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MINI REVIEW

Beyond the atomic layer: Cutting-edge coating technologies for graphene and MXenes

Nabanita Datta

Department of Chemistry, National Institute of Technology, Rourkela, Odisha, India

ABSTRACT

Graphene and MXenes are two-dimensional (2D) materials that have recently attracted a lot of interest as advanced coating materials because of their remarkable mechanical strength, chemical stability, and distinctive electrical characteristics. Enhancing performance in a variety of industrial and functional applications has become possible due to the incorporation of these materials into coatings. This mini-review gives a summary of current advancements in the creation and application of 2D material-based coatings, focusing on fabrication techniques such as chemical vapor deposition, layer-by-layer assembly, dip-coating, and spray-coating. As far as process simplicity, scalability, or customization of coating topologies, each of these methods has unique benefits that allow for coatings with improved structural and functional qualities. The key uses mentioned are anti-corrosion surfaces for better environmental protection, wear-resistant layers for mechanical durability, and conductive coatings for flexible electronics. When compared to traditional methods, 2D materials have shown notable gains in conductivity, hardness, and long-term stability in these domains. However, obstacles like weak interfacial adhesion, restricted large-scale production, and susceptibility to environmental degradation still prevent wider adoption. Promising approaches of getting over these restrictions are examined, including surface modification, hybrid material design, and eco-friendly processing. The review highlights the significance of scalable, sustainable, and multifunctional coating systems in its conclusion, which offers insights into potential future research avenues. It is projected that the incorporation of 2D materials into next-generation coatings will be crucial to the advancement of electrical, protective, and energy technologies, as well as to meeting the growing need for ecologically friendly solutions.

KEY WORDS

Graphene; MXene; Coating; 2D materials; Hybrid materials

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Introduction

Coatings are ubiquitous in modern technology and infrastructure because they function as the primary engineered interface between a material and its operating environment [1]. At the most fundamental level, coatings protect underlying substrates from chemical attack, mechanical wear, and environmental degradation. In industry, they extend service life, reduce maintenance cycles, and enable new functionalities (for example, electrical conductivity, anti-biofouling behaviour, or electromagnetic shielding) that bulk materials cannot provide on their own. As global demands for lighter, longer-lasting, and multifunctional systems increase across sectors such as aerospace, energy, electronics, marine, and biomedical devices, the design of high-performance coatings has become a strategic priority [2]. Contemporary challenges ranging from the need for corrosion protection in harsh maritime and industrial atmospheres to electromagnetic interference shielding in compact electronics require coatings that combine multiple, often competing, properties in thin, conformal layers [3].

Two-dimensional (2D) materials, notable among them graphene and the family of transition-metal carbides/nitrides known as MXenes, have emerged as particularly promising additives and coating components because they introduce a rare combination of properties at the nanoscale [4]. Graphene delivers exceptional mechanical strength, high intrinsic thermal and electrical conductivity, and outstanding impermeability to gases when organized into continuous films [5]. MXenes, by contrast, provide metallic conductivity coupled with hydrophilic surface terminations and very high specific surface areas, rendering them exceptionally versatile for interfacial engineering [6]. When formulated as coatings or as components within composite coatings, these materials can substantially enhance barrier performance, impart electrical pathways for conductive applications, and reduce friction or wear when properly oriented and dispersed [7].

Despite a rapidly growing number of reports, several important gaps persist in the literature. Much of the published work focuses narrowly on synthesis methods or highlights specific laboratory-scale demonstrations (for instance, a single manufacturing technique or an isolated application test), often without systematic comparison across deposition strategies, substrate types, and environmental exposures [8]. Reviews tend to treat graphene and MXenes separately or concentrate on electronic/optoelectronic device applications rather than on coating purposes, leaving a shortage of integrative assessments that relate fabrication choices to long-term coating performance, scalability, and industrial feasibility [9]. In particular, there is limited synthesis of (i) how different deposition approaches influence adhesion, defect density, and large-area uniformity; (ii) how oxidation, moisture uptake, or mechanical cycling affect long-term stability across real-world service conditions; and (iii) what trade-offs are introduced by strategies designed to improve environmental stability (for example, polymer encapsulation versus preserving conductivity) [10].

***Correspondence:** Ms. Nabanita Datta, Department of Chemistry, National Institute of Technology, Rourkela, Odisha, India, email: n20datta@gmail.com

This mini-review aims to provide a concise yet targeted synthesis of recent advances in graphene- and MXene-based coatings with an explicit focus on bridging the experimental lab demonstrations and practical deployment. The review compares commonly used fabrication techniques and evaluates how processing governs coating morphology and resulting functional properties. It then surveys the principal application areas where 2D coatings have demonstrated meaningful performance benefits, such as anticorrosion, wear resistance, electrical functionality, and electromagnetic interference shielding, highlighting representative results and pointing out limitations in experimental design and reporting. Finally, the review identifies key technical bottlenecks (scalability, adhesion, environmental stability, and cost) and proposes research directions such as standardized performance metrics, green processing routes, hybrid architectures, and coupled modelling with experiment workflows that can accelerate translation. By explicitly mapping fabrication, structure, and performance relationships and emphasizing gaps in stability testing and scale-up, this review provides a practical roadmap for researchers and engineers seeking to develop robust, multifunctional coatings based on 2D materials [11].

Fabrication Techniques of 2D Material Coatings

The performance of 2D material-based coatings is highly impacted by the fabrication techniques, which influence uniformity, thickness, adhesion, and functional properties [12]. Various techniques have been observed for the deposition of graphene, MXenes, and related 2D materials onto the substrates.

Dip coating

Dip-coating is a straightforward and popular technique that entails submerging the substrate in a mixture of 2D materials and then slowly pulling it out. This method works well for expansive coatings and provides consistent coverage. However, issues like poor adherence and aggregation require improvement by means of surface alteration or the application of binders [13].

Spray coating

Spray-coating offers quick and scalable deposition of 2D materials, making it appropriate for industrial applications. Through modification of the spray cycles, it offers versatility in managing thickness. This technique has proven very useful for decorating metals and polymers with conductive and corrosion-resistant materials [14].

Layer-by-layer assembly

Layer-by-layer assembly relies on the alternate adsorption of oppositely charged species, where the coating thickness and architecture may be precisely controlled. This approach works well with graphene oxide and MXenes because of their surface functional groups. When customized multilayer structures with high barrier qualities are required, Layer-by-Layer coatings are frequently utilized [15].

Chemical vapour deposition

CVD is a popular method for creating superior graphene coatings with outstanding mechanical and electrical qualities. Although CVD offers excellent regularity and crystallinity, its scalability for applications is limited by the high temperatures and complex equipment it requires [16].

To combine scalability with regulated performance, hybrid and cutting-edge techniques, including electrophoretic deposition, spin coating, and inkjet printing, are also being investigated. The fabrication technology is decided mainly based on targeted application, intended coating performance, and cost effectiveness.

Applications

The distinctive combination of barrier performance, high electrical conductivity, and tunable surface chemistry makes graphene- and MXene-based coatings attractive across a wide spectrum of application domains. Their two-dimensional morphology, consisting of atomically thin, high-aspect ratio sheets, provides an inherent advantage in forming compact films with minimal defect pathways [17]. This structural quality, when combined with their surface functionalisation and excellent mechanical robustness, underpins the versatility of these materials in coatings technology.

Anticorrosion coatings

In corrosion protection, graphene and MXenes function both as dense, impermeable barriers that slow the diffusion of aggressive species and as conductive components capable of modifying local electrochemical reactions at the metal–coating interface. The lamellar stacking of graphene creates a tortuous pathway that effectively restricts the ingress of chloride ions and water molecules. At the same time, MXenes introduce negatively charged surface terminations (–O, –OH, –F) that enhance dispersion in polymer matrices and improve coating adhesion. Strategies that incorporate 2D fillers into epoxy resins, polyurethane, or waterborne polymers have demonstrated markedly reduced corrosion rates in saline environments. Hybrid designs, such as MXene combined with sacrificial inhibitors (e.g., CeO_2 nanoparticles) or surface modifiers like polydopamine, provide synergistic effects by blocking ionic transport while simultaneously stabilizing the interface. These approaches are particularly important for protecting standard engineering alloys such as steel and aluminium, which are highly susceptible to localized corrosion.

Liu et al. had fabricated a MXene-CeO_2@polydopamine (PDA) hybrid filler in waterborne epoxy, which produces a coating with dramatically reduced corrosion rate in 3.5 wt% NaCl, showing strong synergistic active or passive protection due to the combination of MXene, inhibitor, and interfacial modifier [18]. Similarly, Li et al. had synthesised Ti_3C_2MXene@PANI composites to increase the anticorrosion rate of waterborne epoxy coating. He found that intercalating polyaniline (PANI) nanoparticles between MXene layers improved MXene dispersion and produced WEP coatings with enhanced adhesion, mechanical properties, and markedly improved corrosion protection compared to neat epoxy [19]. Furthermore, Zhu et al. had prepared polydopamine-functionalized Ti_3C_2-MXene hybrid reinforced waterborne epoxy nanocomposites, which also show enhanced anticorrosion properties. Core findings of his team were that PDA-functionalization of Ti_3C_2 improved MXene dispersion and interfacial bonding in waterborne epoxy and produced coatings with significantly enhanced corrosion resistance and mechanical robustness (adhesion, flexibility) [20].

Wear-resistant coatings

For tribological applications, graphene and MXenes exploit their atomically thin lamellar structures to generate a lubricating interface with low shear strength. This mechanism

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significantly reduces friction coefficients and surface damage during sliding contacts, especially in gears, bearings, and moving assemblies subjected to repetitive mechanical stress. When uniformly dispersed in matrices such as polymers, ceramics, or metallic binders, 2D fillers can act as reinforcement agents that enhance hardness, toughness, and load-bearing capacity. Additionally, controlled alignment of nanosheets within the host matrix improves stress transfer and wear resistance, yielding a synergistic balance between reduced friction and improved durability. These properties position 2D material–based coatings as attractive alternatives to traditional solid lubricants like MoS_2 or graphite, particularly under conditions where stability and longevity are critical.

Macknojia et al. had synthesised MXene/graphene oxide nanocomposites using spray coating. This produced a scalable solid-lubricant coating that showed reduced friction (to ~0.065 under specified test conditions) and greatly lowered wear volume on rough steel—tribo-film formation and lamellar sliding were identified as operative mechanisms [21]. In another research, Macknojia et al. had fabricated MXene/MoS_2 Heterostructures. These heterostructure coatings produced stable macroscale super lubricity via formation of low-shear tribo-layers and interfacial reorganization under sliding, demonstrating a route to very low friction in practical contacts [22].

Conductive and functional coatings

The outstanding electrical conductivity of graphene, coupled with the metallic-like conductivity of many MXenes, enables the fabrication of thin, conformal conductive layers for a variety of functional uses. In flexible electronics and wearable devices, such coatings can provide reliable conductive pathways while maintaining mechanical flexibility and low weight. Printed and spray-coated graphene-based films have already been integrated into sensors, microheaters, and transparent conductive electrodes. At the same time, MXene coatings are increasingly explored for electromagnetic interference (EMI) shielding due to their high electrical conductivity and tunable surface chemistry. Importantly, these coatings can be deposited at submicron thicknesses, making them ideal where weight savings, optical transparency, or flexibility are design priorities. However, sustaining long-term conductivity requires strategies to mitigate MXene oxidation and prevent mechanical delamination during repeated bending or stretching.

Song et al. had utilized electrochemically exfoliated graphene in their study to produce inkjet-printed electrodes and device layers in fully printed thin-film transistors, showing scalable printed device fabrication using 2D-material conductive inks [23]. Similarly, Zhang et al. had demonstrated high-performance additive-free graphene inks suitable for large-area printing and 3D printing of conductive components, progressing toward scalable, ink-based conductive coatings with good conductivity and processability [24]. In a similar context, Han et al. had prepared a composite by deposition of AgNW/MXene conductive middle layer on filter paper, which makes the composite thin and it showed very high electrical conductivity (~166 S cm^{-1}) and strong EMI shielding (≈30 dB), which is an example of MXene-based conductive coatings for EMI and functional devices [25].

Energy and EMI-shielding applications

Beyond structural and functional uses, graphene and MXene coatings play a critical role in emerging energy technologies. Their high surface area, layered architectures, and controllable electronic transport make them attractive as coating components in electrodes for supercapacitors, batteries, and hybrid energy storage systems. Stacked or hybridized films can deliver high EMI shielding effectiveness per unit thickness, addressing the demand for lightweight protection in aerospace, telecommunications, and portable electronics. In electrochemical energy storage, carefully engineered 2D coatings improve ion accessibility, conductivity, and cycling stability. For example, interlayer spacing control, hybridization with carbon scaffolds, or surface modification with heteroatoms has been shown to mitigate restacking, accelerate ion transport, and enhance long-term performance. These advances demonstrate how 2D material–based coatings can serve not only as protective barriers but also as active, multifunctional components in next-generation energy and electronic systems.

Rui et al. produced binder-free, flexible Ti_3C_2Tx MXene/graphene electrodes with high capacitance and good mechanical properties, demonstrating that MXene thin films/coatings can serve as practical electrode layers for supercapacitors [26]. Zhang et al. showed in their research that layered or graded MXene @AgNW films achieved extremely high specific EMI shielding effectiveness (very large SSE/t) at low areal density and enabled efficient electrothermal heating, providing a direct demonstration of 2D-material coatings engineered for high-performance, EMI shielding, and energy functionality [27]. Similarly, Duygun et al. had synthesized $Ti_3C_2T_x$/rGO/cellulose coatings deposited on textile substrates, which produce flexible electrodes with good areal capacitance suitable for wearable supercapacitors, showing how controlled deposition of 2D coatings yields functional energy devices [28].

Challenges and Opportunities

Although the intrinsic properties of graphene and MXenes are exceptional, several challenges limit their immediate industrial adoption as coatings. Achieving consistent, defect-free coverage over large areas remains difficult with many laboratory-scale deposition methods, and aggregation during processing can create weak points that reduce barrier and mechanical performance. Adhesion at the coating–substrate interface is another recurring issue; without suitable surface chemistry control or interfacial engineering, coatings are liable to delamination under mechanical or thermal cycling. Environmental stability represents a specific concern for MXenes, which are susceptible to oxidation, and for graphene derivatives that can suffer chemical degradation under aggressive conditions; protective strategies such as polymer encapsulation improve stability but may diminish baseline conductivity or other desirable properties [29].

Cost and supply constraints are also nontrivial: high-quality CVD graphene and well-characterized MXenes are not yet widely available at the scales required for many coatings applications, and manufacturing costs must fall for broad uptake in cost-sensitive sectors. Moreover, integrating 2D materials into existing industrial coating lines raises questions about process compatibility, health and safety, and standards for performance evaluation . Addressing these

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challenges is therefore a multidisciplinary task requiring parallel advances in scalable processing, surface functionalization, and rigorous life-cycle and reliability testing.

At the same time, the opportunities are significant. Hybrid and multifunctional coatings that combine 2D materials with polymers, nanoparticles, or other nanostructures can simultaneously address barrier, mechanical, and electrical requirements, leading to self-healing, sensor-integrated, or stimuli-responsive surfaces. Sustainable processing, through waterborne dispersions, green solvents, and bio-derived binders, offers a route to reduce the environmental footprint of coating manufacture while improving worker safety. Advanced fabrication techniques such as inkjet printing and electrophoretic deposition provide the means for patterning and large-area control, and computational modelling coupled with high-throughput experimentation can accelerate optimization by linking nanoscale structure to macroscopic properties [30].

Conclusion and Future Work

Graphene and MXenes represent a powerful toolkit for the design of next-generation coatings that can combine barrier protection, electrical functionality, and mechanical robustness in ultrathin layers. Research to date has demonstrated compelling laboratory-scale successes across anticorrosion, wear resistance, conductive coatings, EMI shielding, and energy-related functions. However, technical barriers, principally related to scalable, uniform deposition, interfacial adhesion, long-term environmental stability, and cost, persist and constrain industrial translation. Overcoming these barriers requires coordinated work on multiple fronts: developing low-cost, green processing methods that retain functional performance; implementing interfacial chemistries and architectures that provide durable adhesion without sacrificing conduction; establishing standardized test protocols that enable meaningful comparisons across studies; and expanding supply chains for high-quality 2D materials [31].

To realize the full potential of 2D-material coatings, the field must also embrace cross-disciplinary approaches that combine materials chemistry, surface science, process engineering, and modelling. Such convergence will not only improve fundamental understanding of structure–property relationships but also accelerate demonstration of real-world, long-duration deployments.

Future work should prioritize scalable manufacturing routes that are compatible with existing coating lines and that use environmentally benign solvents and binders. Efforts to create hybrid coatings that exploit complementary attributes of different 2D materials, polymers, and nanoparticles should be intensified, focusing on design principles that preserve multifunctionality. Standardized ageing and mechanical testing protocols are urgently needed so that performance claims can be reliably compared and validated. Finally, coupling computational screening and multiscale modelling with in-situ characterization and accelerated life testing will expedite the rational design of 2D-based coatings tailored for specific sectors such as aerospace, marine, flexible electronics, and energy storage. With these strategic directions, 2D-material coatings could move from laboratory curiosity to robust, widely adopted engineering solutions.

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