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Review Article

Recent advancement in MXene-based nanomaterials for flame retardant polymers and composites

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ABSTRACT

This review explores the advancements in MXene-based nanomaterials as flame-retardant additives for polymers and composites, driven by increasing fire safety demands across industries. It highlights the critical role of flame-retardant materials in mitigating fire hazards in structures, electronics, transportation, and textiles, emphasizing the need for innovative solutions due to stricter safety regulations. MXenes, a class of two-dimensional nanomaterials with unique structural properties such as high surface area, tunable composition, and superior thermal stability, are presented as promising candidates. The review discusses various synthesis and incorporation techniques for MXenes in polymer matrices, showcasing improvements in flame retardancy, mechanical properties, and thermal stability. Additionally, it emphasizes the multifunctionality of MXenes, which offer conductivity, electromagnetic shielding, and mechanical reinforcement alongside flame suppression. In conclusion, the review underscores MXenes' potential to address challenges in flame-retardant materials, advocating for further research to optimize their applications and explore synergies with other agents to enhance safety and sustainability in engineering materials.

1. Introduction

Flame retardancy in polymers and composites is an essential area of focus to ensure safety and compliance with fire safety standards across a wide range of industries, including construction, electronics, automotive, and aerospace [1,2]. As the demand for high-performance materials capable of withstanding elevated temperatures and slowing or preventing the spread of fire continues to grow, the need for advanced and innovative flame-retardant solutions becomes increasingly critical. In response to these challenges, researchers have been actively exploring cutting-edge materials and technologies to enhance the fire resistance of polymers and composites. Among the most promising developments in recent years is the application of MXene-based nanomaterials [3–5]. These two-dimensional materials, known for their exceptional thermal stability, high surface area, and

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tunable chemical properties, offer unique advantages in improving the flame-retardant performance of polymer matrices [6,7]. By leveraging the synergistic effects of MXenes with other materials, researchers aim to develop more efficient and sustainable flame-retardant systems that meet the stringent safety requirements of modern applications.

MXenes, a class of two-dimensional transition metal carbides and nitrides, have garnered significant attention due to their exceptional thermal stability, high surface area, and excellent electrical conductivity [8,9]. These unique properties make them ideal candidates for incorporation into polymer matrices to impart flame retardancy while maintaining mechanical integrity. In this review, we explore the recent developments in MXene-based nanomaterials for flame-retardant polymers and composites. We delve into the synthesis methods of MXenes and their subsequent incorporation into polymer matrices. Furthermore, we investigate the mechanisms underlying the flame-retardant behaviour of MXenes, shedding light on their effectiveness in suppressing combustion and reducing smoke release. The review also highlights the diverse range of polymer systems and composite materials that have been enhanced through the incorporation of MXene-based nanomaterials. From thermoplastics to thermosets and from glass fibre-reinforced composites to carbon fibre composites, MXenes have demonstrated remarkable versatility in improving flame retardancy across various material platforms.

Moreover, we discuss the challenges and opportunities associated with the practical implementation of MXene-based flame retardant systems, including issues related to scalability, cost-effectiveness, and environmental impact. Additionally, we provide insights into future research directions aimed at further optimizing the performance of MXene-based nanomaterials for flame retardant applications. The significance of this review stems from the pressing need to develop advanced flame-retardant materials that can meet stringent safety requirements across industries. As traditional flame retardants face scrutiny due to their environmental and health concerns, there is a growing demand for sustainable and efficient alternatives. MXene-based nanomaterials offer a promising solution owing to their unique combination of properties and their potential to address the limitations of conventional flame retardants.

By comprehensively examining the recent advancements in MXene-based flame retardant systems, this review serves several crucial purposes. The review synthesizes scattered information from various research studies, providing a comprehensive overview of the current state-of-the-art in MXene-based flame retardant materials. This consolidation facilitates easier access to information for researchers, engineers, and practitioners in the field. By highlighting the potential applications and performance benefits of MXene-based flame retardant materials, the review encourages further innovation and collaboration in this burgeoning field. It inspires researchers to explore new synthesis techniques, characterization methods, and application strategies to maximize the efficacy of MXenes in flame retardant polymers and composites.

In essence, this review aims to catalyze advancements in flame retardant technology by providing a comprehensive overview of the recent developments, challenges, and opportunities associated with MXene-based nanomaterials. By doing so, it contributes to the ongoing efforts to enhance fire safety and sustainability in diverse industrial sectors.

2. Flame retardant mechanisms

Flame retardants are a critical component in many materials and products that reduce the risk of fire and improve overall safety. These materials work based on certain mechanisms to slow or inhibit the combustion process by disrupting one or more steps of the fire triangle, which consists of fuel, oxygen, and an ignition source [10]. This is achieved through the formation of a protective coating (char) on the material surface thereby inhibiting or reducing the thermal decomposition process of the burning material, as shown in Fig. 1. Understanding these mechanisms is critical for developing materials with higher fire resistance capacity. This section highlights the mechanisms of functionality of both traditional and MXene-specific flame retardants.

2.1. Traditional flame-retardant mechanisms in polymers

Flame retardants play a crucial role in enhancing the fire safety of polymers by incorporating various mechanisms that either prevent or slow down the combustion process. Traditional flame-retardant mechanisms in polymers include:

- Halogenation: This method is one of the most prevalent and effective methods in flame retardancy, they are commonly applied in polymers to enhance fire resistance. This mechanism involves incorporating halogen elements, such as bromine or chlorine, into polymer structures or Halogen-containing. During exposure to heat or flames, halogenated polymers release halogen radicals, disrupting the combustion process. The released radicals act as scavengers, interrupting the radical chain reactions critical for sustaining a fire [11]. Halogenation primarily inhibits ignition and retards flame spread, contributing to the fire safety of materials. However, this method of flame retardancy has been recorded to have a negative environmental impact due to the potential release of toxic by-products [12]. This therefore necessitated the development of eco-friendly flame retardants with comparable efficacy, disrupting the radical chain reactions involved in combustion, and slowing down the fire.
- Char Formation: Many flame retardants promote the formation of a protective char layer on the surface of polymers during combustion. Char formation is a vital flame retardant mechanism employed to enhance the fire resistance of materials, particularly polymers. During combustion, certain flame retardants promote the production of a protective char layer on the material's surface. This char is often composed of carbonaceous residues, which act as a physical barrier, insulating the underlying material from the intense heat of flames. The char layer hinders the access of oxygen and heat to the interior of the

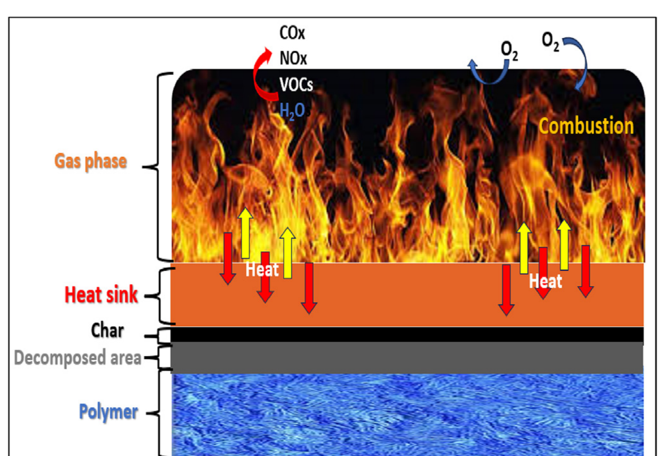

Fig. 1. Processes involved in flame-retardancy.

material, slowing down the combustion process and preventing further degradation [13]. Phosphorus-containing compounds, intumescent agents, and other additives contribute to the formation of this char, making it an essential strategy in retarding flame spread and improving the overall fire safety of various products and structures. The effectiveness of char formation depends on the specific composition of the flame retardant and its compatibility with the material. Moreso, Phosphorus-containing flame retardants can act through various mechanisms. They may promote char formation, reduce the release of combustible gases, or act as free radical scavengers [14,15]. In some cases, phosphorus compounds can inhibit the ignition and flame spread. Thereby serving as a protective covering against the spontaneous combustibility of materials.

- Nitrogen Compounds: Nitrogen compounds play a pivotal role in flame retardancy, particularly in polymers. Commonly used nitrogen-containing flame retardants, such as melamine and melamine cyanurate, release inert gases like ammonia when exposed to heat. This process dilutes the surrounding oxygen and flammable gases, inhibiting combustion. Additionally, nitrogen compounds act as effective flame retardants by promoting the formation of char during fire exposure. The release of non-flammable gases and the contribution to char formation make nitrogen compounds valuable elements in fire safety strategies, enhancing the resistance of materials to ignition and reducing the overall flammability [16,17].
- Inorganic Fillers: Aluminum hydroxide and magnesium hydroxide as inorganic fillers release water vapour when exposed to heat. inorganic fillers, such as aluminium hydroxide and magnesium hydroxide, are essential components in flame retardancy, especially for polymers [18]. When subjected to heat, these fillers undergo an endothermic reaction, releasing water vapour. This process absorbs heat from the surrounding environment, retarding the temperature rise during combustion. Simultaneously, the water vapour helps dilute the concentration of oxygen and flammable gases, inhibiting the propagation of fire. Moreover, inorganic fillers contribute to char formation, creating a protective insulating layer on the material's surface [19]. Their ability to impart flame-retardant properties without introducing hazardous emissions makes inorganic fillers valuable in various applications, enhancing the fire safety of materials while providing additional benefits such as improved mechanical properties and cost-effectiveness in the formulation of flame-retardant polymers.
- Intumescent Systems: This is a sophisticated and effective approach to flame retardancy, widely applied in polymers and coatings. Consisting of a synergistic combination of compounds, these systems undergo a complex series of chemical reactions when exposed to heat or flames. This reaction results in the formation of a voluminous, insulating char layer on the material's surface. The expanded char acts as a barrier, shielding the underlying material from the heat and flames, thereby retarding the combustion process [20]. Components in intumescent systems typically include a carbon source, an acid source, and a blowing agent. The carbon source contributes to char formation, the acid source aids in dehydration and charring, while the blowing agent generates gas, causing the char to expand [21]. Studies have shown that Intumescent systems play a crucial role in passive fire protection, providing a versatile and efficient means of enhancing the fire resistance of diverse materials [21,22].

2.2. MXene-specific flame retardant mechanisms

Flame retardant mechanisms of MXene involve unique properties that make it effective in mitigating fire hazards. MXene's versatile flame retardant mechanisms make it a valuable material in various applications, ranging from electronics to construction, where fire safety is a critical consideration. The interplay of these mechanisms results in effective fire protection, positioning MXene as a promising candidate in advanced flame retardant technologies. The primary flame retardant mechanisms of MXene include catalytic carbonization, char formation, and synergistic effects, others include conductive network and gas phase quenching.

2.2.1. Catalytic carbonization

MXene, a family of two-dimensional transition metal carbides or nitrides [23]. It has emerged as a promising material in flame retardancy due to its unique catalytic carbonization mechanism. In the catalytic carbonization flame retardant mechanism of MXene, when exposed to heat during a fire, MXene nanosheets act as catalysts, initiating the carbonization of adjacent polymeric materials. This process involves the formation of a protective carbonaceous char layer on the surface of the material. MXene's catalytic activity accelerates the conversion of volatile organic compounds into a stable and insulating char, acting as a barrier to heat and flames [24]. This char layer serves a dual purpose: it hinders the release of combustible gases and provides a physical shield, preventing further propagation of the fire. Moreover, MXene's inherent conductivity contributes to improved thermal stability [25]. This innovative flame retardant mechanism addresses challenges associated with traditional flame retardants, offering enhanced fire protection while minimizing the use of halogenated compounds. MXene's versatility, coupled with its catalytic carbonization properties, makes it a valuable candidate for the development of advanced and sustainable flame retardant materials across various industries, ranging from electronics to building materials, industrial fittings, and a host of other products.

In a relevant study, Che et al. [26]introduced a novel and non-traditional approach for the synthesis of carbon quantum dots (CQDs) through the direct pyrolysis of a polystyrene/$Ti_3C_2T_x$-MXene composite, notably without the use of additional catalysts, and at a relatively low temperature. The authors proposed a detailed mechanism for the catalytic dehydrogenation and carbonization of the polystyrene matrix into CQDs in the presence of $Ti_3C_2T_x$-MXene. The study highlighted the unique role of $Ti_3C_2T_x$-MXene nanosheets, which functioned as hollow spherical micro-reactors, effectively trapping the degraded CPS products on their surface and within their interlayer. These trapped products then underwent carbonization reactions, facilitated by the interfacial catalytic dehydrogenation of C—Ti—O groups. The catalytic sites on the $Ti_3C_2T_x$-MXene nanosheets were critical in promoting the growth of CQDs, marking a significant advancement in the synthesis of high-quality carbon-based nanomaterials through a low-temperature, catalyst-free process.

2.2.2. Char formation

The char formation flame retardant mechanism of MXene is a pivotal aspect of its fire-suppressing capabilities. MXene and composites are of great value in promoting the creation of a robust and protective char layer when exposed to heat or flames. During combustion, MXene nanosheets act as catalysts, facilitating the transformation of the polymer matrix into a stable carbonaceous char. This mechanism involves a series of reactions wherein MXene initiates the carbonization process, leading to the formation of a resilient and insulating char layer on the material's surface [27] reported the dual char-forming characteristics of MXene@SiO_2 nanoarchitecture, including the catalytic charring of MXene and the migration of SiO_2 to induce charring. The char layer serves as a barrier, effectively shielding the underlying material from further exposure to heat and flames. This protective char not only hinders the release of combustible gases but also impedes the progression of the fire, contributing significantly to fire safety [14]. The unique char formation flame retardant mechanism of MXene distinguishes it from conventional flame retardants. Its efficacy lies not only in the ability to curb the spread of flames but also in the creation of a durable and self-sustaining char layer, showcasing MXene's potential as a cutting-edge flame retardant material for diverse applications.

Furthermore, phosphorus-containing flame retardants (PFRs) have been widely used to enhance the fire resistance of materials, particularly polymers. These compounds function by promoting char formation. During the char formation, many phosphorus flame retardants release phosphoric acid upon decomposition. This acid catalyzes the polymer's degradation, forming a stable char layer that acts as a physical barrier, protecting the material from heat and preventing further combustion.

2.3. Synergistic effects

The creation of a flame-retardant coating with sensitive fire warning is both necessary and extremely difficult. The flame retardant mechanism of MXene exhibits notable synergistic effects when combined with other fire-suppressing agents. The synergy between traditional flame retardants and MXene enhanced its overall fire protection. A synergistic effect is achieved by integrating MXene with complementary flame retardant mechanisms, such as gas phase quenching or intumescent systems [28,29]. This does not only improves fire resistance capacity but also allows for a more comprehensive and efficient approach to mitigating fire hazards in various materials, making MXene a versatile and promising component in advanced flame retardant formulations.

Zeng et al. utilized a dip-coating approach on a flammable sample to produce a multifunctional fire protection nanocoating (MFNC). Ti3C2TX (MXene), MMT (Montmorillonite) sheets, and UPC (2-ureido-4[1H]-pyrimidinone-containing cellulose) were integrated into the coating through layer-by-layer assembly [30]. The addition of the MXene-UPC layer enhanced the nanocoating's temperature-sensing capabilities and flame retardancy. The untreated wood had a Limiting Oxygen Index (LOI) of 26.5 %, compared to the treated wood with a recorded LOI value of 32.5 % and 34.5 %. Thus indicating significantly increased flame retardancy. Notably, MFNC-8-Wood demonstrated self-quenching quickly after flame extinguishment, increasing its limiting oxygen index to 40 %. This improvement was most likely due to MMT and MXene's outstanding barrier and catalytic carbonization characteristics.

A novel approach for mixing gelatin, PLCNFs (phosphate lignocellulose nanofibrils), and MXene to produce a hybrid composite aerogel (PGM aerogel) with ultralight weight and high porosity was developed by Li et al. [31]. PLCNFs were fabricated using the technique in conjunction with phosphatation and mechanical defibrillation. Furthermore, unlike PLCNF aerogel, which displayed outstanding flame-retardant efficiency, PGM-3 aerogel could retain its morphology and original size due to the synergistic enhancement of gelatin and MXene. Moreso, Hui Wang et al., [29] worked on improving the characteristics of EP composites by integrating Siloxane-decorated MXene Nanosheets. This entailed changing the existing epoxy resin system by treating MXene nanosheets with siloxane on their surfaces as shown in Fig. 2. The study investigated how additives affected the overall performance of composites. The researchers discovered that the addition of 2 % KH550-MXene resulted in EP nanocomposites with perfect flame retardancy, compatibility with liquid oxygen, and remarkable mechanical properties at ultra-low temperatures. Notably, the nanocomposites achieved a V-1 flame-retardant grade, exhibited no sensitivity concerns, and demonstrated a 14.4 % increase in ultra-low-temperature tensile strength (96.43 MPa at 77 K) against pure EP.

Furthermore, Xianwu Cao et al. [32] reported a simple method for preparing cobalt/phosphorus co-doped graphitic carbon nitride (Co/P−C_3N_4) via a scalable thermal decomposition mechanism. The structure of Co/P−C_3N_4 was determined and the corresponding schematic images were presented using scanning electron microscopy (SEM), as illustrated in Fig. XX. It was discovered that phosphorous atoms probably replaced the carbon atoms in g-C_3N_4. Polylactide (PLA) composites' thermal stability improved steadily as the Co/P−C_3N_4 content increased. PLA composites integrating Co/P−C_3N_4 outperformed g-C_3N_4 in flame retardant efficiency and smoke suppression. When 10 wt% Co/P−C_3N_4 was added, the peak heat release rate (PHRR), carbon dioxide (CO_2) production (PCO_2P), and carbon oxide (CO) production (PCOP) values for PLA composites decreased by 22.4 %, 16.2 %, and 38.5 %, respectively.

Furthermore, Zhang et al. fabricated composite aerogels from cellulose nanofibers (CNF), ammonium polyphosphate (APP), and $Ti_3C_2T_x$ by freeze-drying [33]. When subjected to a flame, the resulting $Ti_3C_2T_x$/CNF/APP nanocomposite aerogels demonstrated outstanding fire resistance with negligible shrinking. An 8-mm thick composite with 60 % $Ti_3C_2T_x$ demonstrated substantial electromagnetic interference shielding (55 dB) via an absorption-dominant process.

3. Synthesis and characterization of MXene-based nanomaterials/nanocomposite

3.1. Synthesis

Yuhang Lin et al. [34] developed core-shell Ag@PZS-modified MXene to enhance flame retardancy in polymer composites. Designing multifunctional composite polymers with superior flame resistance, electromagnetic interference (EMI) shielding, antibacterial properties, and mechanical strength remains a major challenge. In this study, a nano-scale filler (Ag@PZS@MXene) was synthesized using electrostatic self-assembly and incorporated into an acrylonitrile-butadiene-styrene (ABS) matrix to form ABS-Ag@PZS@MXene nanocomposites. Further, a hierarchical multi-functional composite (ABS-Ag@PZS@MXene/MXene film) was fabricated using air-assisted thermocompression. The core-shell Ag@PZS structure effectively shields MXene from oxidation, ensuring stability under processing conditions. The synthesis pathway is illustrated in Fig. 3a.

Zexuan Zhao et al. [35] synthesized microencapsulated P−N@MXene flame retardants using a layer-by-layer assembly strategy to enhance the fire resistance of epoxy resin (EP), as shown in Fig. 3b. In this work, MXene served as a protective shell for ammonium polyphosphate (APP) modified with *p*-phenylenediamine, forming P−N@MXene capsules. The synthesis involved the sonication of an aqueous MXene solution (3.00 g) for 10 min, dispersion of the P−N hybrid in deionized (DI) water and stirring for 30 min. Incorporation of MXene into the suspension, followed by stirring at room temperature for 4 h. Centrifugation and sequential washing with DI water and ethanol. Vacuum drying at 80 °C for 24 h. The resulting P−N@MXene flame retardant significantly improved the thermal stability and fire safety of epoxy composites (EP) with minimal additive content. Notably, EP-6% P−N@MXene, containing 6 wt% P−N@MXene, achieved a UL-94 V0 rating. Moreover, compared to pure EP, the composite exhibited substantial reductions in fire hazard indicators: Peak heat release rate (pHRR) decreased by 58.09 %. Total smoke production (TSP) was reduced by 51.76 %, Peak CO production rate (pCO) was lowered by 37.76 %. These findings highlight the effectiveness of

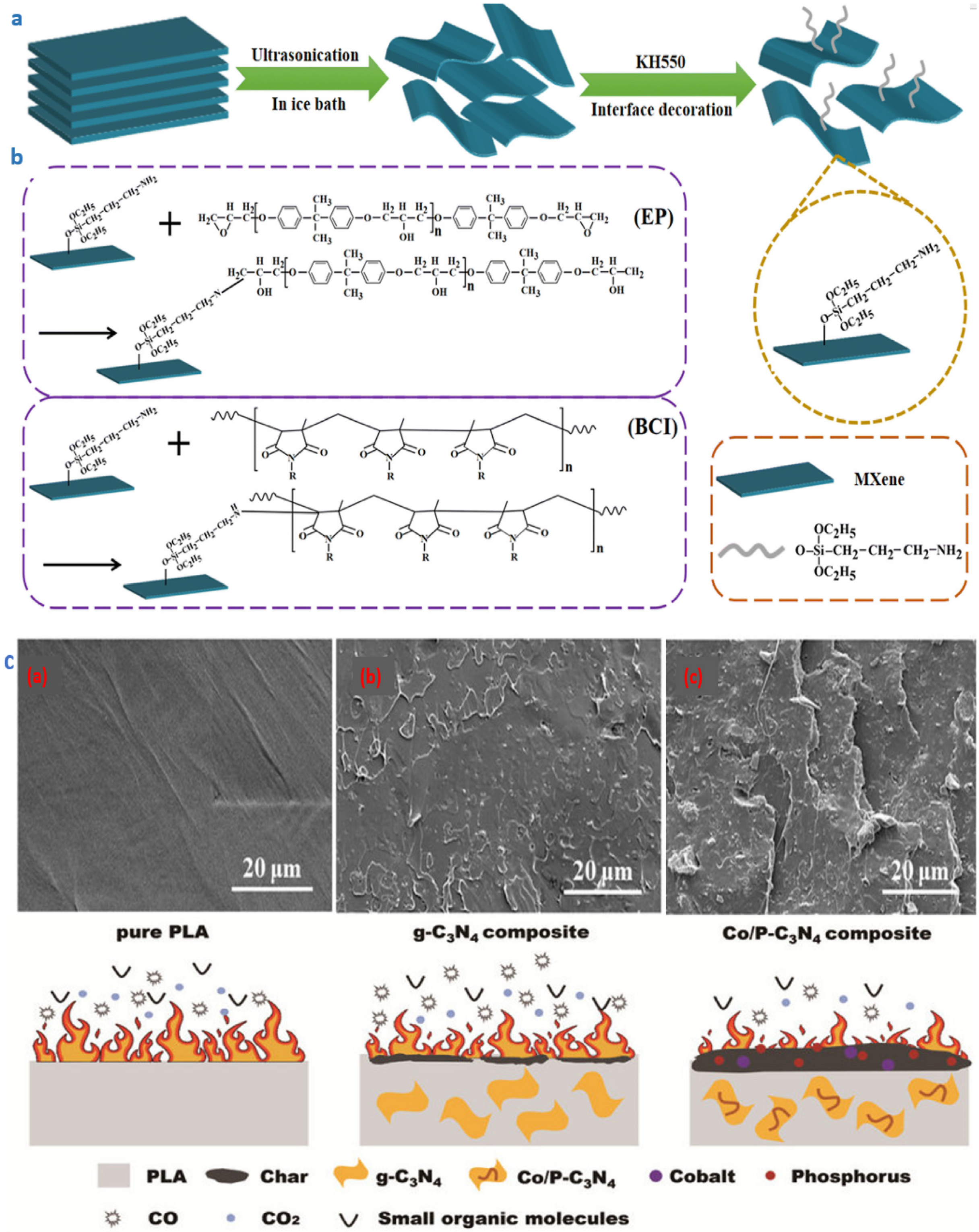

Fig. 2. Showing a-b; synthesis of Siloxane-decorated MXene nanosheet-reinforced EP composites [29]; c SEM micrographs and schematic diagram of the flame retardant mechanism of pure PLA and PLA composites. (a) pure PLA, (b) Co/P—C3N4-2%, (c) Co/P—C3N4-10 % [32].

MXene-based flame retardants in enhancing fire-resistant polymer composites.

Kaili Gong et al. [36] developed MXene nanohybrids by assembling phytic acid-modified UiO-66 (PA-UIO) onto $Ti_3C_2T_x$ MXene nanosheets (MXene/PA-UIO) through electrostatic interactions. The synthesis process is illustrated in Fig. 4a. These nanohybrids demonstrated strong interfacial bonding and uniform dispersion in the epoxy matrix, enabling simultaneous enhancement of both mechanical strength and flame retardancy. Notably, epoxy composites with 2 wt% MXene/PA-UIO exhibited improved mechanical

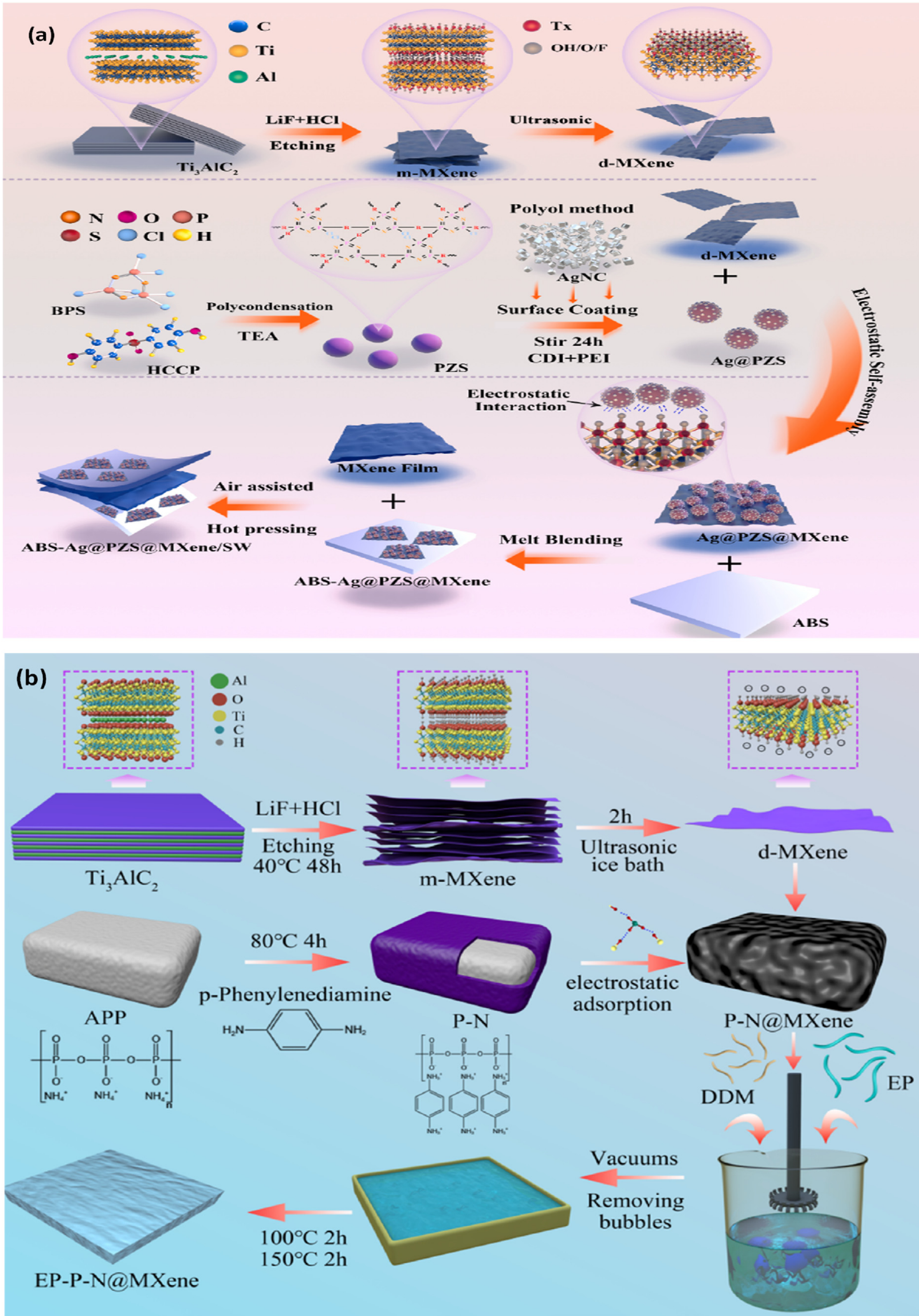

Fig. 3. Showing the synthesis route of (a): Core-shell Ag@PZS modified Mxene [34] and (b): P–N@Mxene nanocomposite [34].

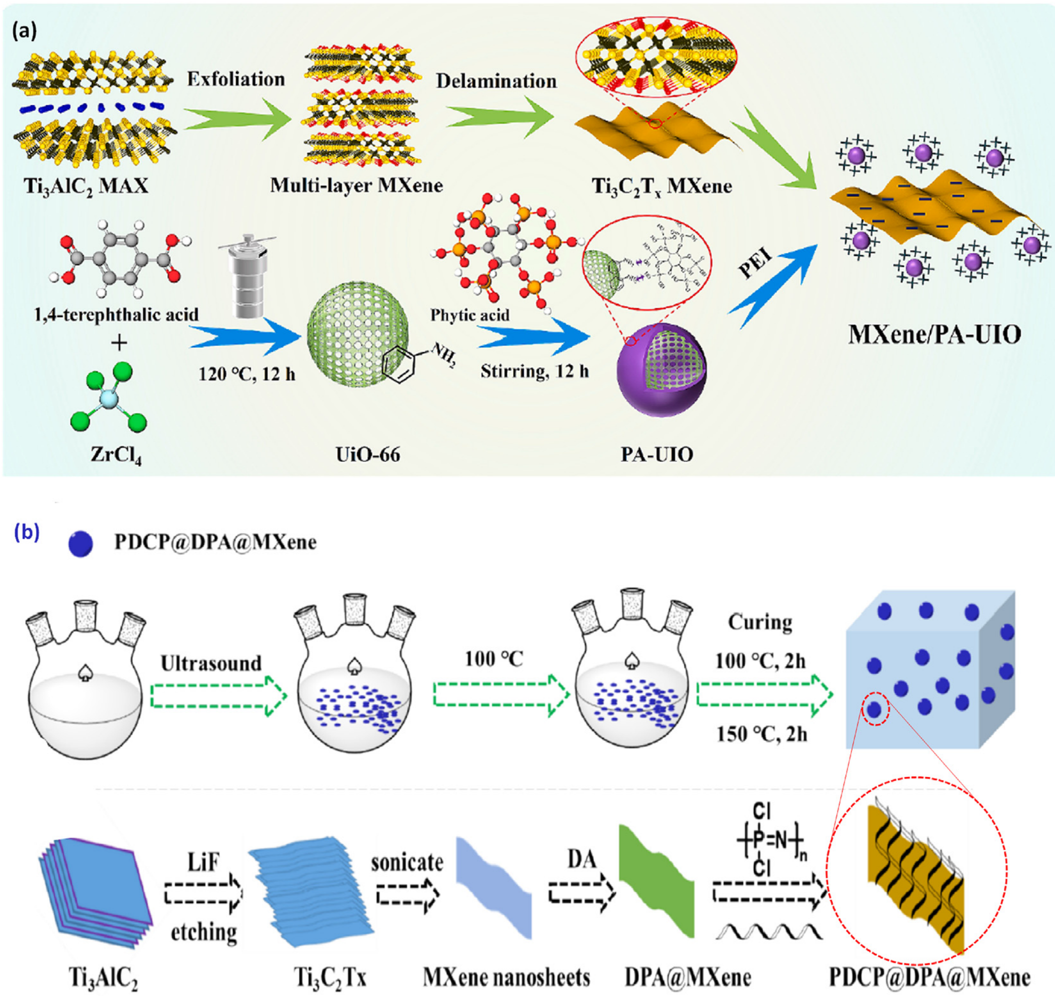

Fig. 4. Showing the synthesis of (a): phytic acid-modified UiO-66 (PA-UIO) onto $Ti_3C_2T_x$ MXene nanosheets [36] and (b): sprayable soy protein–MXene–hydroxyapatite (SP-MXene-CHA) hybrid nanocomposite [37].

and thermal performance, as seen in the increased storage modulus and tensile strength, along with a 28.3 % reduction in the maximum mass loss rate (Rmax).

Faezeh Ghorbanizamani et al. [37] designed a sustainable, sprayable soy protein–MXene–hydroxyapatite (SP-MXene-CHA) hybrid nanocomposite to enhance fire resistance. The SP-MXene-CHA composite was synthesized as follows: A solution containing hydroxyapatite (HA, 5.0 mM) and caffeic acid (CA, 56 mM) was dissolved in 100 mL of distilled water, followed by ultrasonic dispersion for 30 min and stirring at 50 °C for 3 h. The resulting CHA nanoparticles were dried. The formation of MXene-CHA hybrids was achieved by stirring the following, CHA (0.56 g), EDC (91 mM), and NHS (65 mM) for 30 min, then MXene-NH_2 (1.9 %) was added and mixed for 2 h to form MXene-CHA hybrids. The soy protein (SP) solution was prepared by weighing 5.0 g of SP powder and 1.5 g of glycerin was dissolved in 93.5 mL of distilled water and stirred for 15 min. Different amounts of MXene-CHA hybrids (50, 100, and 150 mg) were then added and mixed at 80 °C for 30 min to ensure uniform suspension. Additionally, cellulose and glutaraldehyde cross-linkers were investigated to further modify the MXene-CHA hybrids. Furthermore, Guangyong Jiang et al. [38] synthesized linear polydichlorophosphazene (PDCP) and $Ti_3C_2T_x$ MXene nanohybrids and applied them to epoxy resins (EP) for enhanced fire resistance and mechanical properties, as depicted in Fig. 4b. The incorporation of 1.5 wt% PDCP@DPA@MXene significantly improved impact strength (12.1 kJ/m^2, +63.5 %), tensile strength (57.4 MPa, +18.4 %), and elongation at break (13.0 %, +17.1 %) compared to pure EP. The increase in tensile strength is attributed to the high stiffness of $Ti_3C_2T_x$ MXene, which reinforces the epoxy matrix. Additionally, the interwoven structure of PDCP@DPA@MXene chains helps prevent fracturing and absorbs impact forces, enhancing toughness. The phosphorus, nitrogen, and titanium components promote the formation of a densified char layer, improving fire resistance. The synthesis scheme is illustrated in Fig. 4b.

3.2. Characterization

Quite a number of techniques are commonly utilized for characterization in material science as shown in Table 1. This gives insight into their structural, morphological, and chemical properties [39–41]. The MXene-based nanomaterials have their properties tailored towards flame retardancy in polymers and its corresponding composites. The accurate determination provides insight into the thermal behaviour, chemical composition, mechanical strength, and morphologies [42]. Moreover, understanding these qualities promotes innovation and makes it possible to produce materials with customized characteristics and properties

Table 1
Shows the Techniques for the analysis of MXene-based nanomaterials for flame retardant polymers and composites.

S/n	Techniques	Purpose	Ref
1	Electron microscopy (EM)	EM is critical for the determination of the probable characteristics of any material. It provides high-resolution imaging, allowing for accurate characterization of MXene dispersion inside the polymer matrix. This approach provides critical insights into interfacial interactions, dispersion uniformity, and possible agglomeration, all of which have an impact on materials performance. By visualizing nanoscale characteristics, EM assists in the optimization of MXene-polymer composites, allowing for the development of materials with improved mechanical, thermal, and electrical properties. The accurate characterization is critical for improving MXene-based composites and their applications.	[28,41]
2	Cone calorimetry	This technique is very important and critical in fire safety research and material development. It involves subjecting a sample to controlled heat in a standardized setup while measuring factors such as heat release rate, smoke production, and ignition time. This method provides accurate insights into a material's fire behaviour, allowing for a thorough evaluation of flame-retardant performance. Cone calorimetry makes it easier to identify crucial fire-resistant features, which can help guide material design for applications.	[43]
3	X-ray diffraction (XRD)	XRD is used to examine the crystalline phases, interlayer spacing, and orientation of MXene inside the polymer matrix. The generated diffraction patterns assist in determining the degree of exfoliation or aggregation, which is critical for optimizing material properties. The quality of MXene dispersion is given by analyzing peak positions and intensities, allowing for the fabrication or development of innovative composites with superior mechanical and thermal properties for a wide range of applications.	[44]
4	Thermogravimetric analysis (TGA)	TGA is an important technique for determining flame retardant characteristics in materials. This method includes heating a sample to a regulated temperature and then monitoring the weight loss over time. The resulting thermogram reveals information on the material's thermal stability, decomposition rates, and the efficacy of flame retardants. The data from the thermogram can be used to determine the commencement of decomposition and the susceptibility of the material to igniting by analyzing the temperature at which considerable weight loss occurs. TGA is useful in optimizing flame retardant compositions and influencing the development of materials that are more resistant to heat deterioration by giving essential data on material behavior at elevated temperatures.	[45]
5	Fourier-transform infrared (FTIR) spectroscopy	FTIR is a useful tool for evaluating flame retardant qualities in materials. This approach analyses the interaction of infrared radiation with a material, yielding comprehensive information about its molecular makeup. FTIR provides information on the unique absorption bands associated with flame-retardant chemicals. Changes in these bands represent chemical changes and interactions that occur during combustion which can be used to determine the efficacy of flame retardants in suppressing certain combustion-related chemical processes. This approach aids in the optimization of flame retardant formulations while also providing insights into the chemical mechanisms that underpin fire resistance which can be used to produce customized materials with improved flame retardant qualities.	[28,44]
6	**Rheological studies**	The rheological study provides an essential understanding of material processing and performance by investigating the flow and deformation characteristics of MXene-polymer composites. The viscosity, shear rate, and storage modulus measurements aid in determining the dispersion state and interfacial interactions of MXene and the polymer matrix. Understanding rheological qualities is essential for optimizing processing conditions, guaranteeing uniform dispersion, and improving the mechanical and rheological properties of the produced composites. The MXene-polymer formulations for specific applications, including as flexible electronics and structural materials, can be achieved through the accurate rheological information of the material thereby allowing for innovative composites with tailored rheological properties and improved or enhanced performance.	[46,47]

that are vital for mitigating challenges associated with material safety. It is therefore imperative to characterize MXene-based nanomaterials for flame retardant polymers polymers and composites to have a complete grasp and full utilization of its probable applications.

4. Overview of key studies on MXene-based flame-retardant polymers

In recent years, MXene has been an important topic of discussion, and its relevance in polymer complexes as fire retardants is currently a hot topic [48]. This is due to the possibility that MXene's dispersion in polymer substrates will improve mechanical, thermal, anti-dripping performance, and flame-retardant properties [49]. MXene has previously proven to be able to greatly improve the characteristics of the polymer matrix [50]. It is more likely that MXene nanocomposites will be utilized to enhance the activity of water-soluble polymers, making them appropriate materials for early fire detection and electromagnetic interference shielding, because they can produce excellent mixes in water and generate a homogeneous solution [51,52].

MXene-based composites have demonstrated encouraging prospects, relevant in warning sensors in the event of flame, in particular, thanks to their special characteristics of unique electrical conductivity, UV protection, photothermal transformation, reproducible response, and reduced signal-to-noise ratio, smoke suppression properties [53–55]. In the work of Mao et al. [56], polymeric-modified TiO_2@MXene networks that demonstrated dual-mode fire sensing were fabricated including cyclic warning capacity and rapid-fire warning responses. After coming into contact with a flame bombardment, the MXene sheets oxidize to form C/N doped TiO_2 layers, which after self-healing provide flame suppression and fire warning qualities in contact and non-contact modes. By exploring natural polymers-modified MXenes, Zeng et al. [57] constructed an MXene/cellulose nanocoating that, when burned, can activate the fire alarm system in less than 4 s. The material's exceptional flame hindrance was attributed to the multilayer barrier effect and the catalytic carbonization of MXene and montmorillonite, which were utilized to reinforce the biopolymer. Meanwhile, biobased casein/MXene composites have been shown to consistently display distance-dependent changes in resistance within 3 s when subjected to the impact of a flame that is approached repeatedly [58]. This provides an attractive accessibility for flame position detection. To create a large-scale wireless real-time fire alarm network with the ability to transmit the monitored signal to remote locations in just 3 s and avert potential fire mishaps that could result in significant loss of life and financial damage, the composite material can be applied to flexible fabrics with ease [59].

Polyethylene glycol or polyvinyl pyrrolidone polymer decorated $Ti_3C_2T_x$ with outstanding resistance to flames as well as delicate fire cycle warning performance has been devised to provide an ultra-fast, recyclable, and weather-proof fire alarm material [60]. Moreover, MXene networks modified with silane offer reclaimable and weather-proof fire warning responses, following outdoor exposure for a year, while also bestowing exceptional superhydrophobicity and exceptional flame resistance upon combustible substrates.

Furthermore, MXene-polymer-based aerogels with responsive temperature-sensing have shown great fire-alert capabilities, improved thermoelectric properties, significant heat insulation, unique thermostability, and long-lasting piezoresistive sensing for smart fire protection in building, transportation, and aerospace [61–63]. An electronic textile for fire safety that is wearable and self-powered, utilizing silver nanowires, aramid nanofibers, MXene, and aerogel fiber for fire protection in firefighting apparel [64]. The autonomous fire warning manufactured materials may be incorporated into firefighting apparel to accomplish a broad-spectrum detection of temperatures at 100–400 °C because of MXene's thermoelectric property. This might inform firemen to exit the area as soon as possible to avoid damaging their protective gear. Other MXene-based polymeric composite materials that have been explored as flame retardants with persistent fire warning sensing during direct fire incidents are summarized in Table 2.

Recent developments have demonstrated that the pyrolysis product distribution can be tracked under varying heating temperatures and have clarified the pyrolysis impediment provided by a flare retardant system using numerical simulations. The simulation conducted with ReaxFF-MD showed how the numerical framework can be a useful evaluation tool for designing advanced frame retardant materials, predicting their pyrolysis behavior, and providing atomistic information for future frame retardant research. Particularly in nanoscale and two-dimensional composites, where it is difficult to characterize frame retardant chemistry using experimental equipment [65].

In another relevant study, Yu and co-workers [66] conducted a significant study on the stabilization of aqueous dispersions of exfoliated Ti_3C_2, which was achieved through a two-step process. Initially, Ti_3AlC_2 was selectively etched using lithium fluoride (LiF) in concentrated hydrochloric acid (HCl), followed by ultrasonic treatment in deionized (DI) water to obtain exfoliated Ti_3C_2 nanosheets. To enhance their compatibility and functionality, the exfoliated nanosheets were subsequently modified using two cationic surfactants: cetyltrimethylammonium bromide (CTAB) and tetrabutyl phosphine chloride (TBPC). These surface modifications were strategically chosen based on their distinct molecular structures and elemental compositions, which were expected to influence both the dispersion stability and flame-retardant properties of Ti_3C_2 in thermoplastic polyurethane (TPU) matrices.

A key advantage of the selected modifiers lies in their cost-effectiveness and commercial availability, making them viable candidates for large-scale applications. Moreover, TBPC, which contains phosphorus—a well-known flame-retardant element—was anticipated to enhance the flame-retardant efficiency of the Ti_3C_2 nanosheets. On the other hand, CTAB, with its long hydrophobic alkyl chains, was postulated to interact more effectively with the TPU matrix, thereby improving the dispersion and interfacial adhesion of the nanosheets within the polymer. These structural and compositional differences were considered crucial in determining the overall fire safety performance of the TPU nanocomposites. The study further explored the fire resistance properties and flame-retardant mechanisms of the TPU nanocomposites, providing insights into how surface modification of Ti_3C_2 influences its effectiveness in flame retardancy. The findings underscored the potential of modified

Table 2
Recent advances in MXene-based flame-retardant composite materials.

MXene-based flame retardant	Method of synthesis	Flame retardancy/functional properties	Key findings	Ref.
PVB/HPUPO/$Ti_3C_2T_x$ nanocomposites	Two-step phase change and freeze-drying	Reduction in pHRR 64.0 % and 45.9 %	MXene networks and HPUPO may operate in concert to increase thermal stability and decrease pyrolyzed volatiles, pHRR, and total heat release (THR)	[67]
PS/O–Ti_3C_2 nanosheet	Solution-mixing	Reduction in pHRR by 32 %	The MXene–organic hybrid nanosheets' thermal stability and 2D mass- and thermal-transfer bareffect were crucial in postponing the degradation of the polymer.	[68]
TPU/APP@CS@$Ti_3C_2T_x$ composites	Layer-by-layer assembly and microencapsulation technology	Reduction in the THR (73.0 %) and TSR (77.3 %), as well as reduction in CO (75.3 %) and CO_2 (75.3 %) yield	The catalytic charring action, the composite hybrid's obstruction impact in the condensed phase, and the dilution and capturing effect in the gas phase are all responsible for the improved flame retardancy features.	[69]
($Ti_3C_2T_x$)/polypropylene composite	Coating, spraying, and hot pressing	A decreased THR of 3.7 kJ/g and a lowered HRR of 50.0 W/g by 78 % and 87 %, respectively.	The unique interlocking structure of the composite materials and 2D phosphorylated MXene nanosheets allowed the composites to exhibit significant electromagnetic interference capability.	[70]
$Ti_3C_2T_x$/natural rubber nanocomposite films	Vacuum-assisted filtration	High-quality electrical conductivity of 1400 S m^{-1} and exceptional 53.6 dB EMI shielding performance.	The MXene provided remarkable reinforcement to the natural rubber matrix by the sturdy, 3D MXene network, which exhibits increased tensile strength and modulus by 700 % and 15,000 %, respectively	[71]
PVA/$Ti_3C_2T_x$ film	Multilayered casting	A particular EMI shielding effect of 9343 dB cm^2 g^{-1}, an ultimate EMI shielding efficiency of 44.4 dB, and an electrical conductivity of 716 S/m are all present.	Owing to the MXene layer's strengthening, the PVA matrix concurrently demonstrated exceptional EMI shielding and thermal conductive performance. For the conduction of heat and electrons, they offered a continuous network.	[72]

Table 2 (*continued*)

MXene-based flame retardant	Method of synthesis	Flame retardancy/functional properties	Key findings	Ref.
PVA/$Ti_3C_2T_x$ composite foam	Freeze-drying	The highest specific shielding efficiency of 5136 dB cm^2g^{-1} and the lowest reflection effectiveness (SE_R) of below 2 dB are achieved.	The combination of different porosity architectures, interior reflection, and the polarization effect (dipole and interfacial polarization) results in improved absorption efficiency and increased EMI shielding efficacy.	[73]
TPU/Co-MOF@$Ti_3C_2T_x$ composites	Selective etching and solvothermal	Smoke production rate and total smoke output decreased by 58.8 % and 47.5 %, respectively, whereas pHRR and THR were 28.3 % and 14.5 %, respectively.	The combination of MXene's barrier properties and Ti and Co catalytic effects was identified as the material's flame-retardant mechanism.	[74]
EP/CuP-MXene	Rational design	pHRR and TSR were reduced by 63 % and 131 % respectively	The flame-retardant effect is produced by the catalytic carbonation of CuP and the physical barrier of MXene. Its toughening and reinforcing effects are related to the presence of mechanically powerful 2D MXene and the chemical cross-linking action of CuP.	[75]
Bimetallic $Mo_2Ti_2C_3T_x$ endowed EP nanosheet	Solution etching and exfoliation	Reduced pHRR by 34 %, PSPR by 32.7 %, TSP by 57.7 %, PCO by 30.8 %, SF value by 72.7 %	The strong catalytic attenuation and charring impact of transition metal Mo—Ti components for bimetallic $Mo_2Ti_2C_3T_x$, together with the nanosheet structure, gave EP composites a good fire-retardant performance.	[76]
Lignocellulose (LCNF) nanofibrils and MXene	Vacuum-assisted alternate self-assembly	Superior fire alarm response (0.32 s) and a continuous alarm signal (about 3073.0 s)	The inclusion of APP improved the stability of the char residual structure and the LCNF layer's ability to produce char, according to the related analysis of the fire alarm and flame-retardant systems.	[77]
Of MXene/CCS@CF	Layer-by-layer assembly	High limiting oxygen of 45.5 %, pHRR reduced by > 66 %	The material's adjustable Joule heating capabilities allowed it to be used at extremely cold temperatures and allowed it to detect a range of human emotions	[78]
PVA/MXene nanocomposites	Casting/evaporation	pHRR and THR were reduced by 25.7 % and 25.5 % respectively	The interfacial relationship between MXene and the PVA matrix resulted in improved tensile strength and elongation at break.	[79]

PVB = polyvinyl butyral, HPUPO = Hyperbranched poly (Urethane-Phosphine Oxide), pHRR = peak heat release rate, THR = Total heat rate, TSR = Total smoke release, TPU = Thermoplastic polyurethane, APP = Ammonium polyphosphate, CS = Chitosan, EMI = Electromagnetic interference, PVA = Poly (vinyl alcohol), MOF = Metal organic frameworks, EP = Epoxy resins, CuP = Copper organophosphates, PSPR = peak of smoke production rate, TSP = Total smoke production, PCO = Peak CO, SF = Smoke factor, CCS@CF = Chitosan-coated cotton fabric

Ti_3C_2 nanosheets as multifunctional additives for TPU-based materials, demonstrating a promising strategy for developing high-performance flame-retardant polymer nanocomposites.

5. Performance improvements in flame retardant polymers and composites

The purpose of a flame-retardant is to obstruct combustion or slow down the process of burning when an ignition occurs. With the exploration of nanoscience in the past few decades, the remarkably small size and high surface area of these nanomaterials, such as metals and transition metal oxides, carbon nanotubes, MOFs, and polyhedral oligomeric silsesquioxanes (POSS), enable better interactions, dispersion, and integration with the surrounding polymeric network [80–83]. These nanomaterials have demonstrated significant flame-retardant properties. As a result, strong cross-linked nanomaterial structures with the polymer matrix are created, which are essential for forming a non-porous carbonaceous layer during burning [84]. These nanomaterials act by suppressing the combustion chain reaction through pyrolysis. They can also generate highly reactive free radicals and non-combustible gases [85]. Additionally, they make the polymer more viscous, which reduces dripping and melt flow. Furthermore, some nanomaterials can emit non-flammable gasses when they burn, which helps to stop the spread of flames. Moreover, the compounds of transition metal oxides such as SnO_2, TiO_2, and Al_2O_3 function as catalysts to encourage the production of protective layers on the material surface and the breakdown of combustible gasses, which prevents the spread of flames [86,87]. The effectiveness of the nanomaterial as a flame-retardant is greatly influenced by its compatibility with polymers and their interfacial interactions [88]. Enhancing the compatibility, dispersion, and interfacial adhesion of nanoparticles inside polymer matrices is a frequent use of surface modification, which involves functionalizing the surface of the nanomaterial with compounds or materials by surface grafting, covalent bonding, non-covalent association, π-π stacking, and/or hydrogen bonding [89,90].

Polymeric materials have demonstrated widespread uses in several industries because of their exceptional abilities, including high strength-to-weight ratio, good extensibility, and ease of processing [91]. Strong, durable, and flame-retardant polymeric materials with excellent ductility have been sought after for their practical uses in the sector [92]. Regretfully, current materials design approaches usually fail to combine outstanding strength with exceptional toughness in polymers without compromising the ductility of the matrix polymers. The employment of nanoparticles in polymer-based composites for flame retardancy purposes, either as doping agents or fillers, has advanced quickly. The addition of a small amount of a nanomaterial to polymer composites can significantly increase their thermal stability, smoke release quantity, peak heat release rate, and the rate at which flames spread throughout the nanocomposites, even when they do not naturally exhibit good fire retardance [93]. Furthermore, MXene's interfacial engineering with polymeric substrates has produced extremely robust and resilient polymer nanocomposites with outstanding fire safety and great ductility [94]. These have also imparted highly stretch-ability, and fatigue resistance in polymer nanocomposites [95]. To suppress smoke and lessen the risk of fire, 2D materials-based nanohybrids have been widely developed for a variety of polymers and have demonstrated better physic barrier and catalytic charring. [96]. Meanwhile, By combining them with flame retardants based on nitrogen and phosphorus, 3D MXene frameworks may greatly increase the flame retardancy of hydrophobic polymer nanocomposites, improving the fire safety of polymer composites [67].

Furthermore, it is imperative to note that, MXenes are highly prone to oxidation, especially at high temperatures. When exposed to temperatures above 200 °C, their oxidation rate increases, leading to significant deterioration in their properties. In polymer processing, where high temperatures are needed for melting and mixing, MXenes can react with oxygen, forming TiO_2. This reaction alters their electrical, mechanical, and thermal characteristics [97,98]. Additionally, MXenes have surface groups (-OH, −F, −O) that make them highly reactive with water and oxygen, particularly under heat. Prolonged exposure to high temperatures during polymer blending increases the risk of oxidation [99,100]. To improve their stability, careful optimization of processing conditions, surface modifications, and composite design is essential. To maintain the functional properties of MXenes in polymer composites, studies have shown several strategies which has been implemented, these include:

- Low-Temperature Processing Techniques: Using solution-based methods like solvent casting or in-situ polymerization instead of high-temperature extrusion. For example, $Ti_3C_2T_x$/polyvinyl alcohol (PVA) films fabricated via solution casting prevent oxidation [101–103].
- Protective Coatings: Coating MXenes with antioxidants, polymers, or organic molecules (e.g., dopamine, silanes) to shield them from oxidation [104–106]. A notable example is polydopamine-functionalized MXene, which enhances its stability in polymer matrices.
- Oxygen-Free Processing Environments: Performing polymer blending in an inert atmosphere (argon or nitrogen) to reduce oxidation [107]. For instance, $Ti_3C_2T_x$/polyurethane nanocomposites [107,108] processed inside a glovebox minimize degradation.
- Encapsulation in a Polymer Matrix: Dispersing MXenes within a polymer before heating to limit direct exposure to air [109–111]. A practical example is MXene embedded in epoxy resins, which helps retain electrical conductivity and mechanical strength.

MXenes' oxidation sensitivity poses issues in high-temperature polymer manufacturing. However, strategic measures including low-temperature synthesis, protective coatings, inert processing conditions, and polymer encapsulation can significantly improve their stability. By optimizing these processes, MXenes can maintain their outstanding properties, ensuring their successful incorporation into sophisticated polymer composites for a wide range of high-performance applications.

6. Challenges and opportunities for industrial application

The engineering of fire-retardant materials across different industries has grown over the years owing to the enormous environmental disasters and economic losses due to fire accidents. From cooking in prehistoric times to operating an engine today, fire has played a positive but underappreciated role in the advancement of human civilization [112]. To curb the menace arising from fire outbreaks, extensive application of MXene-reinforced polymer composites has progressively gained recognition and applied in many industries such as communication, aerospace, energy, construction, transportation, and electric devices such as flame or smoke detectors, fire alarms, flame shielding, temperature sensors, insulators, and so on [113–115].

6.1. Energy storage and electronic devices

The increased demand for electronic devices such as electric vehicles, portable electronics, and renewable energy storage systems has inspired the necessity to design novel battery technologies with outstanding energy densities that can override those of conventional lithium-ion (Li-ion)-based batteries [116]. However, the electrochemical activities of Li-ion batteries containing sulfide moiety are greatly limited by poor insulating properties and unstable operational functionality due to the antagonistic effect of polysulfide shuttling [117]. Notwithstanding, the increased sulfur loading in these energy-generating sets can pose serious safety concerns considering the flammability properties of sulfur [118]. In the energy-generating sector, the utilization of MXene nanosheets can be very helpful as cathode materials to minimize or obstruct flammability concerns [119]. Ideally, the titanium atoms on the skeletal framework of MXene could accelerate the chemical trapping, and chemisorption of polysulfides by generating a Lewis acid-base relationship between MXene and lithium polysulfides, and intriguing catalytic conversion of polysulfides [120]. Zhang et al. [121] reported a Magnolol-modified $Ti_3C_2T_x$ that was purposely designed as a potent cathode host material and can be adjusted by using the nucleophilic substitution technique. Owing to the increased C−Ti−O bond formation and reduced diallyl group terminations during dehalogenation and nucleophilic addition processes, the modified MXene electrode was able to successfully suppress the shuttling of lithium polysulfides through chemisorption and the creation of C−S covalent links.

Van der Waals forces may also cause MXene in the composite material to rapidly self-restack, which might be detrimental to both their fundamental function and the availability of electrolyte ions [122]. In this situation, it is extremely desirable to devise effective methods to reduce self-restacking while also improving MXenes' qualities. Using materials with certain formations as intercalants is seen to be a good tactic [123]. MXene-based flame-retardant composites with high electrical conductivities, three-dimensional porous architectures, and polysulfide chemisorption centers can also be used to complement this [124]. In a typical experiment, a 3D porous nitrogen-doped carbon foam (NCF) framework embedded in electrostatic self-assembled MXene/Ammonium Polyphosphate (APP) (Fig. 5a and b) was created by Li et al. [125]. This framework can enhance the physicochemical adsorption and conversion of polysulfides while reducing the combustion behavior of flammable sulfur-active compounds. Therefore, even in situations with high sulfur loading, the fabricated composite material makes a substantial contribution to obtaining a great electrochemical energy storage capacity and improving the safety of Li−S batteries. In the event of a battery thermal runaway, the material can efficiently divert polysulfides at higher operating temperatures as well as

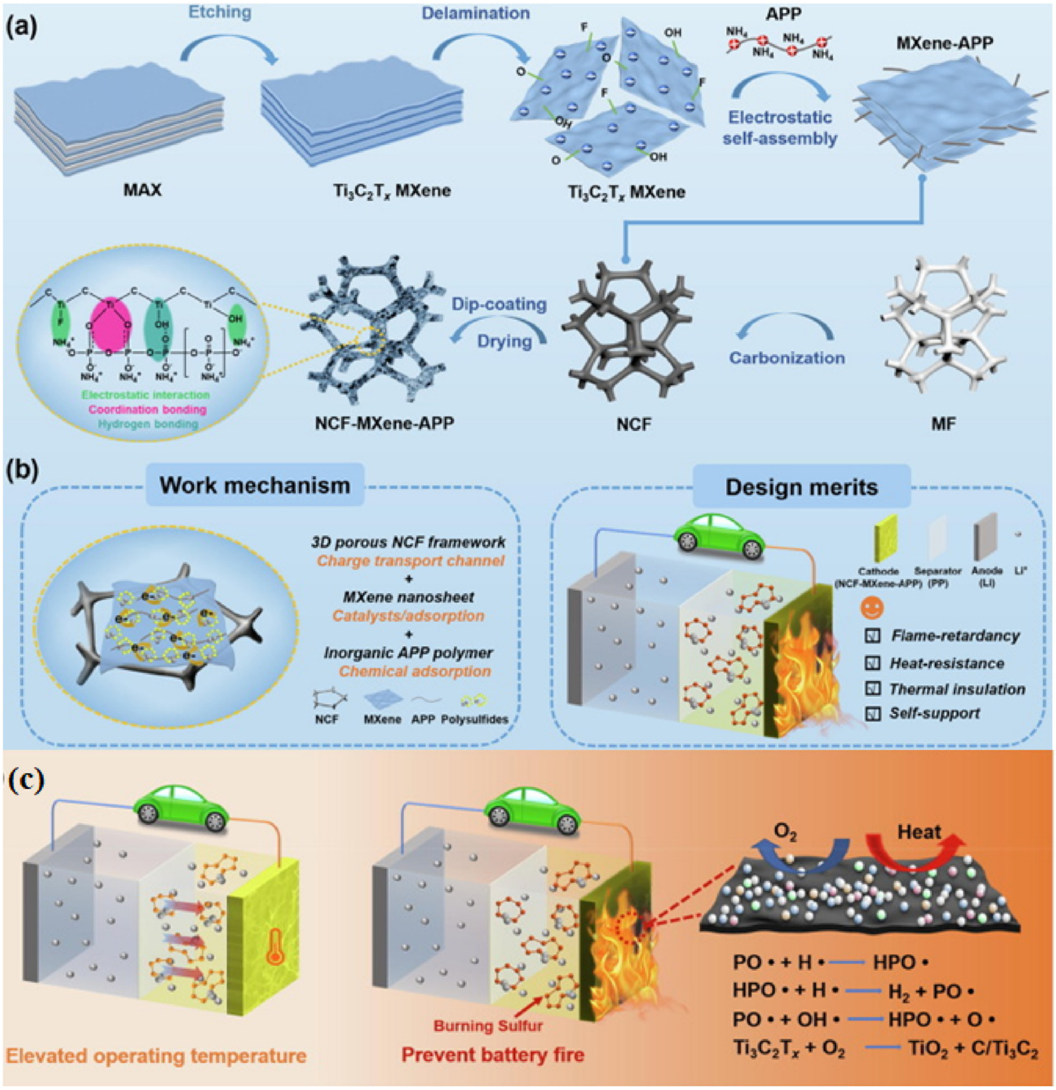

Fig. 5. Schematic illustration of (a) fabricating process showing the multiple interactions and (b) mechanism of NCF-MXene-APP host (c) NCF-MXene-APP-Li_2S_6 cathode with thermal-triggered flame-retardant properties for Li–S batteries. Reproduced from Ref. [125]. Copyright 2023 Science Press and Dalian Institute of Chemical Physics, Chinese Academy of Sciences. Published by ELSEVIER B.V. and Science Press.

form an efficient heat and oxygen barrier to stop the spread of fire (Fig. 5c). In another study, metal-organic framework-modified MXene nanosheets (ZIF-8@MXene) and a polymer mixture (PE-ZIF-8@MXene) were combined to create a polymer composite electrolyte [126]. The synthesized, nonflammable ZIF-8@MXene nanosheets have a large number of Lewis acid sites and functional groups in addition to a large specific surface area. ZIF-8@MXene nanosheets accelerated Li-ion transportation in the composite electrolyte by increasing the dissociation of lithium salts and providing pathways for ion transport. They also improved PE-ZIF-8@MXene's thermostability, flame resistance, tensile strength, long cycle life of 2000 h, and battery retention capacity of 89.6 % after 500 cycles.

Additionally, the covalent grafting of a conjugated microporous polymer to an MXene as the electrocatalytic sulfur host can enhance the electrochemical performance of sulfur cathodes [127]. The interaction of APP with Li-ion increases ion transfer, whereas the significant binding affinity of APP's main chain with lithium polysulfides serves to limit the diffusion of polysulfide anions and suppresses their shuttling impact, hence promoting the cathode reaction's kinetics [128]. These technologies can effectively provide the next generation high energy density Li–S batteries to drive the renewable energy and electronic device sector.

6.2. Fire alarm sensors

As fire alarm sensors, MXene-based polymeric composites have emerged as a promising material owing to their high electrical conductivity, mechanical flexibility, and excellent thermal stability [129]. Their intriguing electrical conductivity makes them stand out for detecting changes in temperature or heat in an incidence of a fire outbreak. The incorporation of MXene-based composite into a polymer matrix allows for a quick response to temperature changes by altering its electrical resistance. Meanwhile, their high thermal stability enables them to survive in extreme temperature conditions. When exposed to heat or flame, the polymeric composite undergoes structural changes, leading to a measurable change in electrical conductivity or resistance, which can trigger an alarm [130].

During a fire outbreak, the fire alarm sensor is triggered due to response to high-temperature changes or detection of flames in the environment that cause the polymeric component to degrade or expand, while the conductive MXene network is disrupted [131].

This leads to a sufficient rise in the electrical resistance that can be detected by an external circuit to cause the fire alarm to sound. Zhang et al. [132] exemplify the fabrication of a flame-retardant paper with thermosensitive fire-alarm response and self-cutting performance based on polyurethane (PU) and MXene obtained by facile electrospinning and vacuum filtering processes. This stimuli-responsive PU paper can undergo self-programming into various shapes and instantly recover to its original shape within 10 s. When temperatures rise above the T_g of the PU, the shape memory paper can quickly return to its initial state. This allows it to reconnect with the alarm lamp in the cut-off circuit and successfully send out a timely warning signal to people so they may take emergency action.

Another system based on a flexible sandwich-like film (AMA) has been designed with a highly remarkable sensitivity to low temperatures and flame signals. This device was constructed by using vacuum-assisted self-assembly and hot-pressing technology with aramid nanofibers (ANF) and MXene has long-lasting fire warning capabilities with an instant response time of 400 ms and a continuous alarm signal ~900 s when a flame signal is detected within its surrounding [133]. MXene-based polymeric composites, with their unique combination of electrical, thermal, and mechanical properties, present a very promising platform for the creation of new fire alarm sensors. These materials could transform fire safety technology with more study and development.

6.3. Wood

Wood is a natural renewable and accessible material that is widely known for its significance in construction, furniture, interior decoration, and transportation [134]. Their industrial application has been geometrically progressed due to their mechanical strength and lightweight [135]. Despite their popularity, their flammability concern has hampered practical application in many public domains. Installing flame sensors and fire warning signals is the best approach to mitigate the ignition challenges, however, using composite materials to solve this problem heavily relies on the ability of intermolecular bonding within the functional layers of the composite materials and intramolecular cross-linkage, which are related to the construction of a continuous conducting network [136]. When these incoherent layers build up on the substrate surface, the adhesion strength might be considerably weakened, decreasing the capacity to alert people to flames [137].

The burning of wood is often associated with the release of volatile organic compounds (VOCs) which are potential air pollution hazards. Smart wood coated with MXene has demonstrated encouraging potential for air purification by photocatalytic oxidation, a process that allows gaseous pollutant molecules to be trapped on the catalytic system's surface [138]. An MXene/epoxy intumescent fire-retardant coating prepared by Huang et al. [139] shows high thermal stability with good fire protection for ancient wooden architectures. Zhang et al. [140] presented an alternative approach that uses cellulose nanocrystals intercalated with an MXene network to create scalable smart wood with stable adhesive covering. The biopolymeric nanocrystals were very helpful in solving the re-stacking of MXene nanosheets. It also acts as a thermoswitch, maintaining the insulative mediator at ambient temperature and facilitating the flow of electrons activated by fires or higher temperatures. To further advance the wood and furniture industries, the incorporation of curing agents with water resistance properties into MXene/polymer composite architecture can achieve waterborne coating with remarkable hardness and adhesion. Additionally, this type of coating can create a strong intumescent char layer, which effectively suppresses the transfer of heat and oxygen and lowers the amount of smoke produced [141].

6.4. Upholstery textiles

Upholstery textiles, typically made from cotton are bio-based materials frequently used in clothing designs. These fabrics are often used for designing and decorating the seat cover of trains, ships, airspace, cars, etc. due to their comfort, softness, biodegradability, and breathability [142,143]. The flammability of cotton materials as well as their water absorption characteristics has been a major hindrance to their extensive industrial application in this field considering that numerous fire outbreaks are easily propelled by the presence of these materials in an ignition scene [144]. To circumvent this setback, flame retardants containing phosphorous, nitrogen, and silicon compounds have synergistically assisted in reducing their flammability and enhancing their thermal stability [145]. For instance, cotton fiber can be shielded from heat radiation and combustible gasses by an organosilicon coating [146]. They can also dilute the oxygen surrounding the flame and serve as a source of blowing. In addition to producing noncombustible gases and increasing char, nitrogen can also boost flame-retardant efficacy and decrease the concentration of combustible volatile compounds [147]. The biocompatibility of MXenes with heteroatoms and organosilicon compounds can be used to afford new architectures for self-extinguishing or detecting flames in textiles. Moreover, the grafting of modified MXene with natural biopolymers such as chitosan with rich nitrogen content and numerous hydroxyl groups can generate novel flame retardants that could facilitate fire resistance by diluting oxygen and developing a protective char layer [148]. Nitrogen-rich urea can be used to complement flame-retardant material where they act by diluting compounds that are combustible with ammonia and reducing the gaseous phase flammability in the combustion process [149]. The introduction of fire-protective phosphates and nitrogen groups in modified starch can produce insulating materials with reduced smoldering effects in flame retardants [150]. The modification of MXene and reinforcement with biopolymers is not only a novel approach to mitigate fire in the transportation sectors, but it will also open new avenues for creating new materials with remarkable functional properties and mechanical strengths.

6.5. Electromagnetic interference (EMI) shielding

The significance of MXene-based polymeric composites in electromagnetic interference (EMI) shielding applications cannot be overemphasized, particularly in environments where fire safety is a critical concern. By leveraging their excellent metallic conductivity, this composite material tends to form conductive networks that attenuate electromagnetic waves [151]. The engineering of MXene-based polymeric composites in EMI shielding and fire resistance by the **incorporation of blended polymer flame-retardant additives** like phosphorus-based compounds, metal hydroxides, or intumescent agents which synergistically form a protective char layer that insulates the underlying material [152–154]. These materials tend to create a physical **barrier effect** by slowing down the spread of flames and reducing the release of flammable gases; meanwhile, the MXene helps to dissipate heat, reducing the risk of localized overheating and ignition [155].

A potentially effective method for producing lightweight, high-performing conductive composites by combining ethyl methacrylate polymer with varying ratios of MXene and Fe_3O_4-g-C_3N_4 was shown in the study by Katheria et al. [156] By comparing the efficacy of MXene and Fe_3O_4-g-C_3N_4, it was shown that the latter may create a compact, interlocking conductive network, which results in remarkable electrical properties and outstanding EMI shielding efficiency for advanced electronics, aerospace, and telecommunications devices.

A unique syndiotacticity-rich poly (vinyl alcohol) (sPVA) and modified MXene sediment (mMS) multilayered composite film were developed using an alternate casting technique [157]. The non-covalent interaction between the dense mMS layer and the stereoselective sPVA layer is responsible for the improved tensile strength. The multilayered composite film also showed intriguing electrical and thermal conductivity that supports the synergistic effect of in-plane thermal conductivity and EMI shielding effect in the X band. Additionally, the mMS layers' continuous network for thermal and electron conduction allowed for effective heat dissipation in interwoven thermal channels and multiple reflection-absorption for microwaves in the composite film. MXene-based polymeric composites offer a promising solution for EMI shielding in fire-prone environments. This can be achieved by capitalizing on the intrinsic properties of MXenes and incorporating flame-retardant strategies, which can provide dual functionality, making these composite materials highly attractive for many industries.

In a significant study, Jin and colleagues [158] systematically investigated the fabrication of MXene-filled polymeric films with outstanding electromagnetic interference (EMI) shielding and thermal conductivity properties. Their approach involved the integration of poly(vinyl alcohol) (PVA) as the polymer matrix, leveraging its ability to establish strong hydrogen bonding interactions with MXene nanosheets, thereby ensuring uniform dispersion and enhanced interfacial adhesion. A multilayered architecture was strategically engineered through a layer-by-layer casting technique, wherein alternating PVA and MXene layers contributed to the formation of a continuous electrically and thermally conductive network. The resulting 27-μm-thick PVA/MXene multilayered film demonstrated remarkable electrical conductivity and EMI shielding effectiveness (EMI SE), along with an impressive specific EMI SE (SSEt) and in-plane thermal conductivity. These properties were attributed to the synergistic effect of the continuous MXene layers facilitating efficient charge and phonon transport. Additionally, the hierarchical structure endowed the film with superior anti-dripping performance, a crucial factor in enhancing flame retardancy. To elucidate the underlying principles governing these enhancements, the study provided an in-depth analysis of the EMI shielding mechanisms, thermal conduction pathways, and flame-retardant behavior in the PVA/MXene system. The findings underscored the pivotal role of MXene in simultaneously improving thermal conductivity and flame resistance in polymeric matrices. This work not only highlights the multifunctionality of MXene-based composites but also presents a viable and scalable strategy for developing high-performance, flame-retardant, and thermally conductive polymeric films tailored for EMI shielding applications.

6.6. Smoke and toxicity hazards

Toxic smoke emission is one of the leading causes of fatalities in fire incidents, posing severe health and environmental hazards. In recent years, MXene-based nanomaterials have garnered significant attention for their potential in enhancing flame-retardant performance while mitigating smoke release and toxicity in polymer composites. MXenes, particularly $Ti_3C_2T_x$, exhibit excellent thermal stability, high char-forming capability, and catalytic activity, which contribute to their effectiveness in reducing smoke density and inhibiting the release of toxic gases. Their unique layered structure and abundant surface functionalities enable them to act as effective barriers, limiting heat and oxygen diffusion, thereby slowing down polymer degradation and combustion. Furthermore, MXenes can synergistically enhance the performance of traditional flame retardants, leading to the development of high-performance, multifunctional fire-resistant materials.

For instance, Lin et al. [159]proposed an advanced interfacial engineering strategy to enhance the properties of acrylonitrile-butadiene-styrene (ABS) nanocomposites by synthesizing defect-engineered La-MOF@MXene nanohybrids (d-LM@MX) with oxygen vacancies via defect engineering and in-situ growth. The incorporation of d-LM@MX into the ABS matrix resulted in a well-dispersed nanohybrid, significantly strengthening interfacial interactions. Notably, the introduction of oxygen vacancies and surface defects in d-LM@MX played a pivotal role in augmenting flame retardancy and smoke suppression properties. Comparative analyses demonstrated substantial reductions in the peak heat release rate (29.52 %), peak smoke production rate (46.70 %), and total smoke production (28.5 %) relative to pristine ABS. Additionally, mechanical performance assessments revealed notable enhancements in both tensile strength and elongation at break, indicating that the nanohybrid not only improved fire safety but also preserved the structural integrity of the material. This study underscores the potential of MXene-based nanocomposites in advancing fire-resistant polymer materials and broadens their applicability across various high-performance domains. In another study, Pan et al. [160] developed a series of ABS nanocomposites with enhanced smoke suppression and toxicity inhibition through facile surface modification of ZHS. The modified composite, ABS/$Ti_3C_2T_x$-PDA-ZHS, exhibited a 15.4 % increase in elongation at break without compromising tensile strength, indicating improved mechanical integrity. Furthermore, the ternary metal catalysis effectively mitigated toxic gas emissions and smoke particulates during combustion, with peak reductions of 17.5 % (PHRR), 34.5 % (HCN), 19.1 % (NO), and 20.0 % (NO_2). The smoke density was reduced by 19.5 %, while light transmittance significantly improved from 21.2 % to 37.7 % at 240 s. These advancements address ABS's inherent flammability and toxicity, broadening its potential applications in industries such as construction and automotive manufacturing.

7. Current challenges

The recent advancements in MXene-based nanomaterials for flame retardant polymers and composites have brought about significant progress in enhancing fire safety and material performance. However, several challenges persist, hindering the widespread adoption and optimization of MXene-based flame retardant technologies. Some of the current challenges associated with this topic include:

Scalability of synthesis methods: While numerous synthesis methods exist for producing MXene nanosheets, many of these processes are laboratory-scale and may not be readily scalable for industrial production. Developing scalable and cost-effective synthesis methods that maintain the high purity and quality of MXene nanosheets is essential for large-scale manufacturing and commercialization.

Dispersion and compatibility in polymer matrices: Achieving uniform dispersion and strong interfacial interaction between MXene nanosheets and polymer matrices remains a challenge. Poor dispersion can lead to uneven flame retardant performance and compromise the mechanical properties of polymer composites. Developing effective dispersion strategies and surface functionalization techniques to improve compatibility with different polymer matrices is crucial.

Understanding flame retardant mechanisms: Despite the promising flame retardant properties exhibited by MXene-based nanomaterials, the underlying mechanisms governing their flame suppression effects are not fully understood. Investigating the interaction between MXenes and polymer degradation products during combustion, as well as their influence on char formation and heat transfer, is essential for elucidating the flame retardant mechanisms and optimizing material performance.

Durability and long-term stability: Ensuring the long-term durability and stability of MXene-based flame retardant polymers and composites is another challenge. MXene nanosheets may undergo degradation or agglomeration over time, leading to reduced flame retardant efficacy and mechanical properties. Developing strategies to enhance the stability and longevity of MXene-containing materials, such as through encapsulation or surface modification, is critical for ensuring sustained fire safety performance.

Environmental and health considerations: While MXene-based nanomaterials offer promising flame retardant properties, their environmental impact and potential health risks need to be thoroughly evaluated. Concerns regarding the toxicity, biodegradability, and ecological persistence of MXenes necessitate comprehensive risk assessments and environmentally conscious design considerations to ensure the sustainable and safe use of these materials.

Regulatory compliance and standards: Adhering to regulatory requirements and industry standards for flame retardant materials poses a challenge for the commercialization of MXene-based nanomaterials. Establishing standardized testing protocols and certification procedures to assess the flame-retardant performance, safety, and environmental impact of MXene-containing products is essential for gaining regulatory approval and market acceptance.

Addressing these challenges requires interdisciplinary collaboration among researchers, engineers, and industry stakeholders to overcome technical barriers, advance scientific understanding, and develop innovative solutions. By addressing these current challenges, MXene-based nanomaterials have the potential to revolutionize flame retardant technologies and contribute to safer, more sustainable material solutions for diverse applications.

8. Conclusion and future outlook

In conclusion, the recent advancements in MXene-based nanomaterials for flame retardant polymers and composites represent a significant milestone in the quest for innovative fire safety solutions. Through a comprehensive review of the literature, we have witnessed the remarkable progress made in harnessing the unique properties of MXenes to enhance the flame retardancy, mechanical strength, and thermal stability of polymer materials. The synthesis and functionalization of MXene nanosheets have enabled precise control over their chemical composition, surface properties, and dispersion within polymer matrices, leading to tailored flame retardant performance. The incorporation of MXenes has demonstrated promising results in suppressing flame propagation, reducing smoke generation, and enhancing char formation, thereby significantly improving the fire safety profile of polymers and composites across various applications. Furthermore, the multifunctionality of MXene-based flame retardant additives extends beyond fire suppression, with additional benefits such as conductivity, electromagnetic shielding, and mechanical reinforcement. This versatility opens up new avenues for developing advanced materials with enhanced functionalities and performance characteristics, catering to diverse industrial sectors including electronics, transportation, construction, and textiles.

Despite the substantial progress achieved thus far, several challenges and opportunities for future research remain. Firstly, further investigation is needed to elucidate the underlying mechanisms governing the flame retardant behavior of MXene-based nanomaterials, particularly in complex polymer systems and under real-world fire conditions. Additionally, optimizing the synthesis methods, scalability, and cost-effectiveness of MXene production will be crucial for facilitating widespread adoption in commercial applications. Moreover, exploring synergistic combinations of MXenes with other flame retardant agents, such as phosphorus-based compounds or carbonaceous materials, holds promise for achieving enhanced flame retardant performance and multifunctional properties. Furthermore, integrating MXene-based flame retardant additives into novel polymer architectures, such as nanocomposites, coatings, and foams, offers exciting opportunities for tailoring material properties and addressing specific application requirements.

In the realm of sustainability, the development of bio-derived MXenes and eco-friendly synthesis routes will be essential for meeting the growing demand for environmentally friendly flame retardant materials. Additionally, investigating the recyclability and end-of-life disposal of MXene-containing polymers will contribute to the advancement of circular economy principles and the reduction of environmental impact. In conclusion, the recent advancements in MXene-based nanomaterials for flame retardant polymers and composites hold immense promise for revolutionizing fire safety technologies and advancing the performance and sustainability of modern materials. By embracing interdisciplinary collaboration, rigorous scientific inquiry, and innovation-driven research, we can unlock the full potential of MXenes as transformative additives in the realm of flame retardant materials, paving the way towards safer, more resilient, and sustainable material solutions for the future.

CRediT authorship contribution statement

Yakubu Adekunle Alli: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Abayomi Bamisaye:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Onome Ejeromedoghene:** Writing – original draft, Validation, Methodology, Investigation, Data curation. **Olusegun Oluwaseun Jimoh:** Visualization, Validation, Software, Formal analysis, Data curation. **Samuel Oluwadadepo Oni:** Validation, Software, Funding acquisition, Data curation. **Gerald Chekwube Ezeamii:** Data curation, Formal analysis, Software, Visualization. **Chukwurimazu Ozoemezim:** Data curation, Formal analysis, Validation, Visualization. **Adeniyi Sunday Ogunlaja:** Formal analysis, Supervision, Writing – review & editing. **Suraya Abdul Rashid:** Formal analysis, Project administration, Validation, Writing – review & editing. **Baljinder K. Kandola:** Conceptualization, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing.

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Declaration of competing interest

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

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