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State-of-the-art developments in mxenes: A comprehensive review

ABSTRACT

In recent years, two-dimensional (2D) materials have garnered significant attention because of their distinctive properties and potential applications in a wide range of applications. Among these materials, MXenes, a family of transition metal carbides, nitrides, and carbonitrides, have emerged as a prominent class of 2D materials with remarkable structural, electrical, thermal, optical, mechanical, and chemical properties. This review explores recent advancements in the synthesis techniques, properties, and diverse applications of MXenes in energy storage, electromagnetic interference (EMI) shielding, sensors, and environmental applications. Additionally, it provides a bibliometric overview, analyzing 10,957 research papers to assess global scientific trends and future research directions using Web of Science (WOS) data and VOSviewer software. This review aims to provide a comprehensive understanding of the state-of-the-art developments in MXene technology, offering insights into future directions and potential advancements in this rapidly evolving field.
Keywords: *2D materials; MXene; synthesis;applications; bibliometric analysis*

1. INTRODUCTION

Over the past 20 years, the discovery of the unique physical properties of single-layer graphene has sparked extensive research into two-dimensional (2D) materials [1]. In addition to graphene, materials such as transition metal dichalcogenides (TMDs) [2], boron nitride[3] and phosphorene [4], and their various derivatives have become some of the most extensively studied. While many of these materials continue to be of academic interest, several have gained significant attention due to their exceptional properties, which have paved the way for practical applications. Notably, carbides, nitrides, or carbonitrides of transition metals, collectively known as MXenes, have emerged as a rapidly expanding family of 2D materials [5]. MXene is derived from its 3D precursor known as the MAX phase, which has a general formula of $M_{n+1}AX_n$, (where n=1−3) [6]. In this formula, M represents a transition metal, A is typically the most commonelement in groups 13 and 14 and X is carbon and/or nitrogen, which are coupled by strong metallic, ionic, and covalent bonds [7]. MXenes, which are characterized by the general formula $M_{n+1}X_nT_x$, where T_x represents surface terminations such as hydroxyl (-OH), oxygen (=O), or fluorine (-F), result from the selective etching of the MAX phase[8]. The removal of the A element during synthesis introduces these surface terminations, which significantly influence the material's properties. The bonds between the constituent parts of the MAX are too strong to be broken mechanically, in contrast to inorganic graphene equivalents, in which the nanosheets are connected by weak Van der Waals force and may be easily delaminated. It is important to note that M and the X atom have mixed chemical bonds that include covalent, ionic, and metallic bonding[9].In contrast, the bonds between M and the A atoms are purely metallic [10]. Consequently, the metallic bond is weaker than the covalent bond. By selecting an appropriate etching reagent, it is possible to break the M–A bonds and effectively remove the elements of the A layer [11]. In 2011, Naguib et al. [12] successfully obtained exfoliated, loosely packed accordion-like Ti_3C_2 2D materials by selectively etching the Al atom layer from Ti_3AlC_2, a typical MAX phase.

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Unlike most other 2D materials, such as graphene, MXenes demonstrate remarkable versatility with a unique combination of properties. They exhibit high electrical conductivity (25,000 S/cmfor $Ti_3C_2T_x$ MXene) [13], surface hydrophilicity[14], robust mechanical strength (tensile strength up to 570 MPa for $Ti_3C_2T_x$) [15],Young's modulus up to 333 ± 13 GPa for $Ti_3C_2T_x$ [16], tunable surface functionality, with surface terminations including O, OH, H, F, Cl, S, Br, Te, NH, in addition to bare MXenes (without surface termination) [17],the ability to absorb electromagnetic waves[18], and a high negative zeta potential[19], which enables the formation of stable colloidal solutions in water. The hydrophilicity of MXenes, in clear contrast to graphene, arises from surface terminations like –O and –OH acquired during synthesis [20]. Additionally, the negative zeta potential is due to surface groups including –Cl, –F, –O, and –OH, which contribute to their colloidal stability and broad applicability in various technological fields [21]. Due to their unique properties, MXenes find diverse applications with outstanding performance in various fields. In the energy sector, they are employed as energy storage devices, such as supercapacitors [22–24] and batteries [25]. Additionally, MXenes are utilized in electromagnetic interference (EMI) shielding [26–29], where their layered structure and high conductivity play a crucial role. In the biomedical field, MXenes are used for drug delivery, bioimaging, and cancer therapy [30–32]. For water purification, MXenes are effective in removing heavy metals and organic pollutants [33–36]. They also find applications in electronic devices, coatings, and additives to improve the properties of composite materials[37]. Further applications for MXenes include sensors [38–41], and photocatalysis [42–44], in addition to many more applications. These wide-ranging applications underscore the versatility and significant impact of MXenes in advancing various technological and industrial solutions.

Owing to their outstanding properties and diverse applications, there has been exponential growth in the number of publications on MXenes since their inception. Figure 1 shows a schematic illustration of the yearly increment in the number of articles, it demonstrates the gradual emergence of the MXene study field with less than 1% of articles published in the first three years, 2012, 2013, and 2014. Due to recent developments in the synthesis of MXene as well as an upsurge in potential applications, there has been an exponential improvement in publications since 2018. Records indicated an increase of over 5000% from 2017 to 2023.

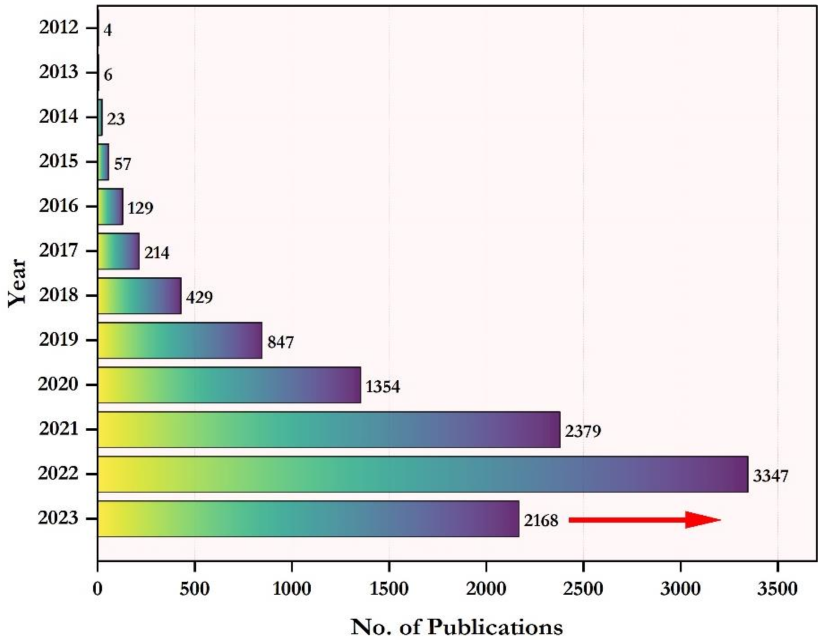

Figure 1. Exponential rise in MXene-based articles

This review article presents a comprehensive overview of the extensive family of 2D layered MXene materials, highlighting their unique structural features and remarkable properties that enable a wide range of applications. It discusses the various synthesis methods developed for producing 2D MXenes, along with their modifications. Finally, we describe various recent applications of MXenes, emphasizing their practical utility. To highlight the significance and impact of MXene research, we also include a bibliometric analysis. This analysis is crucial as it provides insights into the research trends, key contributors, and the overall growth of the field, thereby underscoring the advancements and guiding future studies in MXene research.

2. SYNTHESIS OF MXENES

Two primary methods explored for synthesizing MXenes are the top-down and bottom-up approaches. In the top-down process of producing MXene, bulk materials are either reduced or parts of the overall composition are removed to produce micro to nano-size particles[10]. Selectively etching and exfoliation fall under top-down techniques, while chemical vapor deposition (CVD), and template methods are classified as bottom-up techniques [45]. The top-down approach is widely used for the preparation of multilayer since the first successful removal of aluminum from Ti_3AlC_2 to make multilayer Ti_3C_2 was accomplished using this process [12]. Wet chemical etching using HF acid yields multilayered MXenes of different compositions, including $Ti_3C_2T_x$, V_2CT_x, Ti_2CT_x, and Nb_2CT_x [46]. Despite HF being the main etchant in the MXene synthesis process, alternatives have been investigated because of its extremely volatile and hazardous nature [47]. Alternative etchants, such as electrochemical [48], halogen [49], molten salts [50], and hydrothermal [51], have broadened synthesis methods and resultant properties. Bifluorides of sodium [52], ammonium [53], and potassium [52] have been reported as alternative etchants for the selective removal of Al from Ti_3AlC_2. However, the synthesis of MXenes using HF leads to the intercalation of cations with fluoride or bifluoride salts, resulting in increased interlayer spacing. This interlayer spacing is further expanded when HF is used in combination with fluoride salts compared to using HF alone [52]. In-situ HF synthesis is carried out with reduced HF concentrations (5−10 wt%) within acid mixtures. To synthesize $Ti_3C_2T_x$[54], $Mo_3C_2T_x$ [55], and V_2C [56] MXenes from Ti_3AlC_2, Mo_3AlC_2, andV_2AlC MAX phases, a mixture of HCl and fluoride salts are utilized as the etchant. However, scaling of these techniques is challenging because unetched MXene remains during the exfoliation process [53]. The unetched MXene persists because the in-situ HF etching process may not uniformly penetrate all the layers, leading to incomplete removal of aluminum from some regions. This incomplete etching results from variations in the diffusion of HF through the multilayer structure and the limited access to inner layers, which is influenced by the MXene's intrinsic layer spacing and surface chemistry. Traditional HF aqueous solutions that are acidic cannot effectively etch nitride-based MAX phases. Consequently, producing nitride MXenes, like Ti_4N_3, requires selectively removing aluminum from Ti_4AlN_3 using molten salts. Although numerous studies still use HF or fluoride sources as the preferred etchant for the MAX phase, this acid is extremely toxic and dangerous to handle, particularly for biological applications. Even a small amount of unreacted HF can cause cell death [57]. In humans, HF exposure can result in systemic toxicity that can be fatal [58]. Consequently, the direct use of HF or its in situ formation presents significant safety and environmental risks, impeding the progress of MXenes' applications [58]. Therefore, a fluorine-free etching technique is highly preferable for producing MXenes. Such an approach not only enhances safety and reduces environmental risks but also promotes the broader application and development of MXenes in various fields. There are several other methods for synthesizing MXenes without the use of HF. One alternative is using molten salts, such as molten chloride salts zinc chloride ($ZnCl_2$) [50] and copper chloride ($CuCl_2$) [59], to selectively etch the MAX phase. This method operates at high temperatures, which can enhance the efficiency of the etching process while avoiding the hazards associated with HF. Additionally, an electrochemical intercalation method was developed, where an electrolyte solution facilitates the removal of elements from the MAX phase through an electrochemical reaction, effectively producing MXenes without HF [48]. During the past several years, various bottom-up methods for synthesizing MXenes have emerged, including chemical vapor deposition (CVD) [60], the template method [61], and plasma-enhanced pulsed laser deposition (PEPLD) [62]. These approaches tend to produce higher quality MXenes than traditional top-down techniques, as they allow for greater control over atomic arrangements and surface properties. In 2015, ultrathin α-Mo_2C orthorhombic 2D crystals, just a few nanometers thick and with lateral sizes up to 100 µm, were successfully synthesized using CVD with methane on a copper foil bilayer substrate atop molybdenum foil [60]. This technique was also applied to create ultrathin tungsten carbide (WC) [63] and tantalum carbide (TaC) [64] crystals from tungsten and tantalum, respectively. However, despite these advancements, bottom-up methods have yet to achieve the synthesis of single-layer MXenes, resulting only in the formation of ultrathin films comprising multiple layers. This limitation underscores the challenges in manipulating atomic-scale interactions and achieving precise layer control in material synthesis.

The synthesis and application growth of MXenes, as illustrated in Figure 2a, is closely tied to advancements in their production methods since their discovery. These developments have enhanced the intrinsic properties of MXenes, such as their electrical conductivity, mechanical strength, and chemical stability, making them increasingly viable for a wide range of applications. The timeline in Figure 2a highlights the correlation between synthesis breakthroughs and the expanding scope of MXene applications, underscoring the importance of continued research in refining synthesis methods to unlock the full potential of these versatile materials.Based on the number of atomic layers, MXenes are categorized into the following families: M_2X, M_3X_2, M_4X_3, and, most recently, M_5X_4, as shown in Figure 2b.

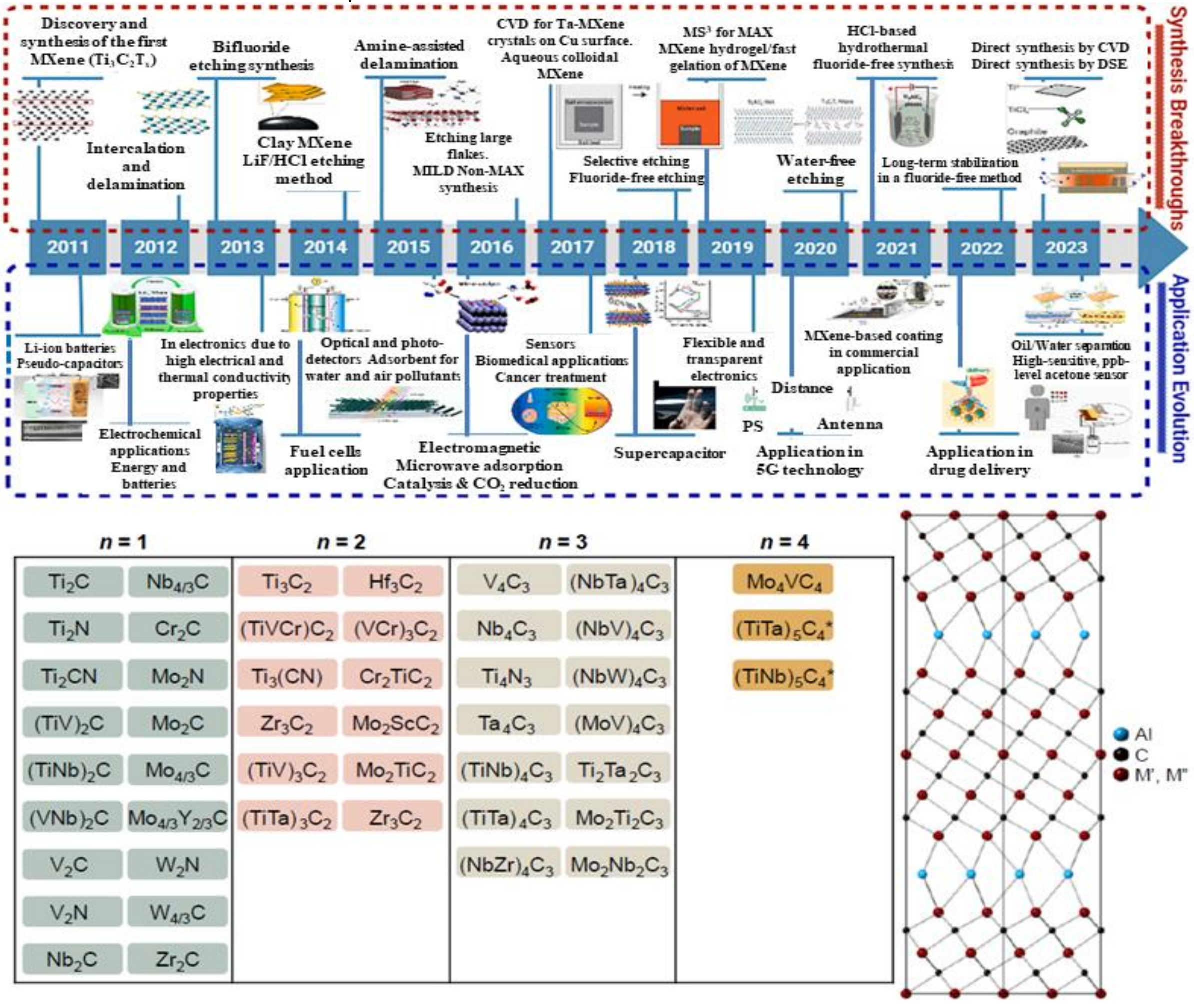

Figure 2. (a) Chronological overview of key synthesis advancements and emerging applications of MXenes from their discovery in 2011 to the present. Reproduced with permission from Reference [78]. © 2023 Elsevier. (b) List of MXenes Reported So Far, showcasing their structural diversity.Reproduced with permission from Reference[105]. © 2023 American Chemical Society

The constituents of MAX and MXene are shown in the periodic table (Figure 3a). The crystal structures of the 211, 312, and 413 MAX phases, along with the exfoliation process of MXene ($M_3X_2T_x$) from the MAX phase (M_3AX_2) to obtain free-standing nanosheets, are illustrated in Figure 3b. Following etching in the HF acid, the multilayered MXene particles exhibit an accordion-like structure (Figure 3d), which is different from the rock-like appearance of the MAX phase (Figure 3c)[53]. After intercalation with dimethyl sulfoxide (DMSO), which causes the layered structure to swell, the interlayer spacing of the expanded multilayer-MXene increases, and the interactions among the layers weaken[65]. When subjected to bath or tip sonication, the multilayer-MXene delaminates, producing smaller nanosheets due to the scissor effect of the sonic energy[66]. The corresponding SEM image is shown in Figure 3e. Figure 3f shows the XRD patterns of the Ti_3AlC_2 and $Ti_3C_2T_x$ powders, confirming the removal of the aluminum layer. The characteristic (104) peak at 39° associated with aluminum disappeared, additionally, the (002) peak at 9.8° shifted to a lower angle, indicating the delamination of MXene layers [67,68]. The water contact angle for the MAX phase was reported as 86°, whereas for MXene, it was 57.8°, indicating that the MXene film is hydrophilic.

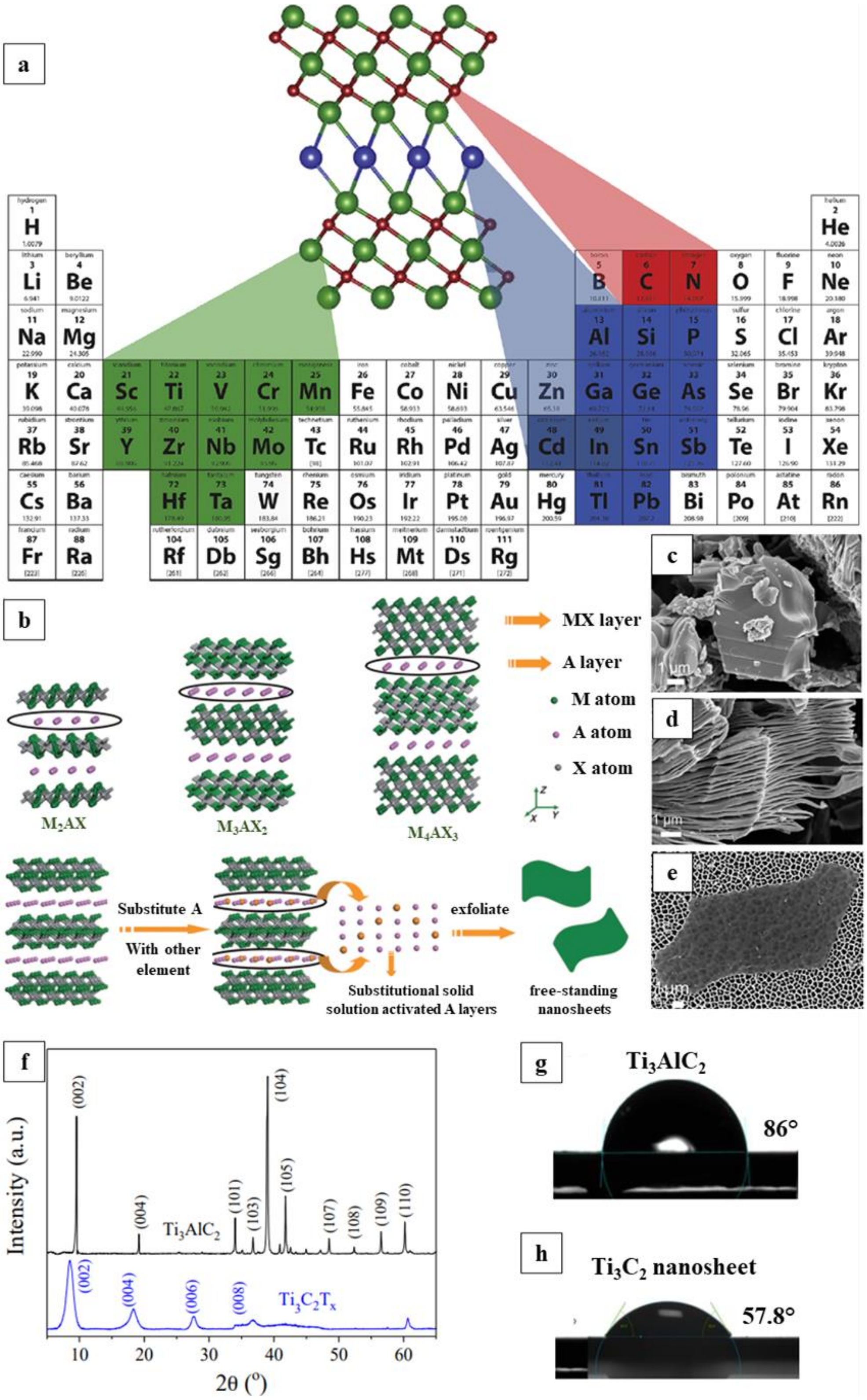

Figure 3. (a) The chemical components constituting MAX and MXenes. Reproduced with permission from Reference [5]. © 2019 Elsevier. (b) Schematic of the synthesis process of MXene. Reproduced with permission from Reference [106]. © 2013 Wiley. SEM images showing (c) MAX phase [66], (d) multilayered MXene. Reproduced with permission from Reference [66]. © 2020 Wiley, and (e) MXene in a delaminated state. Reproduced with permission from Reference [53]. © 2017 American Chemical Society. (f) XRD spectra of MAX and MXene [107]. contact angles of (g) MAX, and (h) MXene [108]

3. PROPERTIES

Over the past decade, 2D materials attracted significant attention owing to their unique properties distinct from their bulk forms. MXenes, in particular, combine metallic conductivity from their transition metal nitride, carbide, or carbonitride framework with hydrophilicity due to surface terminations. These materials exhibit diverse mechanical, electrical, electronic, magnetic, and optical properties. Their performance can be fine-tuned by adjusting their transition metals and surface terminations. A summary of MXene properties is shown in Figure4.

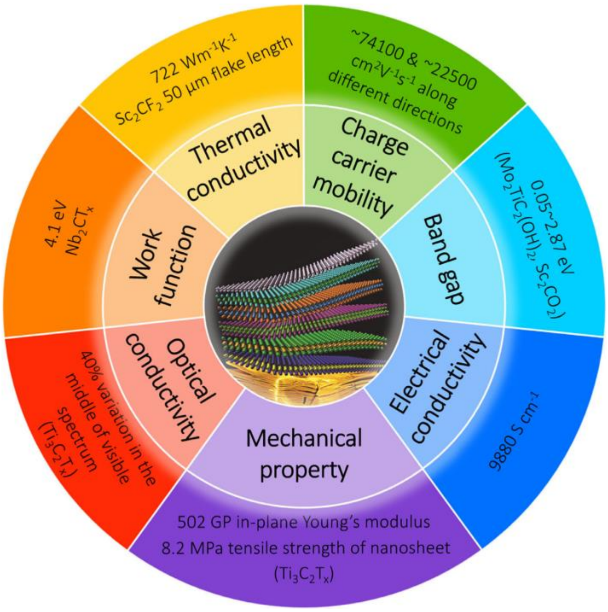

Figure 4. Summary of MXene properties, including thermal and electrical conductivity. mechanical property, work function, optical conductivity, band gap, and charge carrier mobility. Reproduced with permission from Reference [66]. © 2019 Wiley

3.1. Structural properties

In practical applications, MXene is typically enriched with surface termination groups like OH, F, and O following exfoliation from its 3D precursor MAX phase. OH, and O surface terminated MXenes are considered highly stable, as F terminations are swapped out for OH groups, whenever theyare rinsed or stored in water[69]. Studies have shown that metal adsorption or high-temperature procedures can change OH groups into O terminations [69]. Additionally, O-terminated MXene can break down into without surface-terminated MXene as well as metal oxides when exposed to metals like Ca, Mg, or Al[70].

3.2. Hydrophilic

MXenes are highly hydrophilic owing to their unique surface chemistry, which is dominated by the presence of various surface terminalgroups, resulting in negatively charged surfaces [71]. These functional groups enhance their affinity for water and other polar solvents, making MXenes easily dispersible in aqueous solutions [72]. These groups are introduced during synthesis, typically involving selectively etching of A-layers from the MAX precursors using acidic solutions like HF acid[73]. This hydrophilic nature is advantageous in applications requiring dispersion in water-based solutions, such as in inks for printable electronics, humidity sensors, water purification, and composites for enhanced mechanical properties and EMI shielding, where uniform distribution within a matrix is crucial [74].

3.3. Electrical Property

MXenes exhibit exceptional electrical and electronic properties, primarily due to their unique structure and composition, which provide a high density of mobile charge carriers [75]. The layered structure of MXenes allows for efficient charge transport, akin to other well-known 2D materials like graphene[76]. Additionally, the transition metals in MXenes contribute d-electrons, which facilitate metallic conductivity[7]. The existence of conductive channels within the MXene layers and the relatively low energy barriers for electron movement result in high electrical conductivity[77]. This combination of features makes MXenes very well-suited for applications in energy storage devices, sensors, and EMI shielding, where excellent electrical performance is crucial[14].

3.4. Mechanical properties

The unique mechanical strength of MXenes is largely attributed to the robust M–X bond. Beyond bond strength, MXene nanosheets are held together by hydrogen bonds that are around six times higher than those found in graphite as well as MoS_2 sheets [78]. A particular study highlighted that the bare MXenes, which lack termination groups, possess interlayer binding energyas high as 3.3 J/m^2[79]. Earlier first-principles calculations had indicated that the elastic moduli of MXenes are at least double those of their parent 3D MAX phases and other 2D materials [80]. However, the interlayer mechanical characteristics and stiffnessof MXenes are influenced by surface-terminating groups andn-value in the $M_{n+1}X_n$.

3.5. Optical properties

In optics, MXenes have showcased intriguing attributes over recent years, such as optical transparency, efficient photothermal conversion, and plasmonic behavior. These capabilities to interact with light in diverse manners have profoundly influenced the research community[81]. The material's optical properties are predominantly dictated by its surface terminations, underscoring their critical role in modulating how MXenes interact with light. This nuanced understanding is pivotal for leveraging MXenes in advanced optical applications, from transparent electrodes to photonic devices. The optical characteristics of MXenes differ based on their composition and the surrounding medium. Generally, MXenes exhibit minimal light absorption in the UV–Vis range (300–500 nm). However, a 5 nm thick film of $Ti_3C_2T_x$ is largely transparent within this range, with a transmittance of approximately 91% [66]. Variations in optical behavior among MXenes are notable; for instance, although Ti_3N_2 and Ti_3C_2 exhibit similar light reflectivity, Ti_3N_2 is a much better absorber. Conversely, Ti_3C_2 has a higher refractive index of 11.9 compared to 9.9 for Ti_3N_2[66].

4. APPLICATIONS OF MXENES

The distinctive blend of exceptional electrical conductivity and hydrophilicity in MXenes makes them excellent alternatives for a diverse array of applications.Their layered morphology allows for the intercalation of ions and molecules, further enhancing their versatility. Modifying their surface terminationsenables precise control over their electronic properties and chemical reactivity. Additionally, MXenes exhibit flexibility and outstanding mechanical strength making them appropriate for use in flexible electronics and composite materials.Figure 5 illustrates the diverse applications of MXenes, showcasing their broad spectrum, versatility, and effectiveness across multiple domains.

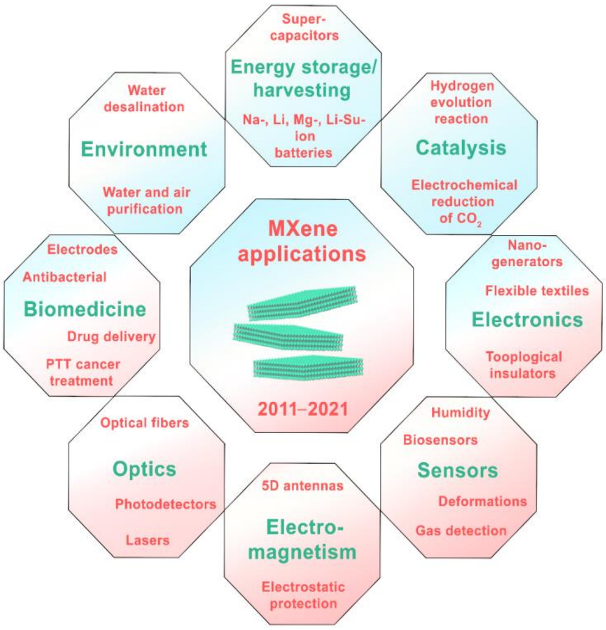

Figure 5. Overview of Various Applications of MXenes [14]

MXenes offer promising applications across diverse fields owing to their unique properties. Some key areas of potential include:

4.1. Energy Storage

Batteries, while widely used for energy storage in portable electronics and electric vehicles, are limited by their lower power densities, and degradation over time [82]. Due to their exceptional electrical conductivity and the ease with which ions can diffuse between their layers, MXenes have demonstrated significant potential as electrodes for sodium [83], potassium [84], aluminum [85], lithium [86], and zinc ion batteries [25]. Most research to date has predominantly focused on sodium and Lithium-ion batteries. For instance, multi-layered $Ti_3C_2T_x$ exhibits a capability of approximately 150 $mAhg^{-1}$ at 260 mA g^{-1} in Lithium-ion batteries [87] and nearly 100 mAh g^{-1} at 100 mA g^{-1} in Sodium-ion batteries [70]. However, electrodes constructed from predominantly single-layered, delaminated flakes are anticipated to achieve even higher capacities because of their increased surface area exposure to the electrolyte.

Supercapacitors offer an alternative for energy storage in electric vehicles and portable electronics but have lower energy densities than batteries[88]. Efforts to improve their energy density focus on increasing volumetric capacitance [89]. Supercapacitors are categorized into electrical double-layer capacitors, which accumulate charge via ion accumulation at the electrode and electrolyte interfaces, and pseudocapacitors, which utilize surface redox interactions for charge storage. While pseudocapacitors generally have higher volumetric capacitance, they often have poor cycling stability. Because of their 2D structure, vast surface area, and defined geometry, MXenes are promising materials for supercapacitor electrodes. The fast electron transport provided by the transition metallic core layers in MXenes enables exceptionally high rates of charge storage within the electrode [90]. Their surface, resembling transition metal oxides, offers redox-active spots essential for pseudocapacitive charge retention. This dual functionality makes MXenes highly suitable for high-performance batteries and ultrafast supercapacitors as electrode materials. Additionally, the ultrathin interlayer spacing among 2D sheets facilitates swift ion transport and intercalation. This spacing can be adjusted through techniques such as pillaring, pre-intercalation, and the creation of heterostructures or hybrids that utilize different 2D materials to accommodate ions of various sizes. Moreover, MXenes' surface terminations can be engineered to optimize specific redox reactions, enhancing their performance in electrochemical applications. MXene-based structures used in batteries as electrode materials are presented in Table 1. The capacitance and related characteristics of MXene as a supercapacitor electrode material are listed in Table 2.

Table 1. MXene-derived structures are employed as electrode materials in batteries

MXene Based Material	Battery type	Electrode	Initial Capacity (mAh·g^{-1})	Current Density	Capacity Retention (mAh·g^{-1})	No. of Cycles	Coulombic Efficiency (%)	Ref.
V_2CT_x	Al-ion	cathode	335	100 mA·g^{-1}	112	20	90	[111]
$Ti_3C_2T_x$	Na-ion	anode	110	30 mA·g^{-1}	73	70	100	[112]
Nb_2C	Li-ion	anode	780	0.5 C	420	100	≈100	[86]
V_2C	Li-ion	anode	467	1 C	291	20	98.6	[113]

Table 2. Electrochemical capabilities of MXene-based electrode materials in supercapacitors

MXene Based Material	Type of Electrode	Electrolyte	Rate	Capacity Retention F·g^{-1}	Cycle Number	Volumetric Capacitance F·cm^{-3}	Ref.
V_2CT_x	film electrode	seawater	2 A·g^{-1}	181.1	5000	317.8	[114]
$Ti_3C_2T_x$	three-electrode system	H_2SO_4 (3 M)	0.5 A·g^{-1}	351	10000	1142	[115]
Ti_2CT_x	porous	30 wt% KOH	1 A·g^{-1}	51	6000	-	[116]
Ta_4C_3	free-standing	0.1 M H_2SO_4	1 V·s^{-1}	481	2000	520	[88]
Ti_3C_2/CNT	hybrid films	KOH (6 M)	1 A·g^{-1}	134	10000	-	[117]

4.2. Electromagnetic Shielding

EMI is the term used to describe the disturbances generated by electronic circuits during their operation, which can adversely affect nearby circuits [91]. As the use of electrical and electronic equipment shows exponential growth in the commercial, industrial, and military sectors, the resulting increase in EMI necessitates effective shielding [92]. Ideal shielding materials must possess excellent electrical conductivity and magnetic permeability to attenuate electromagnetic waves efficiently [93]. Additionally, they should exhibit lightweight and flexible properties to integrate seamlessly into compact electronic devices [94]. Advanced materials like MXenes, with their high conductivity, mechanical flexibility, and tunable surface chemistry are emerging as promising contenders for EMI shielding solutions in modern electronics [95].

Table 3. Performance of various MXene-derived materials in terms of EMI shielding effectiveness.

Composition	Structure	Etchant for Mxene	Wt. %	Thickness [mm]	SE [dB]	Ref. No.
$Ti_3C_2T_x$	Pure	LiF/HCL	100	0.045	92	[118]
Ti_3CNT_x (annealing for 1 h at 350 °C)	Pure	/	/	0.045	116	[119]
$Ti_3C_2T_x$	Pure	LiF/HCL	100	0.000055	20	[120]
$Ti_3C_2T_x$/paraffin	Matrix Composite	HF	90	1	76.1	[121]
$Ti_3C_2T_x$/polystyrene	Matrix Composite	LiF/HCL	/	2	62	[122]
$Ti_3C_2T_x$/Ni/PVDF	Matrix Composite	LiF/HCL	10	0.003	52.6	[123]
$Ti_3C_2T_x$/rGO/Epoxy	Matrix Composite	LiF/HCL	3.3	/	55	[124]
$Ti_3C_2T_x$/ CNF	composite paper	LiF/HCL	50	0.047	25	[125]
$Ti_3C_2T_x$/CNT/CNF	composite paper	LiF/HCL	/	0.038	38.4	[126]
$Ti_3C_2T_x$/ANF	Composite film	LiF/HCL	80	0.0032	40.6	[127]

Figure 6a depicts the block diagram of a vector network analyzer (VNA) setup. Scattering parameters, measured through a VNA, characterize how the incident and transmitted waves interact with a shield, providing insights into its reflection and transmission properties.The possible EMI shielding mechanism is illustrated in Figure 6b. When incoming electromagnetic (EM) waves encounter the outermost layer of MXene ($Ti_3C_2T_x$)/PEDOT:PSS composite film, a portion of the EM waves is promptly reflected becauseof the abundance of the free electrons onto the highly conductive $Ti_3C_2T_x$ surface. Another portion of the radiation is absorbed by the material, leading to multiple internal reflections within the composite layers. This process enhances energy dissipation and ultimately reduces the transmitted electromagnetic radiation, thereby effectively attenuating the incident waves. As illustrated in Figure 6c, MXenes derived from titanium (such as Ti_2CT_x, Ti_3CNT_x, $Ti_{1.6}Nb_{0.4}CT_x$, and $Ti_3C_2T_x$), as well as V_2CT_x, demonstrate electrical conductivity exceeding 1000 S cm^{-1}. In contrast, MXenes derived from niobium exhibit comparatively low electrical conductivity.

Figure 6d displays the total EMI shielding effectiveness (SE_T) for various MXene films with comparable thicknesses (5 ± 0.3 μm) across the X-band (8−12 GHz). Each film shows a nearly linear frequency-dependent trend, with SET values decreasing as the frequency increases. This pattern suggests that the MXenes under investigation share a similar conductive response to frequency variations. Table 3 lists the performance of pure MXene film and several MXene-based composites in terms of electromagnetic shielding effectiveness.

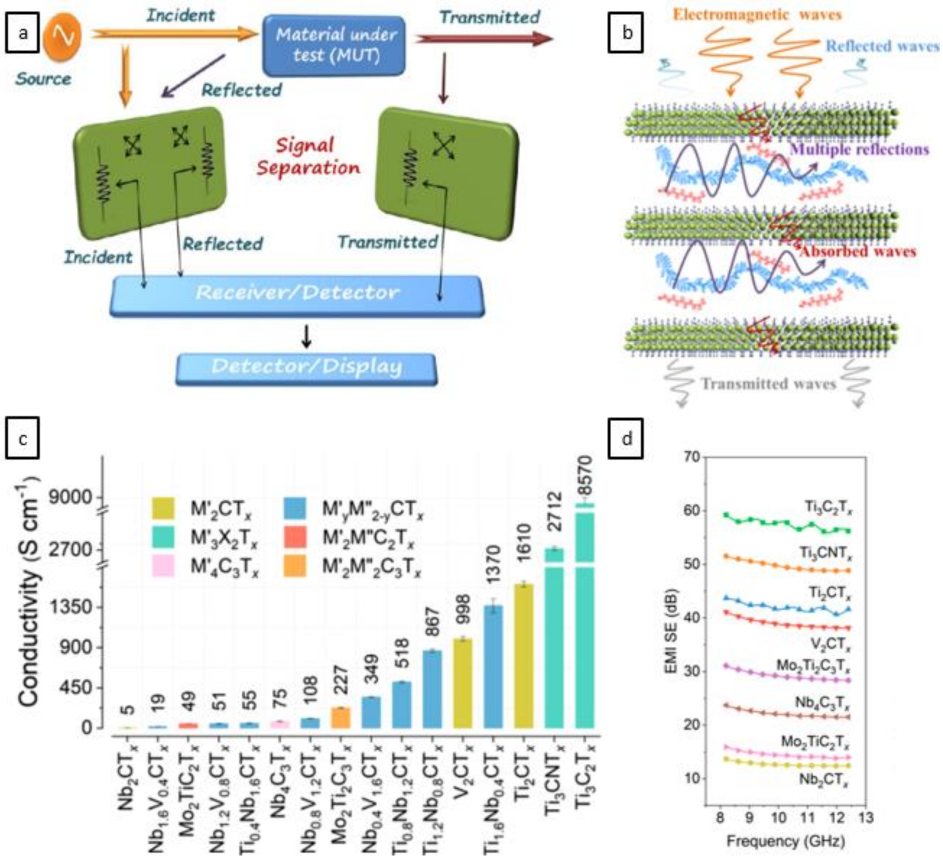

Figure 6. A schematic representation of the VNA. Reproduced with permission from Reference [109]. © 2022 American Chemical Society. (b) Schematic illustration of the EMI shielding mechanism of the MXene ($Ti_3C_2T_x$)/ PEDOT:PSS (composite film of 11.1 μm). Reproduced with permission from Reference [110]. © 2018 American Chemical Society. (c) Electrical Conductivity of Various MXenes [27]. (d) EMI shielding effectiveness of various MXene films in X-band frequency range. Reproduced with permission from Reference[27]. © 2020 American Chemical Society

4.3. Photocatalysis

Photocatalysis is a method that uses catalysts to transform solar energy into chemical fuels and remove pollutants from the surroundings [96]. Since 2014, MXenes have been extensively studied in photocatalysis, leading to a notable rise in research on MXene-based photocatalysts. Several factors contribute to the effectiveness of MXenes in photocatalytic applications: (i) The substantial functional groups that result from wet chemical exfoliation are beneficial for forming an intimate interface between the MXene and attached semiconductor material, (ii) the interfacial chemistry of MXenes can be adjusted to modify bandgap alignment, and (iii) the multilayer structure with high- conductive metal centers enhances metallic conductivity and electron-receiving capabilities [97]. Consequently, MXenes are considered a promising alternative to other 2D materials, being thoroughly investigated for various photocatalytic uses,including water splitting, CO_2 reduction, nitrogen fixation, and pollutant oxidation. In such applications, MXenes can enhance photocatalytic performance by improving charge carrier separation and transfer, limiting photocatalyst size, providing robust support, and increasing reactant adsorption[98].

4.4. Sensing Technology

Materials with high conductivity, flexibility, ease offunctionalization, and prolonged stability are crucial for advanced self-powered sensors[99]. MXenes are employed in sensors for detecting gases, biomolecules, and pollutants, leveraging their unique electronic structure and surface chemistry to enable efficient charge transport and sensitivity, making them ideal candidates for advanced sensing technologies [100].

These diverse applications underscore MXenes' potential across scientific, technological, and environmental domains, driving ongoing research and development to harness their capabilities for practical and impactful solutions.

5. BIBLIOMETRIC ANALYSIS AND CURRENT DEVELOPMENTS IN MXENE RESEARCH

MXene isrecognized as a high-performance material with exceptional qualities. The bibliometric analysis is a useful tool for identifying uniqueness and promise in light of current trends in the evolution of current area studies [101]. For bibliometric research, reliable data must be obtained through a reputable database to assure the reliability of the findings and further the data used as input for the software. The databases that are readily accessible for data collection are Google Scholar, Web of Science, Dimensions, Microsoft Academic, IEEE Xplore, PubMed, and Scopus. Web of Science Core Collection database (https://www.webofscience.com) was selected as the primary information source for this study because of its extensive coverage and thorough content. Bibliometric software is utilized to assess individual performance and visualize publications based on their titles, institutions, authors, countries, and references [102]. VOSviewer has been used to construct and visualize authors, institutions, countries, keywords, journals, and relationships between co-authorship, citation, co-citation, co-occurrence, and bibliographic coupling. The data collection process started with a thorough search of MXene using the WOS search engine. 2012 to 2023 was chosen as the sample collecting period, and 10957 papers were found using the search engine.

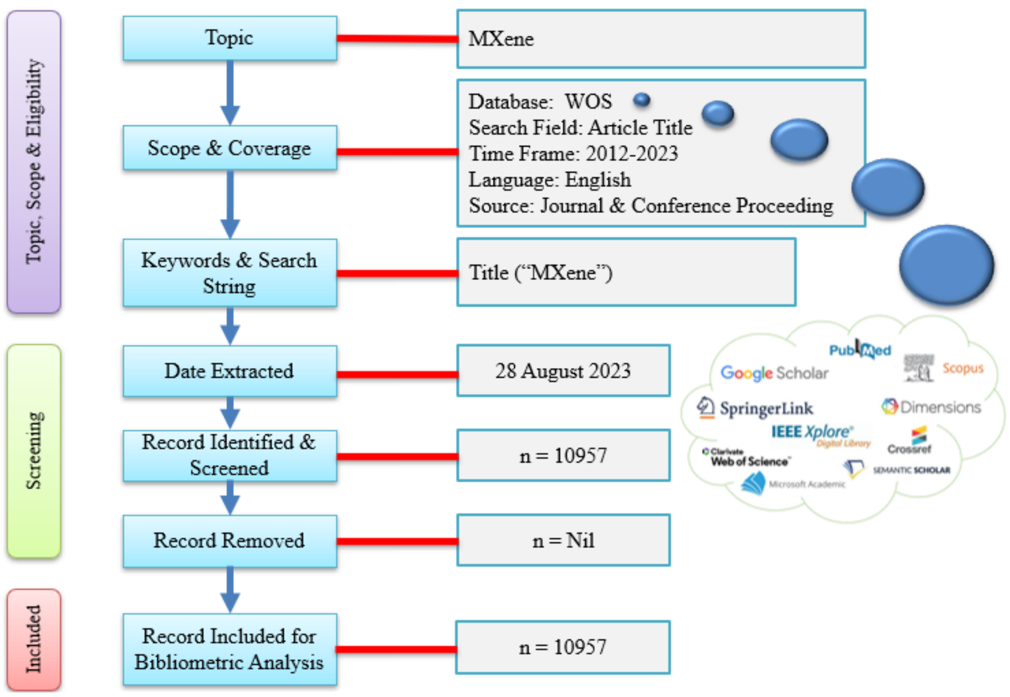

Figure 7. Flow chart of the search process

The whole search approach, including the search string and keywords, is presented in Figure 7. The field for searching was restricted to titles only to increase the accuracy of the outcomes because integrating additional search criteria like keywords and abstract raises the risk of including unrelated publications in our bibliometric analysis (false-positive results). Higher false-positive results necessitate longer pre-cleaning procedures. The methodology employed in the bibliometric analysis follows the approach outlined by Zakaria et al. [103], providing a structured and comprehensive evaluation of the research developments and contributions within the realm of MXene studies.

A statistical technique employed for identifying similar subjects is called cluster analysis. In VOSviewer, clusters do not overlap. Cluster numbers are used to identify clusters. Citation and co-occurrence analysis, which is based on the notion that citations signify the intellectual connections among publications that come from one publication citing another, is a fundamental approach to effective scientific mapping [104]. In this research, the citation count of an article has been used to estimate its effect. Therefore, taking advantage of citations, one may investigate the most significant works in an area to learn about the dynamics in that realm of knowledge.

5.1. Assessment based on participating nations

The nations participating in the MXene studies are ranked according to the number of papers published. About 33918 researchers from 90 different nations accounted for the publication of retrieved documents. China and the USA are the top two contributors to the MXene research domain. The top contributing countries for this research domain are shown in Table 4.

An effective way to evaluate the significance of the articles and the contributors is to look at the ratio of the total number of citations to the number of documents. The USA has an average of 103 citations per document followed by South Korea with 40 citations per document, compared to China with only 34 citations per document. However, China is the major contributor in terms of publications. It demonstrates the prominent level of quality output produced by the USA in terms of citations. Visualization of international collaboration among nations with a minimum output of five documents is displayed in Figure 8.

Table 4. The top contributing nations in the context of MXene publications

Ran-king	Country	Documents	Citations	Citations to documents ratio
1.	Peoples r China	8387	287113	34
2.	USA	1224	126004	103
3.	South Korea	622	24874	40
4.	India	528	8667	16
5.	Australi a	387	25649	66

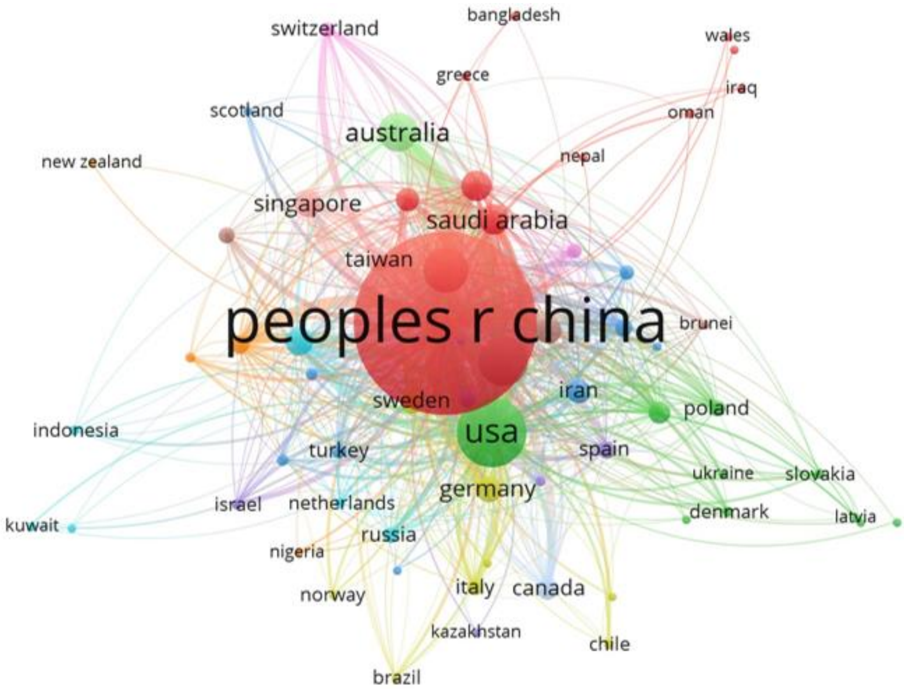

Figure 8. Cooperation among a number of nations

In bibliometric analysis using VOSViewer software, the size of individual nodes (representing nations, authors, or institutions) in a visualized network indicates their impact or contribution within the research field. Larger nodes signify higher levels of influence.

5.2. Assessment based on participating institutions

Chinese Acad Sci gained first place, followed by Drexel University, concerning the number of articles published. Chinese Acad Sci achieved 973 documents with 45709 citations. Despite being ranked second, Drexel University still received a lot of citations (87562) while having less documents (457) as compared to Chinese Acad Sci. Additionally, as a result of the development of this field of study, institutions now place a greater emphasis on matters related to MXene materials. In the area of MXene research, 10 institutions contributed more than 200 articles as displayed in Table 5.

Table 5. Institutional rankings based on the number of articles published on MXene

Ranking	Organization	Documents	Citations	Citations to documents ratio
1.	Chinese acad sci	973	45709	47
2.	Drexel univ	457	87562	192
3.	Univ Chinese acad sci	328	16079	49
4.	Zhengzhou univ	297	13204	44
5.	Univ sci & technol China	254	10218	40
6.	Shenzhen univ	232	8373	36
7.	South China univ technol	213	10402	49
8.	Northwestern polytech univ	211	9166	43
9.	Sichuan univ	211	8335	40
10.	Jilin univ	210	9691	46

For Drexel University, the citations-to-publication ratio is calculated to be ~192, while it is only 47 for the Chinese Academy ofSciences. The ratio's difference demonstrates the significant contributions to this field's research. Overall, bibliometric analysis provides valuable insights into institutional collaboration within the scientific community, which can inform strategic decisions, funding allocations, and collaborative initiatives among research institutions. Figure 9 displays the collaboration networks of institutions.

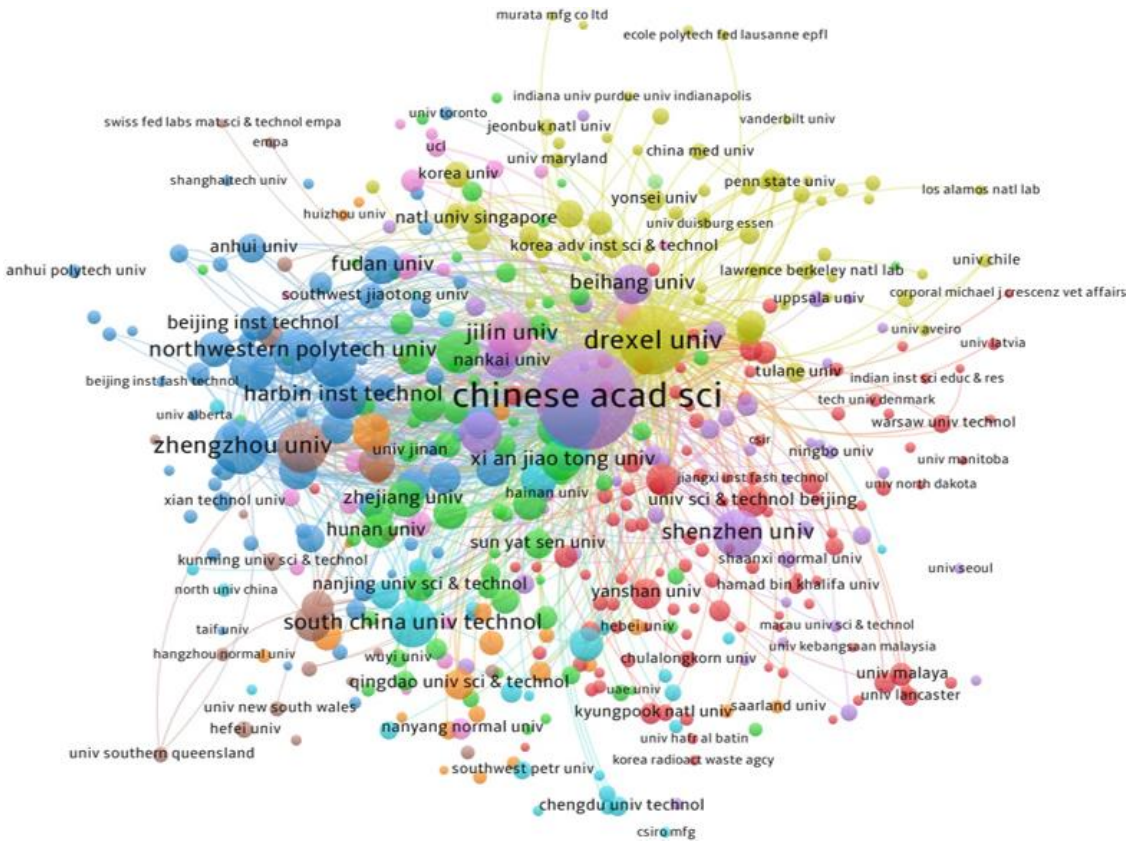

Figure 9. Cluster of institutional collaboration.

5.3. Assessment based on authors

The number of published articles and citations are used to rank the writers. Yuri Gogotsi was found to have the most articles (344) with 82506 citations, followed by Babak Anasori with 122 articles and 29532 citations and Michel W. Barsoum with 99 articles and 33834 citations. They are regarded as the leading researchers in this area. Table 6 presented the top 10 authors who had contributed more than 50 articles in the domain of MXene research.

Table 6. Authors rankings based on number of articles published on MXene.

Ranking	Author	Documents	Citations	Citations to documents ratio
1.	Yury Gogotsi	344	82506	240
2.	Babak Anasori	122	29532	242
3.	Michel W. Barsoum	99	33834	342
4.	Han Zhang	75	3850	51
5.	Michael Naguib	69	22395	325
6.	Lei Wang	68	3393	50
7.	Aiguo Zhou	67	6778	101
8.	Peng Zhang	66	4107	62
9.	Husam N. Alshareef	64	6652	104
10.	Wei Zhang	62	1520	25

Visualization of international collaboration among authors is displayed in Figure 10.

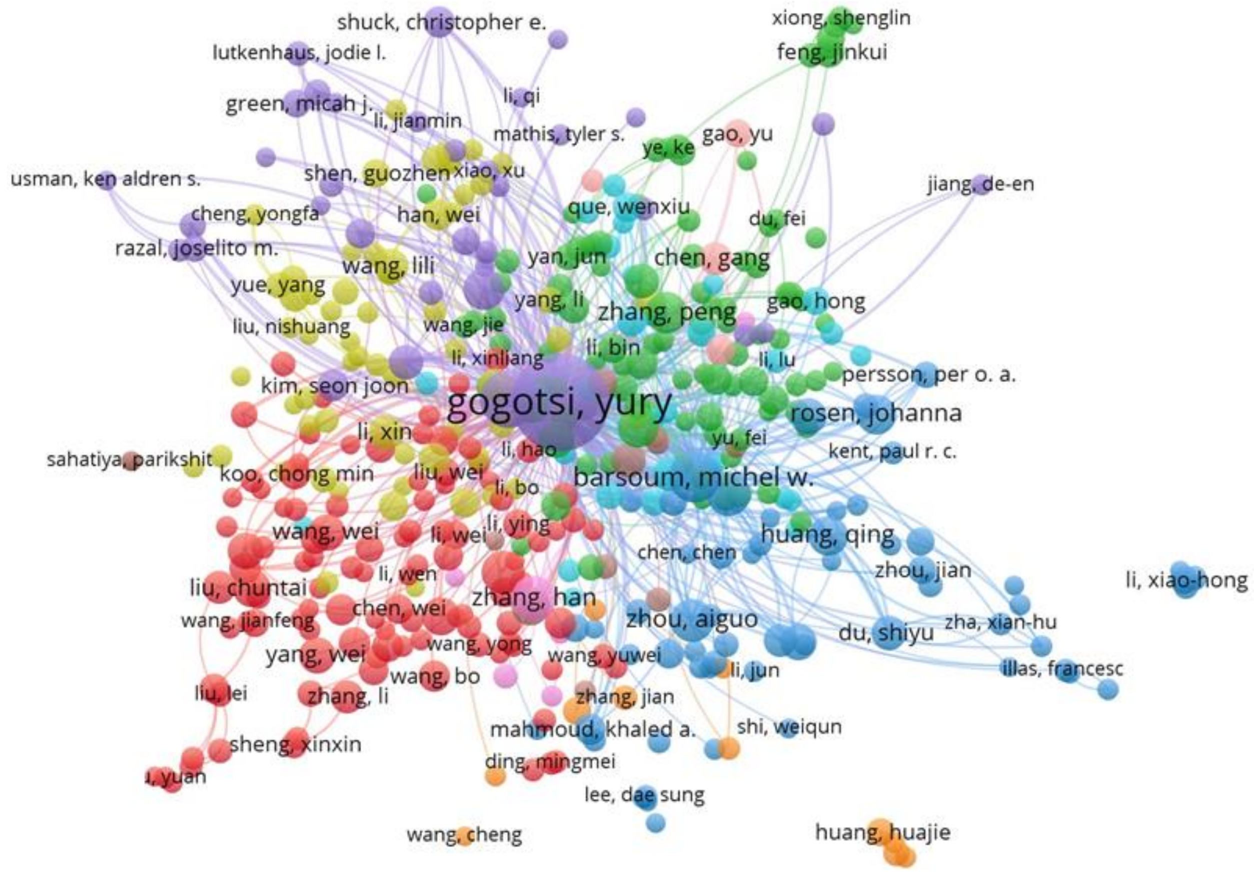

Figure 10. An illustration of the authors contributions to scientific publications in the MXene field

5.4. Assessment based on publications of articles based on MXene

The well-known publications that publish in this area of research have been found through a literature review of the many MXene-based research articles. The ranking of journals is shown in Table 4 according to the quantity of published documents, which was chosen as the ranking criterion. The top ranked journals, according to the quantity of papers published, are Chemical Engineering Journal followed by ACS Applied Materials & Interfaces, and ACS Nano. Table 7 lists the 8 journals that published more than 200 publications in the MXene research field.

The average number of citations per document for the ACS nano journal is 19586 with 317 publications, which is the highest among all other journals. In bibliometric analysis, a cluster typically refers to a grouping of related documents. Research on MXene is being published in all prestigious publications, and Figure 11 shows the clustering patterns.

Table 7. Journal rankings based on number of articles published on MXene

Ran-king	Journal name	Documents	Citations
1.	Chemical engineering journal	535	17949
2.	ACS applied materials & interfaces	479	21580
3.	ACS nano	317	39658
4.	Journal of materials chemistry A	304	17206
5.	Applied surface science	283	7330
6.	Advanced functional materials	266	21451
7.	Journal of alloys and compounds	227	3363
8.	Ceramics international	208	4979

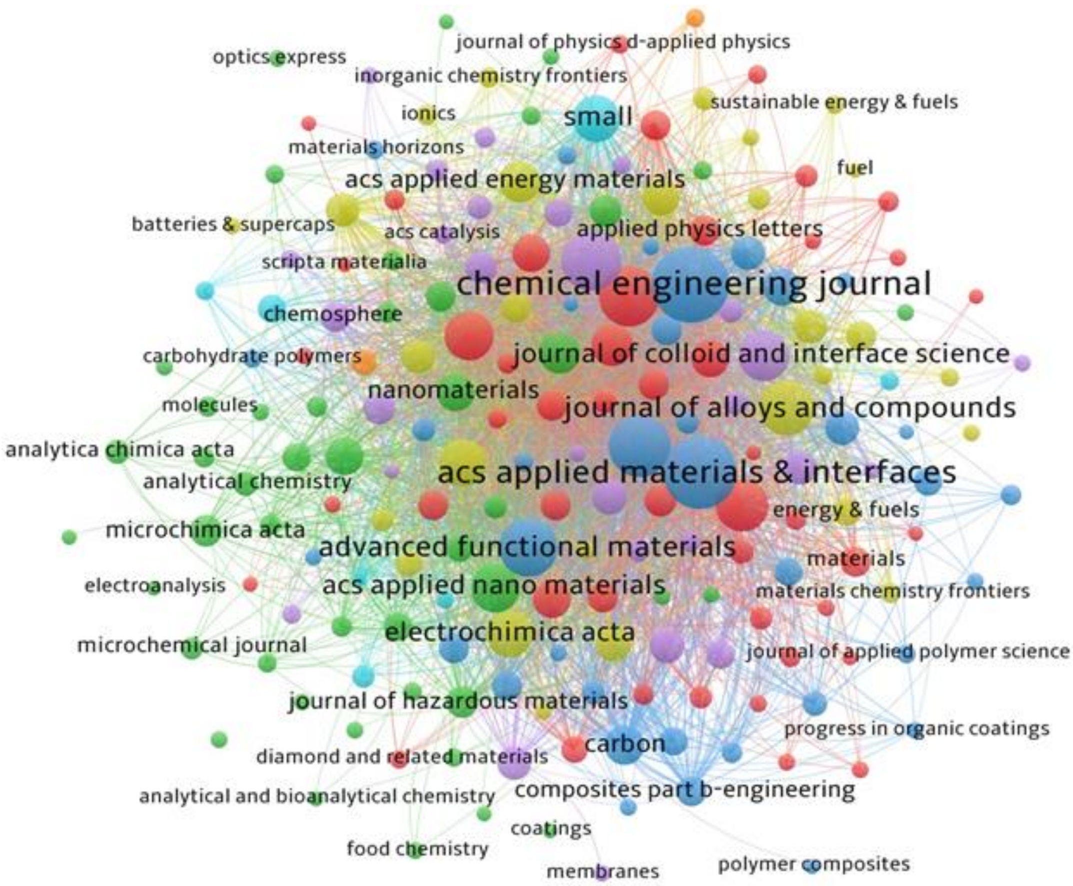

Figure 11. An illustration of the Journals contributions to scientific publications in the MXene field

5.5. Assessment based on Keywords

The use of relevant and appropriate keywords has a significant impact on the operation and efficacy of document searches. The keyword serves as a vital link that separates the reference sources from the wide range of readily available papers. MXene, performance, and Nanosheets are the top three keywords, appearing 4834, 1955, and 1548 times respectively. It is evident to utilize the precise keyword or phrase for quick and accurate document identification. 15 keywords that appear in the MXene research field most frequently (more than 500 times) are listed in Table 8.

The growth of international research in the area of MXene research has been emphasised by this bibliometric analysis. A thorough analysis of the clustering structure gave more information on the teams that collaborated and the caliber of the research articles. The outcomes shown throughout the study period (2012-2023) unmistakably demonstrated the development and continued expansion of MXene as a research area.

A cluster of significant keyword occurrences is displayed in Figure 12.

Table 8. lists keywords in order of occurrence.

Ranking	Keyword	Occurrences
1.	mxene	4834
2.	performance	1955
3.	nanosheets	1548
4.	graphene	1468
5.	mxenes	978
6.	nanoparticles	924
7.	composite	839
8.	composites	813
9.	carbon	774
10.	intercalation	718
11.	ti_3c_2	696
12.	nanocomposites	690
13.	$ti_3c_2t_x$ mxene	673
14.	transition-metal carbides	536
15.	graphene oxide	508

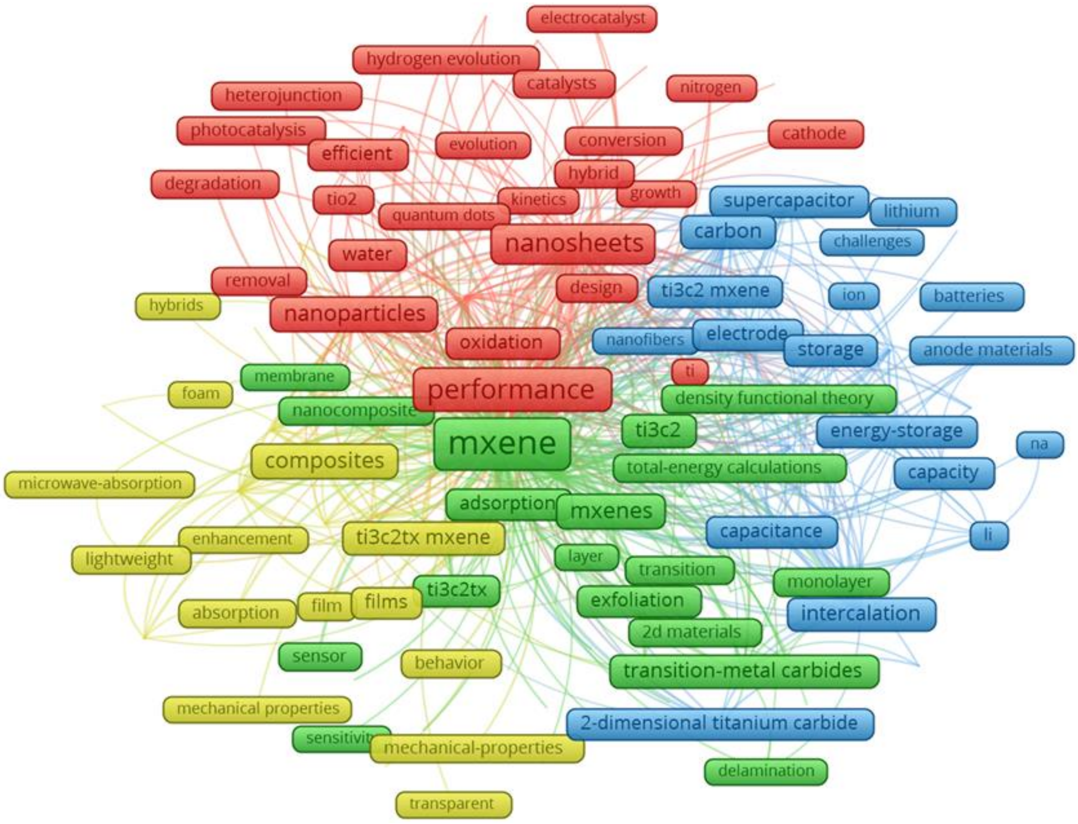

Figure 12. An illustration displaying the co-occurring assessment of keywords in studies on MXene that have been published

6. CONCLUSIONS AND OUTLOOK

Following their discovery, MXenes rapidly gained recognition as a highly promising class of 2D materials, demonstrating significant potential for a variety of scientific and technological applications. The synthesis techniques for MXenes have seen considerable advancements, enabling better control over their properties and expanding their research scope. This progress has facilitated precise tuning of electronic and optical properties through surface terminations and compositional adjustments, allowing for enhanced performance in various applications. MXenes are perfect for energy storage applications since their interlayer spacing can be adjusted to maximize ion transit. The distinctive blend of metal-like conductivity and hydrophilicity in MXenes also offers exciting opportunities for creating EMI shielding materials.As the understanding of their fundamental physical properties deepens, MXenes continue to stimulate revolutionary research directions and innovative experimental techniques, further driving innovation and exploration in the field. Looking ahead, future research will likely focus on advanced synthesis methods, new functionalization strategies, the development of hybrid materials, and the exploration of emerging applications. However, challenges remain, including synthesis complexity, stability issues, environmental and health impacts, and the high production cost. Addressing these challenges through targeted research and innovation will be crucial for the successful commercialization and integration of MXenes into next-generation technologies.

Bibliometric analysis is essential in shaping scientific research, guiding decision-making, and promoting knowledge dissemination and collaboration. The bibliometric analysis employed in this literature underscores the notable expansion of global research in MXene. Our bibliometric investigation indicates that research on MXene is still actively ongoing. A substantial dataset from the Web of Science was systematically analyzed, focusing on research growth across nations, institutions, authors, journals, and keywords. The analysis revealed China as the leading contributor with 8,387 articles, followed by the USA with 1,224 publications. Notably, the USA has a higher average citation count per document (103)compared to China (34), highlighting the quality of US research output. The two largest contributing institutions were the Chinese Academy of Sciences and Drexel University, while Yuri Gogotsi, Babak Anasori, and Michel W. Barsoum were the most prolific authors. The Chemical Engineering Journal and ACS Applied Materials & Interfaces were the most favored journals. Certainly, it is crucial to highlight that despite the comprehensive investigation, this research has notable limitations. For instance, the reliance on data from the Web of Science, although recognized as one of the most reliable and trustworthy sources of information, introduces a potential limitation. The observed patterns and conclusions may vary when data is obtained from different search platforms.

CRediT authorship contribution statement

Bhushan Kumar: Writing – review & editing, Writing – original draft, Methodology, Conceptualization, Data curation, Validation, Visualization, Software. **Sahil Jangra:** Visualization, Data curation.**M.S. Goyat:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Subhankar Das:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

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IZVOD

NAJSAVREMENIJI RAZVOJI U MKSENES-U: SVEOBUHVATAN PREGLED

Poslednjih godina, dvodimenzionalni (2D) materijali su privukli značajnu pažnju zbog svojih karakterističnih svojstava i potencijalne primene u širokom spektru primena. Među ovim materijalima, MKSenes, porodica karbida, nitrida i karbonitrida prelaznih metala, pojavili su se kao istaknuta klasa 2D materijala sa izuzetnim strukturnim, električnim, termičkim, optičkim, mehaničkim i hemijskim svojstvima. Ovaj pregled istražuje nedavna dostignuća u tehnikama sinteze, osobinama i različitim primenama MKSenes-a u skladištenju energije, zaštiti od elektromagnetnih smetnji (EMI), senzorima i primenama u životnoj sredini. Pored toga, pruža bibliometrijski pregled, analizirajući 10.957 istraživačkih radova za procenu globalnih naučnih trendova i budućih pravaca istraživanja koristeći podatke Veb of Science (VOS) i softver VOSviever. Ovaj pregled ima za cilj da pruži sveobuhvatno razumevanje najsavremenijeg razvoja u MKSene tehnologiji, nudeći uvid u buduće pravce i potencijalne napretke u ovoj oblasti koja se brzo razvija.

Ključne reči: *2D materijali; MKSene; sinteza; aplikacije; bibliometrijska analiza*

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