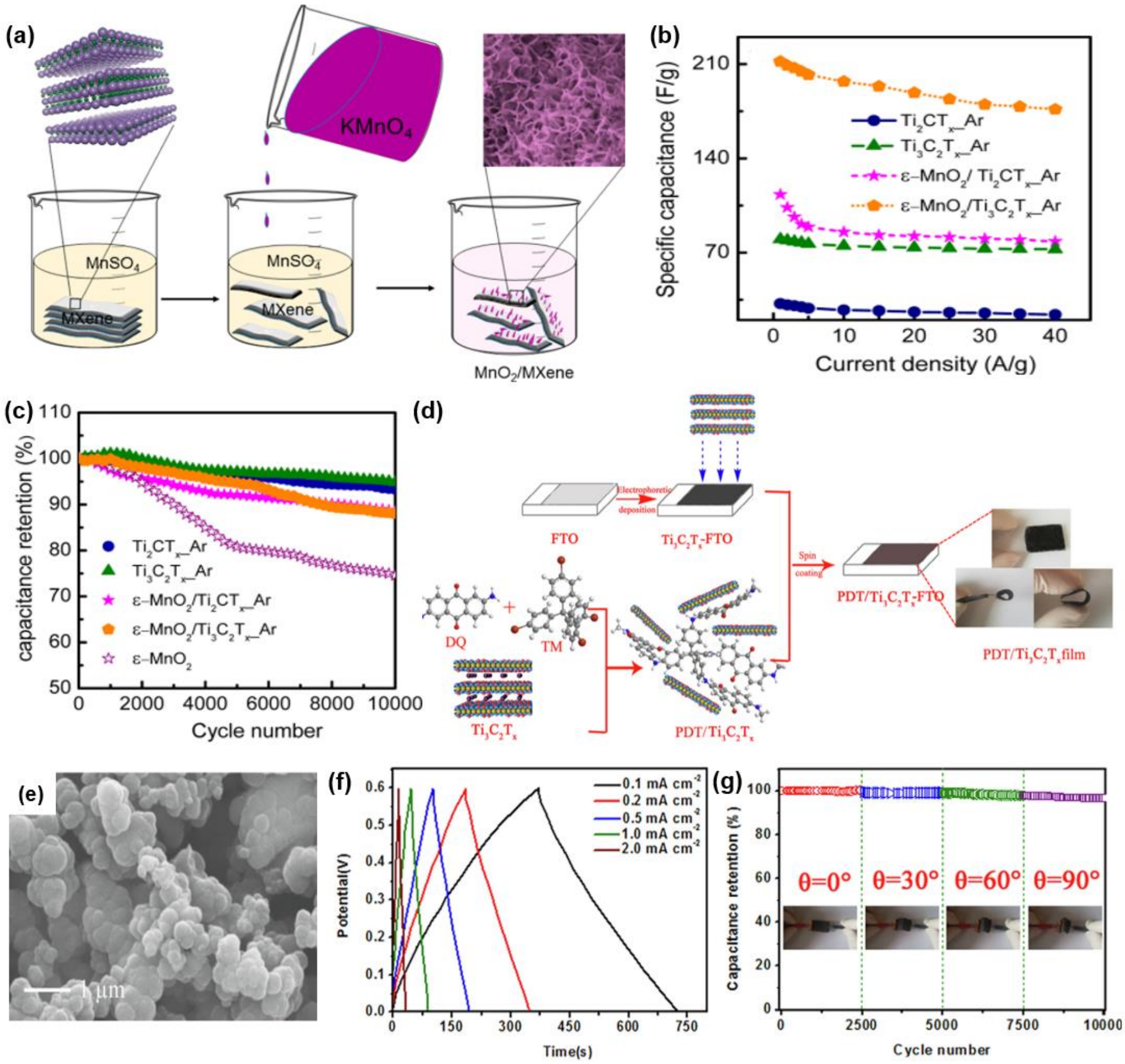

Fig. 5. (a) MnO_2/MXene composite synthesis schematic, (b) specific capacitances of MXene and metal oxide/MXene supercapacitors at various current densities, (c) cycling performance of supercapacitors at 5 A/g over 10,000 cycles. (a-c) (Reprinted with permission from Ref. [64]. Applied Materials & Interfaces, © 2016 American Chemical Society). (d) PDT/$Ti_3C_2T_x$ film electrode fabrication schematic, (e) SEM images of PDT/$Ti_3C_2T_x$ film, (f) GCD curves of PDT/$Ti_3C_2T_x$ supercapacitor, (g) cycling performance under 10,000 bends at four angles. (d-g) (Reprinted with permission from Ref. [65]. Chemical Engineering Journal, Copyright © 2019, Elsevier).

4.2. Battery

MXene-based batteries represent a cutting-edge development in energy storage technologies, leveraging the unique properties of MXenes—two-dimensional transition metal carbides, nitrides, and carbonitrides. These materials boast high electrical conductivity, robust mechanical strength, and customizable surface chemistries, making them exceptional candidates for battery electrodes. The layered structure of MXenes enables efficient ion intercalation, significantly enhancing charge storage capacity. Recent advancements in this field have focused on optimizing MXene performance through the development of composite materials, surface modifications, and structural engineering, addressing key challenges such as scalability and long-term stability. Consequently, MXene-based batteries show immense potential for advancing lithium-ion, sodium-ion, potassium-ion, and zinc-ion battery technologies, positioning them as crucial components in the future landscape of sustainable energy storage solutions.

$Ti_3C_2T_x$ has gained attention as an anode material for LIBs. For the first time, Ti_2CO_x MXene's Li-ion storage capability was demonstrated, showing about five times higher reversible capacity than Ti_2AlC MAX at 0.1 C. Its higher surface area is key to its enhanced capacity [66]. Furthermore, $Ti_3C_2T_x$ anodes for LIBs were prepared using HF alone and HF followed by DMSO intercalation. DMSO-treated $Ti_3C_2T_x$ had a first discharge capacity of 264.5 mAh/g at 1 C, compared to 107.2 mAh/g for untreated $Ti_3C_2T_x$, highlighting the improved Li-ion storage with increased interlayer spacing [67].

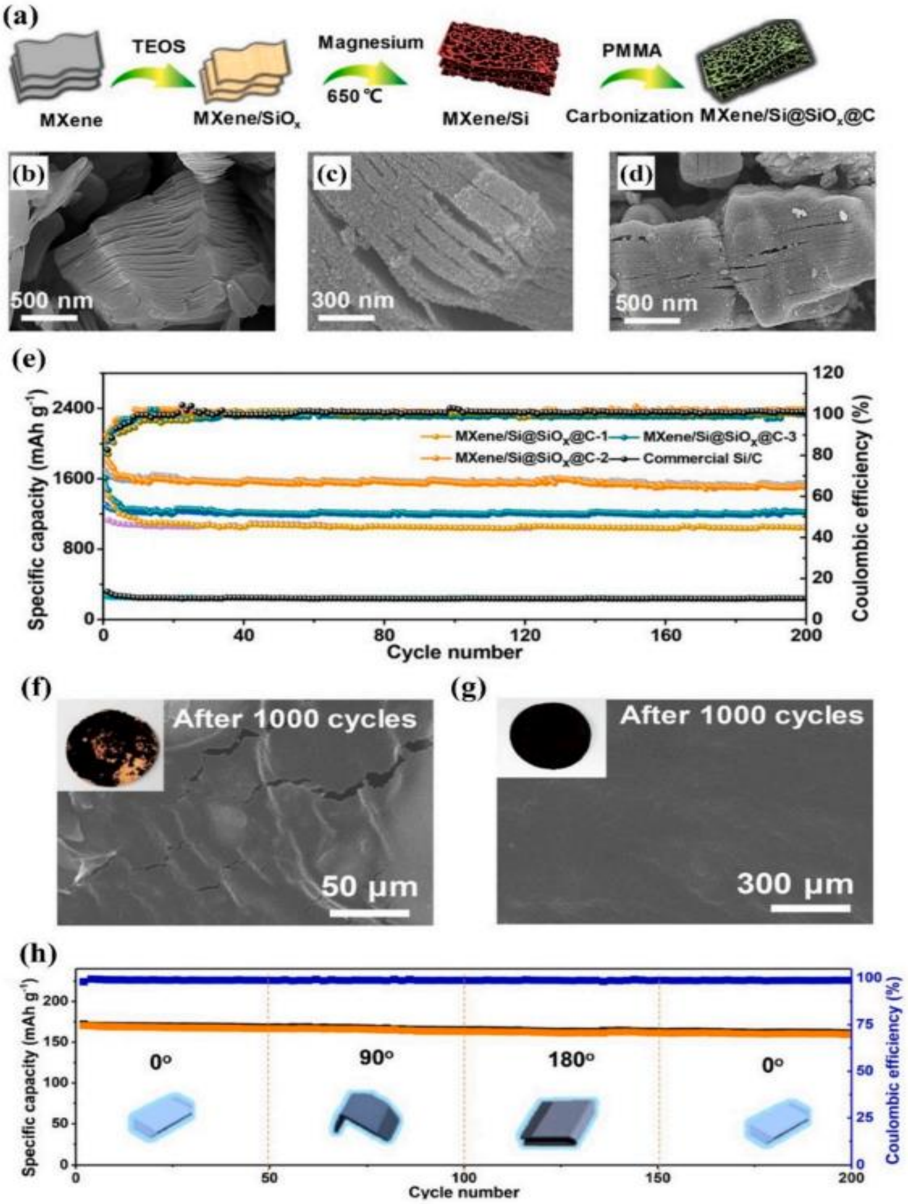

Fig. 6. (a) Schematic of $Ti_3C_2T_x$/Si/SiO_x/C synthesis process, (b) SEM image of MXene, (c) SEM image of $Ti_3C_2T_x$/Si composite, (d) SEM image of $Ti_3C_2T_x$/Si/SiO_x/C composite, (e) cyclic stability at 0.2 C, (f) SEM image of Si/C electrode after 1000 cycles at 10 C, (g) SEM image of $Ti_3C_2T_x$/Si/SiO_x/C after 1000 cycles at 10 C, and (h) cyclic stability. (a-h) (Reprinted with permission from Ref. [68]. ACS Nano, © 2019 American Chemical Society).

A recent study developed a $Ti_3C_2T_x$/Si/SiO_x/C anode for LIBs. Fig. 6 shows its preparation and performance. $Ti_3C_2T_x$ mixed with TEOS, heat-treated under H_2/Ar, and PMMA pyrolysis formed the composite (Fig. 6a). The 74.3 wt% Si composite achieved 1674 mAh/g at 0.2 C and 1547 mAh/g after 1000 cycles at 10 C (Fig. 6d). SEM images showed $Ti_3C_2T_x/Si/SiO_x/C$ maintained its structure, unlike Si/C which cracked (Fig. 6f-g). The NCM cathode displayed high retention (Fig. 6h), and full-cell batteries reached 485 Wh/kg. MXene/Si and MXene/graphene anodes maintained over 1000 mAh/g after 100 cycles at 1 A/g [68].

Although LIBs are widely used, limited lithium resources pose challenges for meeting growing global demand. Developing alternative energy storage solutions is crucial. Sodium-ion batteries (SIBs) share similar electrochemical principles with LIBs and benefit from abundant sodium resources. SIBs could replace LIBs in applications such as large-scale power grids and renewable energy storage. A heterolayer MXene composite (MoS_2-in-Ti_3C_2) has shown promise as a Na-ion battery electrode, delivering a specific capacity of 450 mAh/g at 0.05 A/g and excellent cycling performance. This supports previous DFT results and literature, suggesting that expanded and functionalized MXenes are more effective at storing Na ions [69].

Future research on MXenes should explore their use in Na-ion and K-ion batteries, which offer advantages like abundant materials and lower costs. MXenes, with their excellent conductivity and high surface area, could be optimized for these chemistries to address challenges like larger ionic sizes and different interaction dynamics. Research should focus on how MXene-based anodes and cathodes impact energy density, cycling stability, and overall performance, potentially leading to more sustainable and cost-effective energy storage solutions.

5. METHODOLOGY

The scientific investigation requires, reliable data must be gathered from a reputable database to guarantee the accuracy of the analysis and the data used as input for the software. The available databases for record-keeping include Scopus, Dimension AI, ISI Web of Science, PubMed, and Google Scholar. The Web of Science Core Collection database (http://apps.webofknowledge.com), which has extensive coverage and thorough content, was selected as the primary information source for this investigation. The **"MXene energy storage"** system was used to initiate the data collecting approach with "ALL" search fields. The data collection timeframe was set to 2012–2024, and 4371 documents were found using the search tools. The bibliometric information for the collected articles is processed by employing theMS Excel software.VOSviewersoftware was used for bibliometric analysis and computational mapping. Fig. 7. illustrates the complete search strategy, including the search string and keywords. The primary criteria used as the framework for the analysis are analysing the annual count of literature, type of literature, country wise contribution, Institute wise contribution, author contribution, most cited literature, journals and key words. A statistical technique used to group subjects that are similar and named cluster analysis.

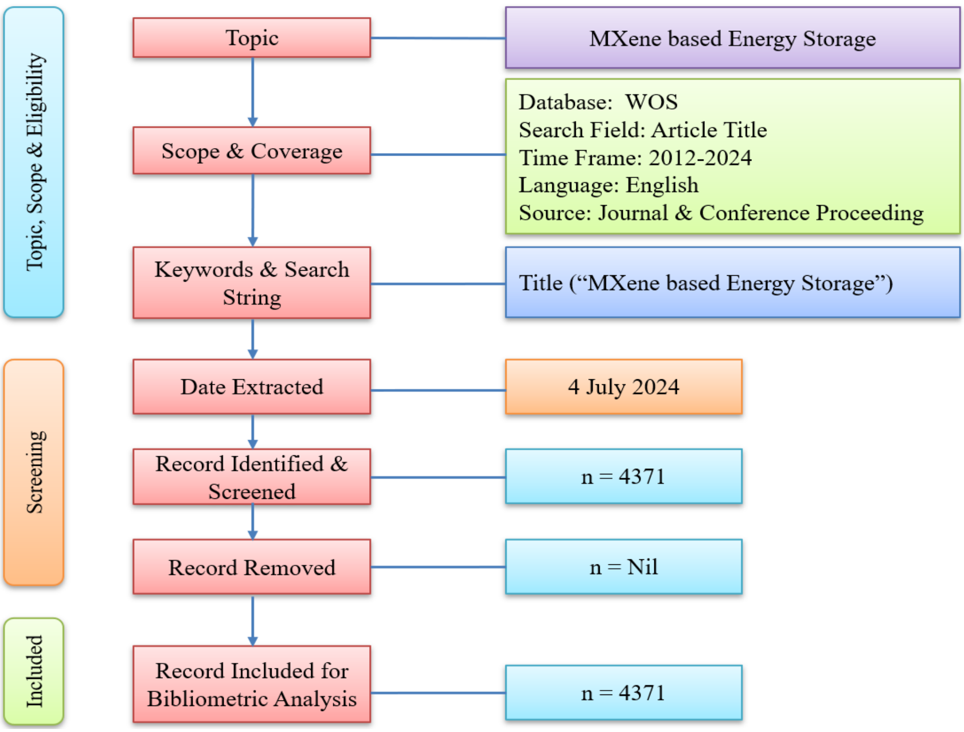

Fig. 7. Flow chart of the search process.

6. RESULT AND DISCUSSION

6.1. An overview of scientific documents

The data set used for this study is gathered for the time frame from 2012 to 2024, and atotal of 4371 records were found. There are 73 contributing nations in total, 12216 authors across 376 journals, and 1846 participating institutions. The frequently utilized words in this database were identified as 200 with 25 minimum number of occurrences of a keyword out of 7874 keywords. Fig. 8 illustrates a schematic representation of the annual growth of publications, which clearly shows the progressive establishment of the MXene-based energy storage research field.

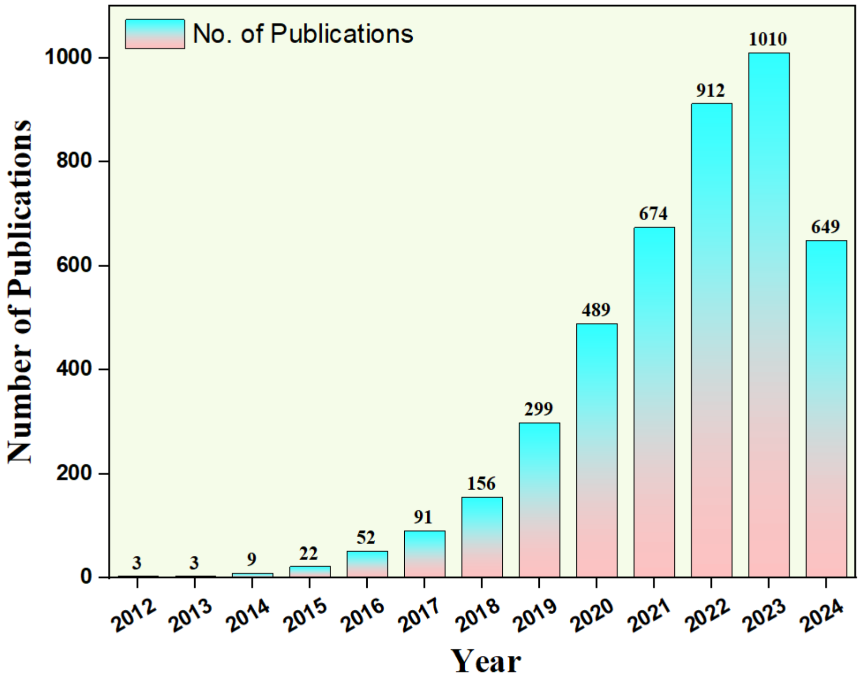

Fig. 8. Number of Publications on topic “MXene based energy storage”. Source: (http://apps.webofknowledge.com) (data accessed on 04 July 2024).

6.2. Assessment based on contributing nations

The top 10 nations fascinated by MXene-based energy storage devices are ordered according to the number of documents produced and are shown in Table 1. The top three nations identified are China, USA and India with 3003, 559 and 360 documents produced, respectively. The number of citations gained by China is 141941, USA gained 86074 and India achieved 7298. China has a lower ratio of citations to documents (47) than the United States (154), which is relatively higher. The higher the number of citations to documents exhibits the quality of research produced by the involving countries in this state-of-the-art research going on MXene-based energy storage devices. The network visualisation of nations with minimum 5 publications are shown in Fig. 9(a).

Table 1.Publication of MXene based energy storage research papers - top countries.

S. No.	Country	documents	citations	Citations to doc. Ratio
1	Peoples r china	3003	141941	47
2	USA	559	86074	154
3	India	360	7298	20
4	South Korea	331	11956	36
5	Australia	207	14457	70
6	Saudiarabia	169	11193	66
7	Pakistan	146	2695	18
8	England	103	4764	46
9	Germany	102	8567	84
10	Singapore	82	6671	81

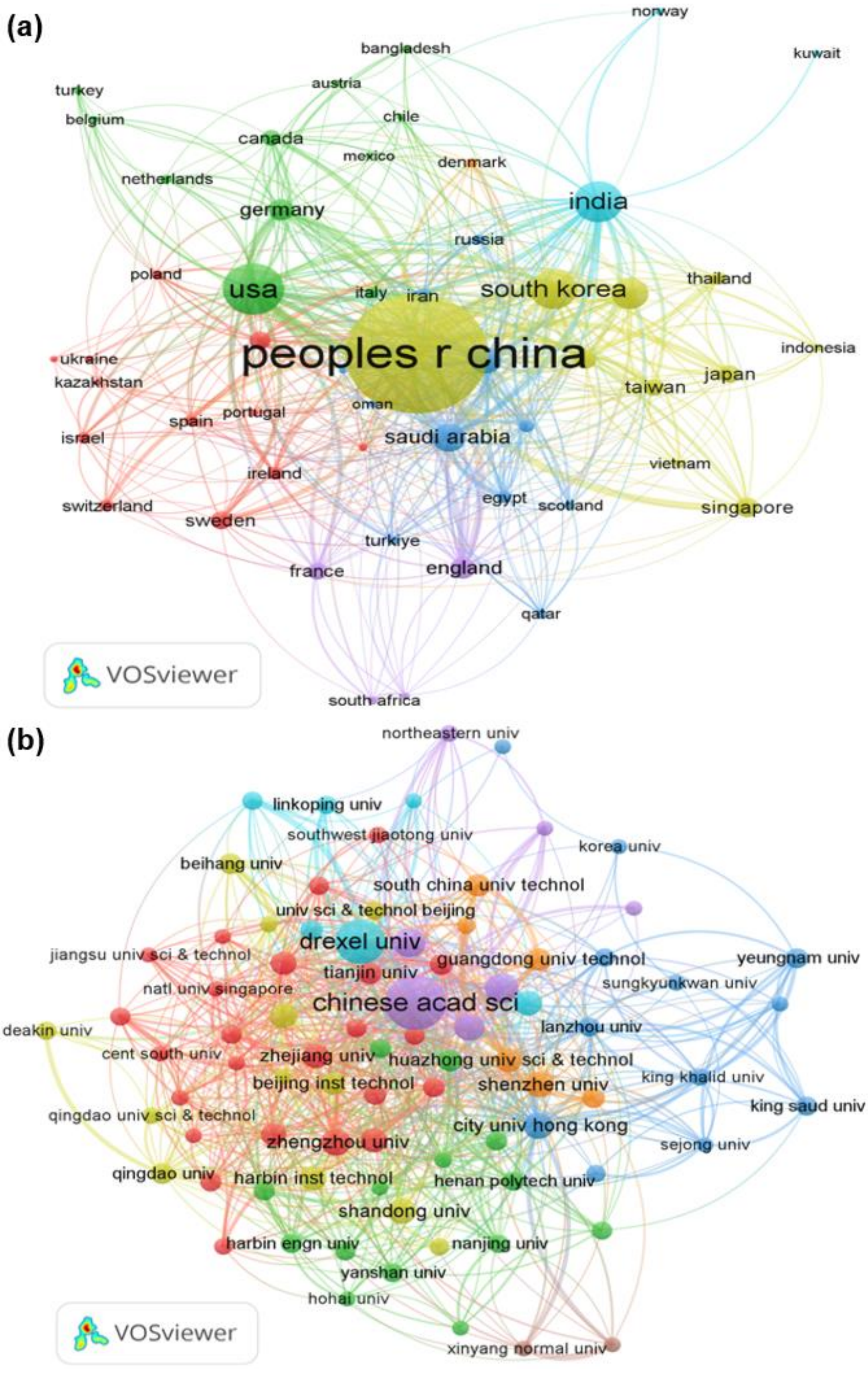

Fig. 9. (a) Network visualisation map showing global collaboration among nations with minimum number of 5 documents of a country. (b) Cluster of institutions collaboration.

6.3. Assessment based on contributing Institutions

The top 10 institutions having the highest research activities that are engaged in the MXene based energy storage devices research field are tabulated in Table 2. The top three institutions identified are China Acad. Sci., Drexel university and Univ.Sci. & Technol.China with 343, 229 and 104 documents produced, respectively. The number of citations gained by China Acad.Sci is 21072, Drexel university gained 67113 and Univ.Sci. & Technol.China achieved 8535. Among them the Drexel university achieved the highest citations to document ratio as 293. Fig. 9(b) illustrates a network of institutional collaboration.

Table 2. Ranking of Organizations based on MXene energy storage documents.

S. No.	Organization	documents	citations	Citations to Doc. Ratio
1	Chinese acad sci	343	21072	61
2	Drexel univ	229	67113	293
3	Univ sci & technol china	104	8535	82
4	Univ Chinese acad sci	100	8260	83
5	Jilin univ	88	5771	66
6	City univ hongkong	83	4596	55
7	Zhengzhou univ	80	5691	71
8	Shandong univ	79	6003	76
9	Shenzhen univ	75	3842	51
10	Tsinghua univ	74	4302	58

6.4. Assessment based on contributing Author

The documents based on MXene based energy storage devices are examined in accordance with the respective top 10 authors that performed these studies as tabulated in Table 3.

Table 3. Ranking of authors based on article contribution.

S.No.	Author	Documents	citations	Citations to Doc. Ratio
1	gogotsi, yury	198	63625	321
2	anasori, babak	59	24192	410
3	naguib, michael	40	15265	382
4	barsoum, michel w.	34	23613	695
5	zhang, wei	34	1605	47
6	wang, guoxiu	33	5221	158
7	zhang, peng	32	2588	81
8	wang, lei	31	1741	56
9	xu, bin	31	2830	91
10	alshareef, husam n.	30	5979	199

The authors are ranked in accordance with the number of articles published. The top three researchers in the respective field are Gogotsi Yury (198), Anasori, babak (59) and Naguib, Michael (40). During this bibliometric analysis, it was found that Gogotsi, Yury is top performing researcher in this field. Fig.10(a) illustrates a network of authors collaboration.

6.5. Assessment based on Keywords:

Use of relevant and appropriate keywords has a significant impact on the efficacy of document search. Among the enormous number of papers available, the keyword serves as a vital link that distinguishes the information sources. The top three keywords identified are MXene (1856), performance (975) and nanosheets (652). Top 10 keywords related to this research are tabulated in Table 4. A network of keywords occurrence is illustrated in Fig. 10(b).

Table 4. Ranking of keywords based on occurrences.

S. No.	keyword	occurrences
1	mxene	1856
2	performance	975
3	nanosheets	652
4	energy-storage	644
5	graphene	550
6	intercalation	489
7	mxenes	481
8	carbon	458
9	storage	456
10	supercapacitors	396

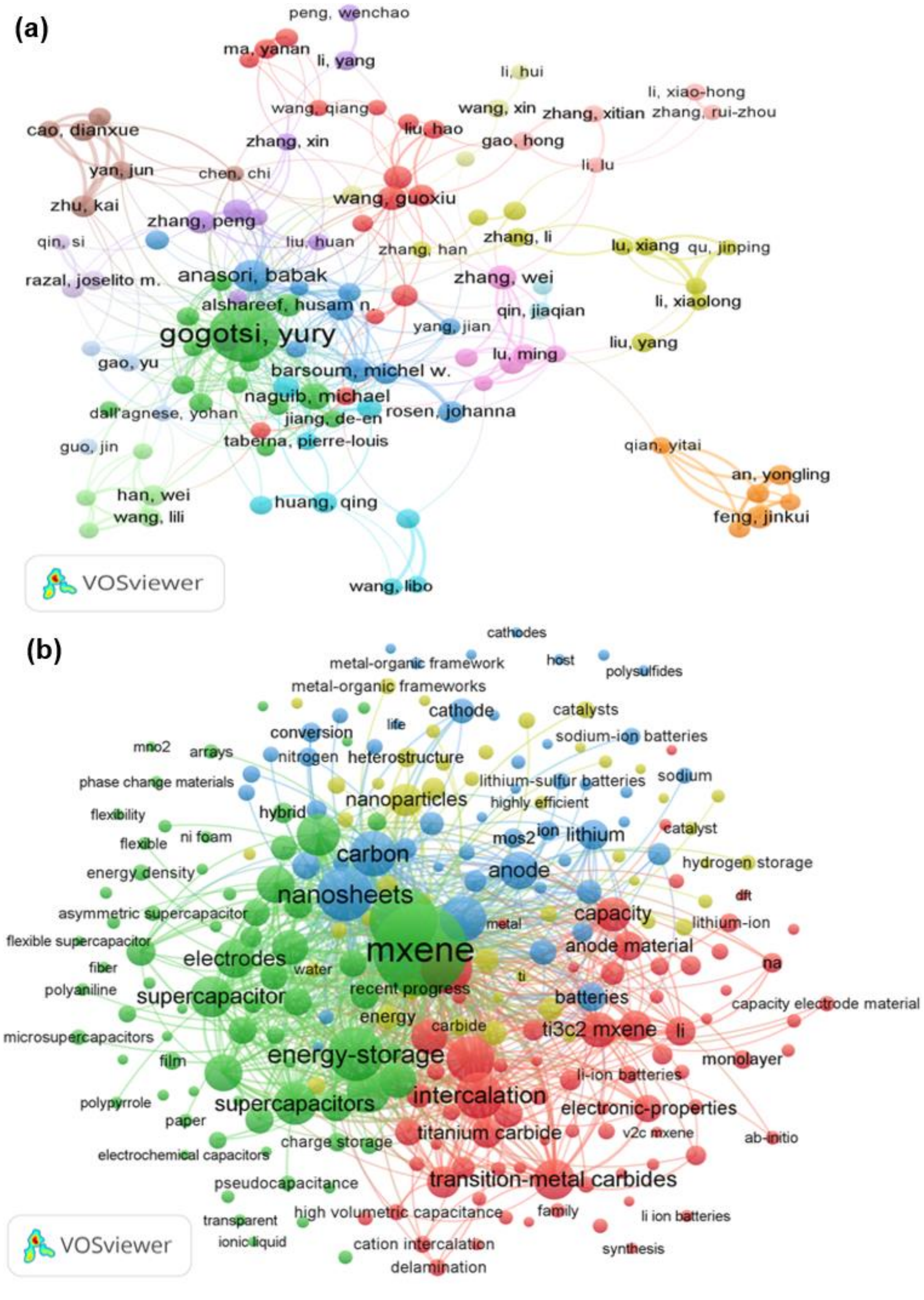

Fig. 10. (a) Cluster of authors collaboration; (b) An illustration of co-occurrence of keywords.

7. CONCLUSIONS

This review comprehensively explores the field of MXenes, focusing on their synthesis methods, key properties, and applications in energy storage technologies. We have detailed various synthesis techniques and examined the unique properties of MXenes, including surface terminations, conductivity, optical and magnetic characteristics. The review further highlights the potential of MXenes in advancing energy storage solutions, particularly in supercapacitors and batteries. Despite substantial progress, a thorough scientometric study was previously lacking, and this review addresses this gap using VOSviewer software to analyze research trends from 2012 to 2024. By examining data across countries, organizations, and authors, we reveal critical collaboration patterns and research themes. The findings underscore MXenes' promising role in meeting global energy demands and suggest future research directions to enhance their practical applications, particularly in the realms of electric vehicles and portable electronics.

Data availability

Data will be made available on request.

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IZVOD

MXenes: SINTEZA, SVOJSTVA I APLIKACIJE U NAPREDNIM TEHNOLOGIJAMA SKLADIŠTENJA ENERGIJE

MXSenes su se pojavili kao veoma obećavajući materijali u oblasti naprednih tehnologija skladištenja energije, zahvaljujući svojim karakterističnim svojstvima i raznovrsnim primenama. Ovaj pregled nudi sveobuhvatnu analizu MXSena, fokusirajući se na njihove metode sinteze, osnovna svojstva i primene u punjivim baterijama i superkondenzatorima. Kao odgovor na sve veće globalne potrebe za energijom, MXSenes predstavljaju ubedljiva rešenja zbog svojih izuzetnih električnih i elektrohemijskih karakteristika. To uključuje visoku provodljivost, veliku površinu, hidrofilnost i jedinstvenu dvodimenzionalnu strukturu koja se sastoji od metalnih karbida, nitrida i karbonitrida. Pored toga, ovaj pregled uključuje detaljnu bibliometrijsku analizu korišćenjem računarskih alata kao što je VOSviever, koji ispituje globalni pejzaž MXSene istraživanja u periodu od 2012. do 2024. Ova analiza identifikuje trendove saradnje između različitih zemalja, institucija, autora i časopisa, naglašavajući vodeće oblasti istraživanja. Sve u svemu, ovaj pregled naglašava značajan potencijal MXSenes-a u unapređenju tehnologija za skladištenje energije. Pruža uvid u buduće pravce istraživanja i praktične primene koje bi mogle efikasno da zadovolje rastuće potrebe za energijom koje pokreću električna vozila i prenosiva elektronika.

Ključne reči: *MXSene; 2D materijali; skladištenje energije; supercapacitor; bibliometrijska analiza*

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1. *Sahil Jangra: https://orcid.org/0009-0004-6217-9496*
2. *Bhushan Kumar: https://orcid.org/0009-0006-8870-5962*
3. *Subhankar Das: https://orcid.org/0000-0002-1724-2722*
4. *Manjeet Singh Goyat: https://orcid.org/0000-0002-0668-6512*
5. *Jaishree Sharma: https://orcid.org/0000-0001-9954-2202*