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REVIEW

Beyond Graphene: A Comprehensive Review of Emerging 2D Materials

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ABSTRACT

The discovery of graphene marked the beginning of a new era in material science, leading to the exploration of a wide array of two-dimensional (2D) materials with unique properties. While graphene's remarkable electrical, mechanical, and thermal properties have been well-studied, its lack of an intrinsic bandgap has limited its applications, especially in digital electronics. This has spurred extensive research into alternative 2D materials, including transition metal dichalcogenides (TMDs), hexagonal boron nitride (h-BN), black phosphorus (BP), MXenes, and other layered compounds. These materials offer diverse properties such as tunable bandgaps, high carrier mobilities, and anisotropic behavior, making them promising candidates for next-generation applications in electronics, optoelectronics, energy storage, catalysis, and sensing. In this review, we aim to present a unified and critical overview of the evolution, classification, and functional potential of emerging 2D materials beyond graphene, highlighting how their intrinsic structural and electronic features govern device performance across multiple domains. It discusses the synthesis techniques, structural characteristics, and unique electronic properties that differentiate these materials from graphene. Moreover, the review explores their integration into devices like field-effect transistors, solar cells, supercapacitors, and catalysis systems. Special emphasis is placed on correlating material properties with practical device outcomes and identifying current challenges related to large-scale synthesis, stability, and compatibility with existing technologies. Finally, the review concludes with a forward-looking perspective that outlines the key strategies—such as heterostructure engineering, doping control, and AI-assisted material discovery—necessary for overcoming present limitations and accelerating the transition of 2D materials from laboratory research to real-world applications. As research progresses, these materials are expected to drive significant advancements in electronics, energy, and environmental technologies.

KEYWORDS

Emerging 2D materials; Graphene alternatives; Transition metal dichalcogenides (TMDs); MXenes and black phosphorus; 2D material synthesis; Next-generation electronic applications.

INTRODUCTION

The advent of two-dimensional materials began with the isolation of graphene in 2004, a monolayer of carbon atoms tightly packed in a two-dimensional honeycomb lattice [**1**]. Graphene rapidly garnered attention due to its extraordinary mechanical strength, high thermal conductivity, and exceptional electrical mobility. Its quantum Hall effect, ambipolar electric field effect, and ballistic transport over submicron distances under ambient conditions opened up new horizons in fundamental physics and nanotechnology [**1–4**]. However, despite these remarkable features, graphene exhibits several inherent drawbacks that restrict its widespread technological application. The most significant limitation is its zero-bandgap electronic structure, which makes it behave as a semimetal rather than a semiconductor. This absence of an intrinsic bandgap prevents graphene-based transistors from achieving a high on/off current ratio, an essential requirement for digital logic circuits. Attempts to induce a bandgap through chemical doping, quantum confinement, or substrate interactions often lead to a substantial decrease in carrier mobility, thereby degrading device performance. Moreover, graphene's weak spin–orbit coupling limits its potential in spintronic applications, and its chemical inertness poses challenges for surface functionalization and catalytic processes. The lack of out-of-plane polarity also restricts its use in optoelectronic devices where light absorption and emission are critical. In addition, large-area synthesis of high-quality, defect-free graphene remains technologically challenging and cost-intensive. These demerits collectively inspired the exploration of other layered materials that could retain graphene's exceptional carrier mobility while offering tunable electronic and optical properties suitable for specific applications [**5**,**6**].

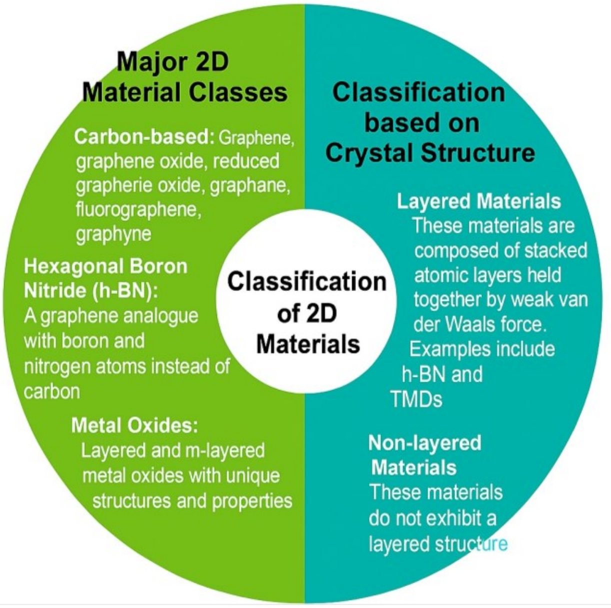


Fig. 1. Classification of 2D materials.

This limitation prompted researchers to investigate a broader class of 2D materials derived from layered van der Waals solids. These materials, held together by weak interlayer forces, can be mechanically exfoliated or chemically synthesized to produce atomically thin layers [**7**,**8**] Unlike graphene, many of these materials exhibit semiconducting, insulating, or metallic behavior, thus offering tunable properties for targeted applications. From semiconducting transition metal dichalcogenides to insulating hexagonal boron nitride, anisotropic black phosphorus, and highly conductive MXenes, the landscape of 2D materials has grown immensely diverse [**1**,**3**,**4**,**9–13**]. These materials are now being explored not only for electronics and optoelectronics but also for energy storage, catalysis, biosensing, and quantum technologies [**1**,**3**,**4**]. The classification of 2D materials is given in **Fig. 1** and atomic structures of representative 2D materials are shown in **Fig. 2.**

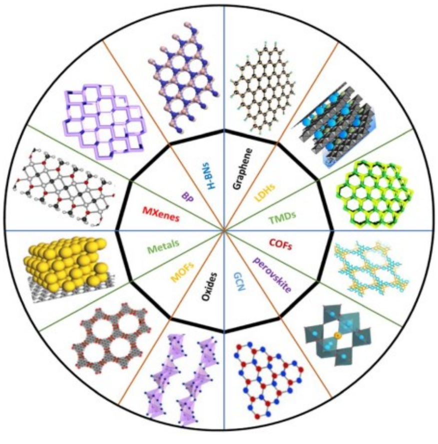


Fig. 2. Illustration of different kinds of typical 2D materials [4].

The industrial relevance of two-dimensional (2D) materials extends far beyond academic research, positioning them as critical enablers of technological advancement across multiple sectors. Over the past decade, the global market for 2D materials has witnessed remarkable expansion, reflecting growing recognition of their technological potential and industrial applicability. According to recent market analyses, the global 2D materials market was valued at approximately USD 1.2–1.5 billion in 2023 and is projected to grow at a compound annual growth rate (CAGR) of 18–22% through 2030, significantly outpacing the broader advanced materials market (5–7% CAGR). This trajectory is expected to drive the market to USD 6–8 billion by 2030, with projections exceeding USD 15 billion by 2035, fueled by advancements in scalable synthesis, material integration, and commercialization across multiple industries.

In the semiconductor sector, 2D materials are emerging as strategic solutions to overcome the physical limitations of traditional silicon-based electronics as device dimensions approach the sub-5 nm scale, where quantum tunneling and heat dissipation pose major challenges. The global semiconductor market—valued at over USD 550 billion annually—increasingly relies on novel materials to sustain Moore’s Law and enhance computational efficiency.

In the energy domain, 2D materials are catalyzing innovation in batteries, supercapacitors, and fuel cells, with several analyses projecting annual growth exceeding 15% through 2030 in energy-related applications. Global companies are investing heavily in 2D material-based energy storage and conversion technologies to meet the rising demand for electric vehicles, renewable energy integration, and grid-scale storage systems.

The catalysis industry recognizes 2D materials as transformative platforms for environmental remediation and sustainable chemistry, particularly in hydrogen evolution and CO_2 reduction reactions—both vital for achieving carbon neutrality. Similarly, the healthcare and biomedical sectors are rapidly integrating 2D materials into biosensors, diagnostic platforms, and targeted drug delivery systems, with the market for 2D material-based biomedical devices expected to expand significantly as point-of-care diagnostics gain prominence. In the environmental technology sector, 2D materials are driving innovation in water purification, air quality monitoring, and pollutant removal, addressing urgent global sustainability challenges.

The strategic importance of mastering 2D material synthesis, characterization, and integration cannot be overstated. Nations and corporations alike view this as a cornerstone of 21st-century technological competitiveness. Early commercialization efforts by major technology firms and startups highlight a clear industrial demand for scalable, cost-effective, and high-quality production methods. This convergence of scientific opportunity and industrial necessity underscores that understanding emerging 2D materials beyond graphene is not merely an academic pursuit, but a technological and economic imperative shaping the future of global innovation.

Various synthesis techniques have been developed and refined to produce high-quality 2D materials with controlled thickness, crystallinity, and lateral dimensions. Broadly, these methods fall into two categories: top-down and bottom-up approaches as shown in **Fig. 3**. Top-down methods, such as mechanical exfoliation, liquid-phase exfoliation, and electrochemical exfoliation, involve breaking down bulk layered crystals into atomically thin sheets [**14**].

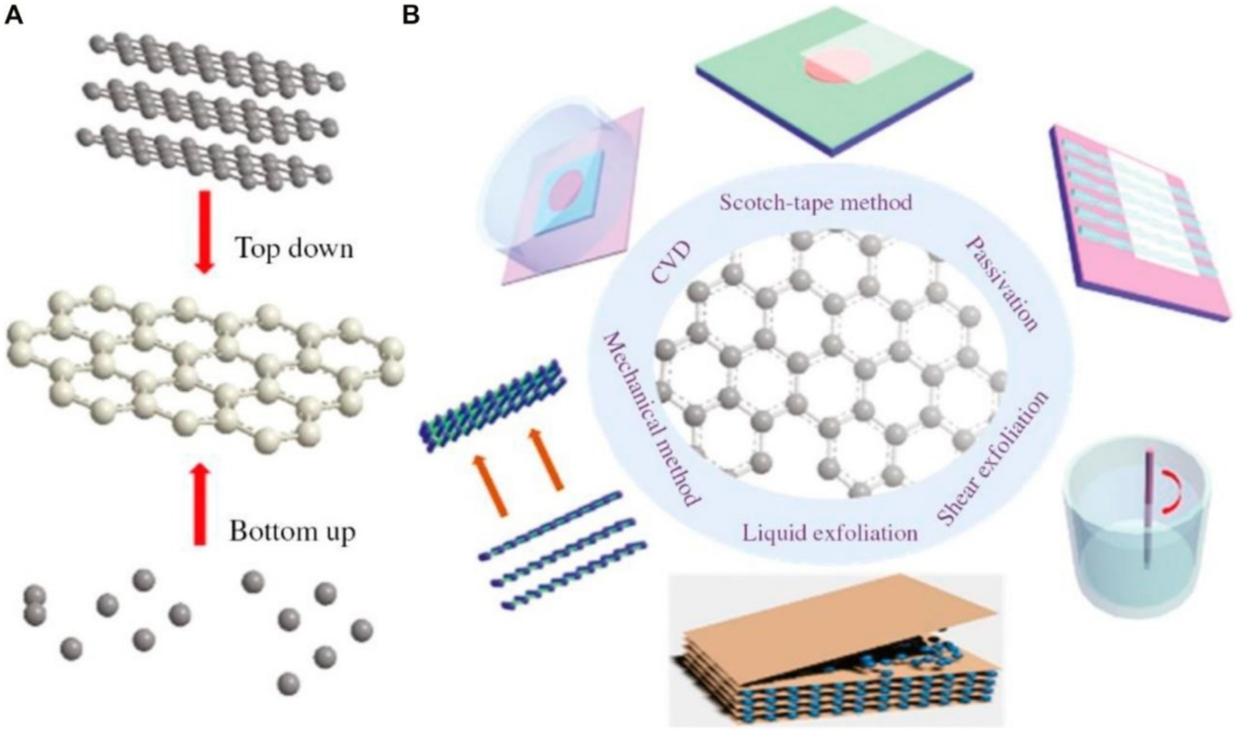


Fig. 3. Synthesis methods of 2-dimensional Nanomaterials. (A) There are two primary strategies: top-down exfoliation and bottom-up growth. (B) A series of different extensive fabrication techniques to synthesize 2D Nanomaterials [14].

Mechanical exfoliation, exemplified by the scotch-tape method, yields pristine monolayer flakes with minimal defects and record-breaking electrical properties, making it essential for fundamental physics studies and device performance validation. However, mechanical exfoliation suffers from severe scalability limitations: the process is labor-intensive, produces random flake distributions, and generates only milligram quantities of material unsuitable for practical applications. In contrast, liquid-phase exfoliation (LPE) employs solvent-mediated disruption of van der Waals bonds to produce dispersed 2D nanosheets at gram-to-kilogram scales with dramatically improved cost economics. While LPE sacrifices material quality compared to mechanical exfoliation-producing smaller lateral dimensions (micrometers versus millimeters), higher defect densities, and less uniform thickness distributions-this trade-off enables scalable production for applications tolerating moderate structural imperfections. Electro-chemical exfoliation represents an intermediate approach, combining controlled layer separation with potential for scalability, though reproducibility remains challenging. On the other hand, bottom-up techniques like chemical vapor deposition (CVD), molecular beam epitaxy (MBE), atomic layer deposition (ALD), and solution-based synthesis offer greater control over film uniformity, crystallinity, and substrate compatibility compared to top-down approaches. CVD has emerged as a dominant method for synthesizing large-area monolayers of transition metal dichalcogenides, hexagonal boron nitride, and other emerging 2D materials with tunable properties. The critical advantages of CVD include wafer-scale production capacity, monolayer-precision thickness control, and excellent crystallinity, positioning CVD-grown materials for high-performance device applications. However, CVD requires elevated temperatures (600–900°C), specialized vacuum or controlled atmospheric reactors, and typically crystalline substrates, substantially increasing capital equipment costs and manufacturing complexity. MBE enables atomically precise growth under ultra-high vacuum conditions, offering unparalleled control over layer stacking and composition—ideal for heterostructures and quantum systems —but at significantly higher capital and operational costs limiting practical commercialization. Additionally, novel methods such as salt-assisted synthesis, laser ablation, and microwave-assisted techniques are being explored to overcome challenges like low yield, poor reproducibility, and environmental concerns. The fundamental strategic choice between top-down and bottom-up approaches reflects an inescapable quality-scalability trade-off: applications demanding highest material quality justify CVD complexity and cost, while applications tolerating moderate defects benefit from scalable liquid-phase production. The continuous evolution and integration of these synthesis techniques are essential for advancing the field of 2D materials beyond graphene, enabling their scalable production and functionalization for practical device applications.

Specific target-oriented techniques for the mass production of 2D materials are described in **Fig. 4**. The roadmap presents a strategic framework that transcends simple method categorization to align synthesis approaches with application-specific material requirements. The central insight—represented by the horizontal axis spanning from high crystal quality to vast specific surface area—reveals that different applications impose fundamentally different demands on material properties, necessitating deliberately aligned synthesis strategy selection. On the left side of the roadmap, chemical vapor deposition and related bottom-up techniques yield high-quality crystalline films with exceptional uniformity, minimal defects, and large lateral dimensions. These materials are essential for applications demanding structural precision and excellent electrical properties: electronics applications benefit from controlled doping, minimized scattering, and reproducible transport characteristics; spintronics requires crystalline perfection to preserve quantum coherence and enable spin-dependent transport manipulation; wearable electronics demand sufficient quality for reliable mechanical flexibility through extended deformation cycles. As we progress rightward along the roadmap, techniques like liquid exfoliation offer a compromise between quality and scalability by delaminating bulk layered materials into nanosheets using solvents or surfactants. This intermediate region serves applications requiring acceptable material quality without demanding the highest purity levels: certain energy storage applications benefit from exfoliated graphene or TMD additives without requiring pristine single crystals. On the far right, wet chemical synthesis such as hydrothermal or solvothermal approaches produces nanostructured materials with high porosity and large surface areas, and engineered defect sites, but accepting lower overall crystallinity as the trade-off. The bottom section of the roadmap establishes explicit linkages between synthesis strategies and application domains, providing a strategic guide for research prioritization. High-quality 2D films are essential for electronics, spintronics, and wearable electronics due to their excellent electrical properties and structural control. Applications like batteries, oxygen reduction, and hydrogen evolution reactions benefit from materials with high surface areas that enhance catalytic and electrochemical performance. Meanwhile, opto-electronics and solar cells require a balance of structural order and light-matter interaction efficiency. Corrosion protection and sensor technologies utilize the high reactivity and surface interaction potential of exfoliated or chemically synthesized 2D materials. Overall, the roadmap underscores a critical strategic principle: no single synthesis approach optimizes all applications; rather, a diversified synthesis portfolio, each pathway optimized for specific technological needs, represents the realistic future of 2D materials manufacturing. It serves as a comprehensive guide for researchers to align material properties with technological needs across diverse fields [**15**].

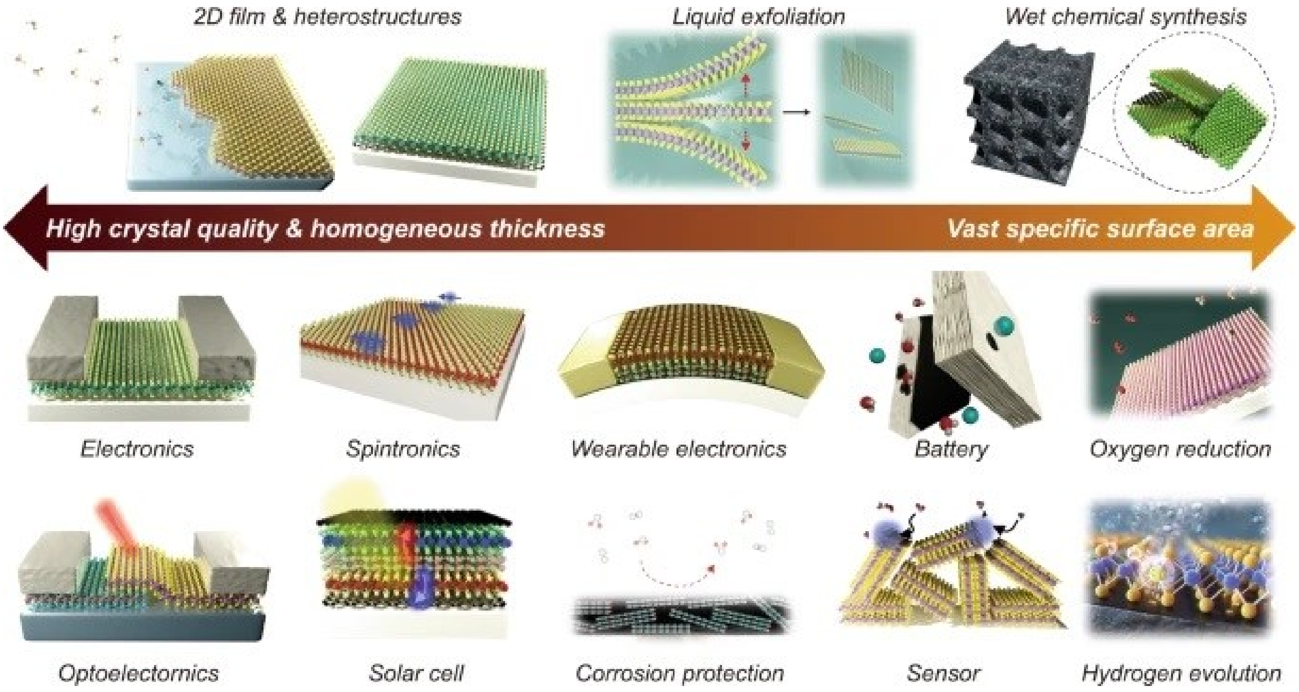


Fig. 4. Specific target-oriented techniques for the mass production of 2D materials [15].

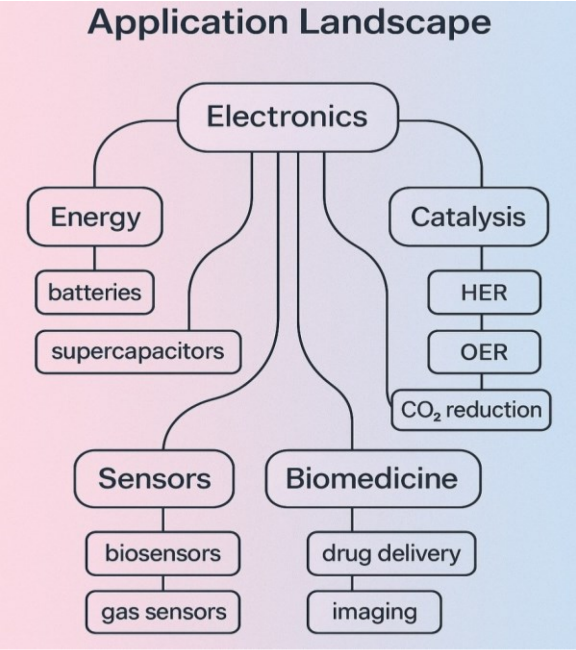


Fig. 5. Application landscape of 2D materials.

The unique physicochemical properties of emerging two-dimensional materials beyond graphene have opened up a broad spectrum of applications across multiple technological domains as shown in **Fig. 5**. These materials, including transition metal dichalcogenides, black phosphorus, MXenes, and hexagonal boron nitride, exhibit tunable bandgaps, high surface-to-volume ratios, mechanical flexibility, and exceptional electronic and optical characteristics.

Such features make them highly suitable for next-generation nanoelectronics, where they serve as channel materials in FETs with enhanced performance and reduced short-channel effects. In optoelectronics, their strong light–matter interactions support applications in photodetectors, light-emitting devices, and solar cells. Furthermore, their layered structure and high chemical reactivity have enabled significant advancements in energy storage and conversion systems, such as batteries, supercapacitors, and electrocatalysts for hydrogen evolution and CO_2 reduction. Biomedical applications, including biosensing, drug delivery, and photothermal therapy, also benefit from the biocompatibility and tunable surface chemistry of certain 2D materials. As research progresses, the integration of these materials into multifunctional devices and heterostructures continues to expand their applicability, demonstrating the immense potential of 2D materials beyond graphene in shaping the future of advanced technologies.

Furthermore, the intrinsic anisotropy, tunable band structures, and diverse surface chemistries of these materials offer a unique platform for engineering novel quantum and topological states of matter. The advent of van der Waals heterostructures created by stacking different 2D materials layer by layer without the constraint of lattice matching has unlocked new degrees of freedom for designing multifunctional devices. These artificial structures enable precise control over interlayer interactions and band alignment, paving the way for high-performance transistors, neuromorphic circuits, and quantum information systems. As such, the study of 2D materials has become a cornerstone of next-generation materials science, blending physics, chemistry, and engineering in unprecedented ways [**1,16-21**].

Table 1. Comparative Overview of Graphene and Emerging 2D Materials

Material	Composition / Type	Bandgap (eV)	Key Properties	Common Synthesis Methods	Typical Applications
Graphene	Carbon (monolayer)	0 (semi-metal)	High conductivity, mechanical strength, high mobility ($\sim 10^6$ $cm^2/V\cdot s$)	Mechanical exfoliation, CVD, epitaxial growth	High-speed electronics, sensors, composites, energy storage
MoS_2	Transition metal dichalcogenide (TMD)	1.2–1.9 (indirect-direct)	Semiconducting, good ON/OFF ratio, photoluminescence	CVD, mechanical exfoliation	Transistors, photodetectors, flexible electronics
WS_2	TMD	1.3–2.1	High optical response, spin–orbit coupling	CVD, liquid-phase exfoliation	Optoelectronics, solar cells
Black Phosphorus (Phosphorene)	Elemental	0.3–2.0 (thickness-dependent)	High carrier mobility, anisotropic transport, tunable bandgap	Mechanical exfoliation, plasma thinning	Infrared photonics, FETs, gas sensors
h-BN	Boron Nitride	~5.9 (insulator)	Excellent dielectric, thermal and chemical stability	CVD, exfoliation	Gate dielectrics, insulators, UV devices
MXenes (e.g., $Ti_3C_2T_x$)	Transition metal carbides/nitrides	Metallic / semi-conducting (depending on surface groups)	High conductivity, tunable surface chemistry	Etching of MAX phases, solution exfoliation	Energy storage, EMI shielding, sensors
Silicene	Silicon analogue of graphene	~1.1 (theoretical)	Compatibility with silicon tech, flexible	Epitaxial growth on Ag(111), UHV	Nanoelectronics, spintronics
Germanene	Germanium-based	~0.7–1.0	Dirac fermion behavior, high mobility	Molecular beam epitaxy (MBE)	Quantum computing, field-effect devices
Antimonene	Elemental Sb	~1.2–1.7	Chemically stable, semiconducting	Liquid exfoliation, CVD	Thermoelectrics, gas sensing
Tellurene	Elemental Te (helical chains)	~0.35–1.5	High carrier mobility, anisotropic	Solution growth, vapor phase	Field-effect transistors, IR detectors
$g\text{-}C_3N_4$	Graphitic carbon nitride	~2.7	Metal-free semiconductor, photocatalytic activity	Thermal polycondensation	Water splitting, photocatalysis, environmental remediation

Comparative overviews of Graphene and emerging 2D materials are listed in **Table 1**. This review aims to provide a comprehensive overview of emerging 2D materials beyond graphene, highlighting their unique electronic, optical, and mechanical properties. It explores their potential applications in next-generation devices, and the challenges they face. By comparing these materials with graphene, the review seeks to inform researchers about promising alternatives for overcoming graphene's limitations, particularly in semiconductor and optoelectronic technologies. Although numerous reviews have been published on 2D materials, most of them focus primarily on specific subclasses—such as transition metal dichalcogenides, MXenes, or black phosphorus—or discuss individual aspects like synthesis or electronic applications. In contrast, the present review offers an integrated and comparative perspective that bridges structural classification, synthesis strategies, and application-oriented functionality of a wide spectrum of 2D materials beyond graphene. It systematically correlates the intrinsic physical and chemical properties of these materials with their device-level performance in electronics, optoelectronics, catalysis, and energy storage systems. Furthermore, the article highlights recent advancements in large-scale synthesis, heterostructure engineering, and AI-assisted material design, providing a roadmap for future research and industrial translation. By combining both fundamental understanding and practical outlook, this work aims to serve as a comprehensive reference that unifies the diverse developments in the field and identifies emerging trends that distinguish next-generation 2D materials from graphene and earlier counterparts.

TWO DIMENSIONAL MATERIALS BEYOND GRAPHENE

Transition Metal Dichalcogenides (TMDs)

Transition metal dichalcogenides represent one of the most widely studied families of 2D materials beyond graphene. These compounds follow the general formula MX_2, where M is a transition metal such as molybdenum (Mo), tungsten (W), or titanium (Ti), and X is a chalcogen element like sulfur (S), selenium (Se), or tellurium (Te). Prominent members of this group include MoS_2, WS_2, $MoSe_2$, and WSe_2. Unlike graphene, which lacks an intrinsic bandgap, many monolayer TMDs possess direct bandgaps in the range of 1–2 eV, making them particularly attractive for use in next-generation electronic and optoelectronic devices such as field-effect transistors (FETs), photodetectors, and light-emitting diodes [**22–28**]. **Fig. 6** presents a comprehensive view of structural engineering and electronic properties in transition metal dichalcogenides (TMDs). In **Fig. 6(a)**, six distinct modification strategies for tailoring TMD nanosheets are depicted. These include vacancy-containing, heteroatom-doped, alloyed, and Janus TMD nanosheets, as well as TMD heterostructures (both vertical and lateral), and crystal-phase-based structures such as the 2H and 1T phases. Each approach introduces variations in atomic composition or stacking, thereby altering the physical, chemical, or electronic properties of the TMD materials. These engineered configurations expand the tunability of TMDs for diverse applications ranging from electronics to catalysis [**29**]. **Fig. 6(b)** shows the evolution of the electronic band structure of a TMD as it transitions from bulk to monolayer. Notably, the bandgap changes from indirect in bulk to direct in the monolayer, with the conduction band minimum and valence band maximum both aligning at the K-point. This direct bandgap in the monolayer form is crucial for optoelectronic applications [**30**]. **Fig. 6(c)** visualizes the spin–valley coupling in monolayer TMDs, where distinct valleys (K and K') possess spin-polarized states due to broken inversion symmetry and strong spin–orbit coupling. Together, the three panels highlight how structural modifications and dimensional scaling of TMDs can drastically influence their electronic and optical behavior, enhancing their utility in next-generation technologies [**31**].

One of the defining characteristics of TMDs is their layer-dependent electronic structure. For instance, MoS_2 exhibits an indirect-to-direct bandgap transition as the thickness is reduced to a single monolayer. This property arises from quantum confinement and the changing interlayer interactions and significantly enhances their light-matter interaction in the monolayer form. Additionally, TMDs can exhibit strong spin-orbit coupling and valley polarization effects, which open the door to valleytronics and spintronics applications. The crystal structure of TMDs consists of a hexagonal arrangement where a layer of transition metal atoms is sandwiched between two layers of chalcogen atoms. These layers are held together by weak van der Waals forces, allowing for mechanical exfoliation similar to that used in graphene [**22–27,32–34,34,35**]. Beyond mechanical exfoliation, scalable synthesis methods have been developed, including chemical vapor deposition, physical vapor deposition, and liquid-phase exfoliation. CVD, in particular, enables the growth of large-area, high-quality monolayers on various substrates, which is crucial for practical device integration. In terms of applications, TMD-based FETs have demonstrated promising performance metrics, including high on/off current ratios and substantial current densities. Their sensitivity to surface adsorbates also makes them suitable for chemical and biological sensing. Moreover, heterostructures combining different TMDs or stacking TMDs with other 2D materials like h-BN or graphene have been fabricated to create novel device architectures with tailored properties [**36–42**].

From a materials science perspective, the tunability of TMDs through strain engineering, doping, and defect introduction adds another layer of functionality. For example, applying uniaxial or biaxial strain can modulate the bandgap and optical absorption characteristics. Doping can enhance conductivity or introduce magnetic properties, while defect engineering can tailor reactivity for catalytic applications, such as hydrogen evolution reactions (HER). Overall, TMDs are versatile, multifunctional materials that offer a rich platform for fundamental studies and technological innovations. Their combination of semiconducting properties, structural flexibility, and compatibility with other 2D materials ensures that they will remain at the forefront of 2D materials research in the coming years [**40–44**].

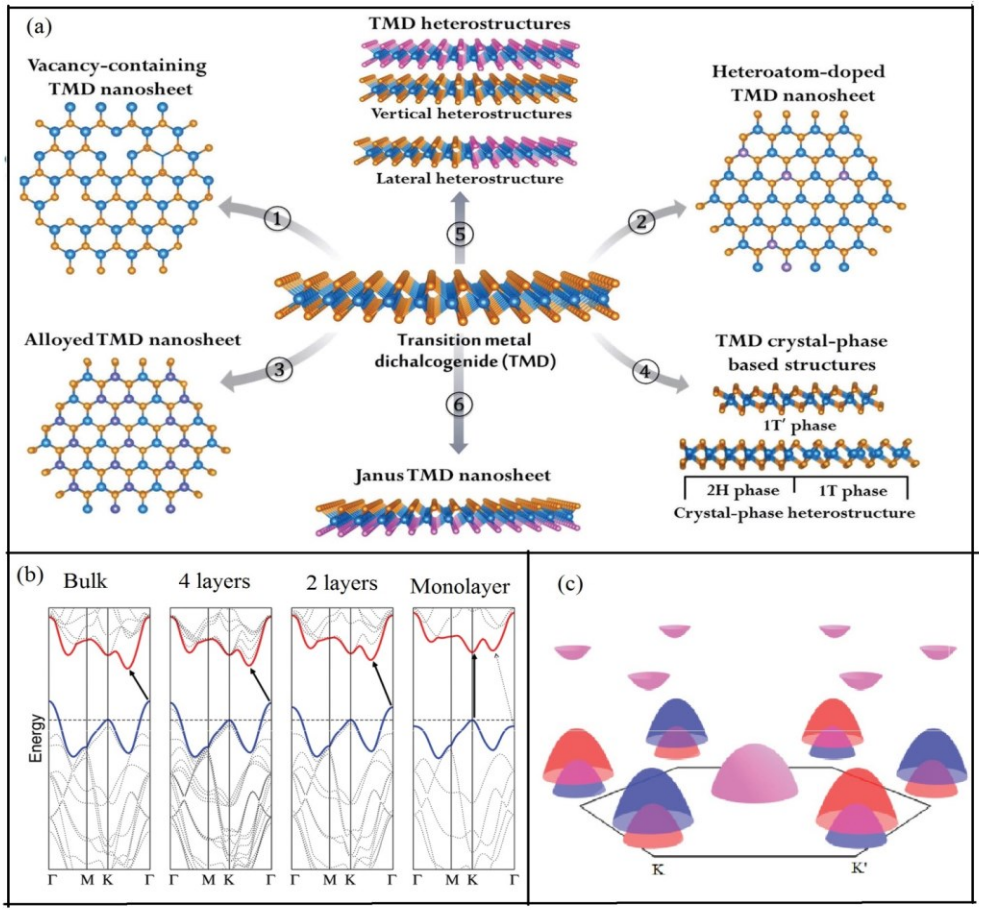


Fig. 6. (a) Schematic illustration of the recently emerged novel-structured TMD nanosheets [29]. (b) Evolution of the band structure of 2H-MoS_2 calculated for samples of decreasing thickness [30] and (c) Schematic representation of the band structure of monolayer 2H-MoS_2, showing the spin splitting of the bands at the K and K´ points on the corners of the Brillouin zone. Red and blue colours indicate up and down spin polarization [31].

Hexagonal Boron Nitride (h-BN)

Hexagonal boron nitride, colloquially termed "white graphene," is a structurally analogous but electronically distinct 2D material compared to graphene. Composed of alternating boron and nitrogen atoms arranged in a hexagonal lattice, h-BN is a wide-bandgap insulator with a bandgap of approximately 5.9 eV. This substantial bandgap, along with exceptional chemical inertness and thermal stability (withstanding temperatures above 1000°C), makes h-BN particularly well-suited for use as an insulating dielectric layer in 2D material-based electronics. One of the hallmark properties of h-BN is its atomically smooth surface, which lacks dangling bonds and surface states. This makes it an ideal substrate for graphene and other 2D materials, preserving their high mobility by minimizing charge impurity scattering and substrate-induced perturbations. Devices fabricated on h-BN substrates have demonstrated significantly improved carrier mobility and reduced charge inhomogeneity compared to those built on conventional silicon dioxide (SiO_2) substrates. Furthermore, h-BN exhibits high mechanical strength, excellent thermal conductivity (~600 W/m·K in-plane), and chemical stability, which support its role in next-generation nanoelectronic and nanophotonic systems.[3,45–53] In addition to its use as a substrate, h-BN is widely utilized as an encapsulating layer in van der Waals heterostructures. These heterostructures created by stacking different 2D materials in a controlled sequence leverage the insulating properties of h-BN to electrically isolate functional layers while maintaining structural integrity and minimizing interlayer contamination. The atomically flat nature of h-BN facilitates high-quality interfaces, which are critical for quantum transport studies and the development of tunneling devices such as vertical FETs and tunneling FETs.

Fig. 7 illustrates the atomic structure and versatile engineering strategies for hexagonal boron nitride (h-BN). **Fig. 7(a)** shows the crystal structure of h-BN, composed of alternating boron (B) and nitrogen (N) atoms in a hexagonal lattice. The intralayer B–N bond length is 1.45 Å, while the interlayer spacing is 3.33 Å, indicating strong in-plane covalent bonding and weak interlayer van der Waals forces. **Fig. 7(b)** depicts the edge configurations and atomic arrangement of h-BN nanosheets, highlighting the zigzag and armchair terminations. These edge types influence the electronic and magnetic properties of nanostructures and are crucial in defining their reactivity and potential for device integration. **Fig. 7(c)** demonstrates the structural versatility of h-BN through various engineered nanostructures. These include nanotubes, nanoscrolls, and nanoribbons, each possessing unique mechanical and electronic characteristics.

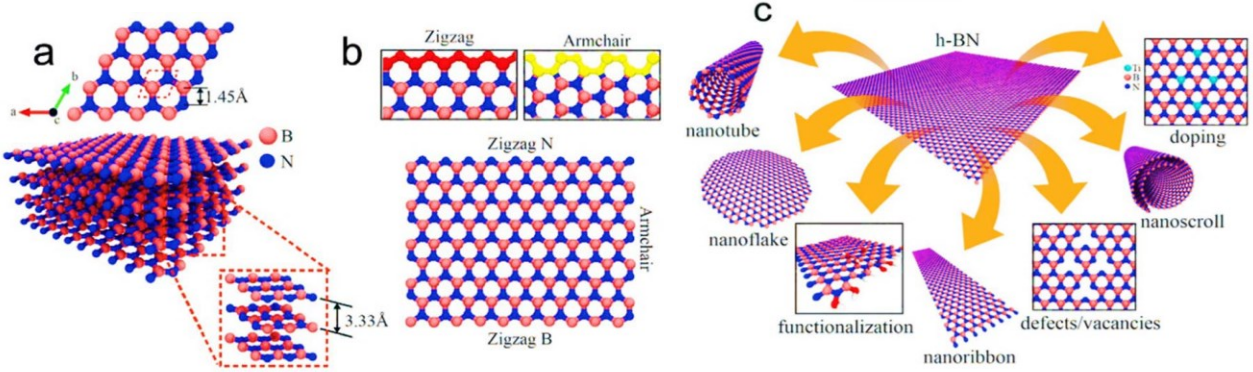


Fig. 7. a) Geometrical structure of h-BN; the unit cell is represented in red dash lines. b) Displaying the probable atomic distribution of B and N atoms in different orientations; c) Illustrations showing possible configurations that can be derived using h-BN [54].

Additionally, nanoflakes, doping, and defect engineering (such as vacancies) are presented as methods to tune the chemical and physical properties of h-BN. Functionalization further expands its application range by enabling surface modification for tailored interactions. Together, these approaches enable h-BN to serve in a wide array of applications, including electronics, catalysis, and sensing. The figure emphasizes the adaptability of h-BN and its potential in nanoscale material science through structural, chemical, and morphological manipulation [**54**].

Beyond its passive dielectric applications, recent studies have explored the potential of h-BN in active roles. For example, under certain conditions, defects in h-BN can exhibit single-photon emission, making it a candidate for applications in quantum optics and photonic quantum computing. Moreover, h-BN's high thermal stability and ability to form atomically thin layers make it a valuable component in thermal management systems for electronic devices. Synthesis techniques for h-BN include mechanical exfoliation, chemical vapor deposition, and physical vapor deposition. Among these, CVD has emerged as the most promising for large-area, high-quality h-BN film growth compatible with industrial fabrication processes. However, challenges remain in achieving uniform monolayer deposition and precise control over crystal orientation [**3,45–49,55–58**]. Overall, h-BN serves as an essential material in the 2D material toolkit—not only as a high-quality insulating substrate and protective layer but also as a potential platform for emerging applications in quantum technologies. Its unique combination of electrical, mechanical, and thermal properties continues to drive research into its integration with other 2D materials for multifunctional, next-generation devices.

Black Phosphorus (BP)

Black phosphorus, also known in its monolayer form as phosphorene, is a layered allotrope of phosphorus that has attracted considerable attention as an emerging 2D material. Structurally, BP consists of puckered layers held together by van der Waals forces, with each layer exhibiting an anisotropic structure due to its ridged lattice. This anisotropy imparts unique direction-dependent physical properties, distinguishing BP from isotropic 2D materials like graphene. One of the key features of BP is its tunable direct bandgap, which ranges from approximately 0.3 eV in the bulk to around 2.0 eV in the monolayer form. This bandgap tunability, achievable through both thickness modulation and strain engineering, positions BP as a promising material for broadband optoelectronic applications, spanning from infrared to visible light detection and emission. Additionally, BP exhibits high intrinsic carrier mobility, reaching values over 1,000 $cm^2/V \cdot s$ at room temperature, and significantly higher at low temperatures. These electrical characteristics make BP an ideal candidate for FETs, photodetectors, and other high-performance electronic components.

Another salient aspect of BP is its strong in-plane anisotropy, which affects its thermal, electronic, and optical behavior. For example, the effective masses of electrons and holes, as well as mobility, differ significantly along the armchair and zigzag directions of the lattice. This anisotropy can be exploited in designing polarization-sensitive photodetectors and directionally sensitive transport devices. Furthermore, BP demonstrates excellent on/off current ratios in FETs, often exceeding 10^5, a performance metric not easily achievable with graphene.

Despite its attractive properties, BP suffers from a major drawback: environmental instability. Exposure to oxygen, light, and especially moisture leads to rapid oxidation and degradation, forming phosphorus oxides that deteriorate its electronic performance. This sensitivity necessitates encapsulation strategies for practical device applications. Several methods have been developed, including encapsulation with materials such as h-BN, Al_2O_3, and polymeric films. More recently, advances in in situ passivation during synthesis and the use of non-aqueous processing environments have further improved BP's ambient stability [**65–72**].

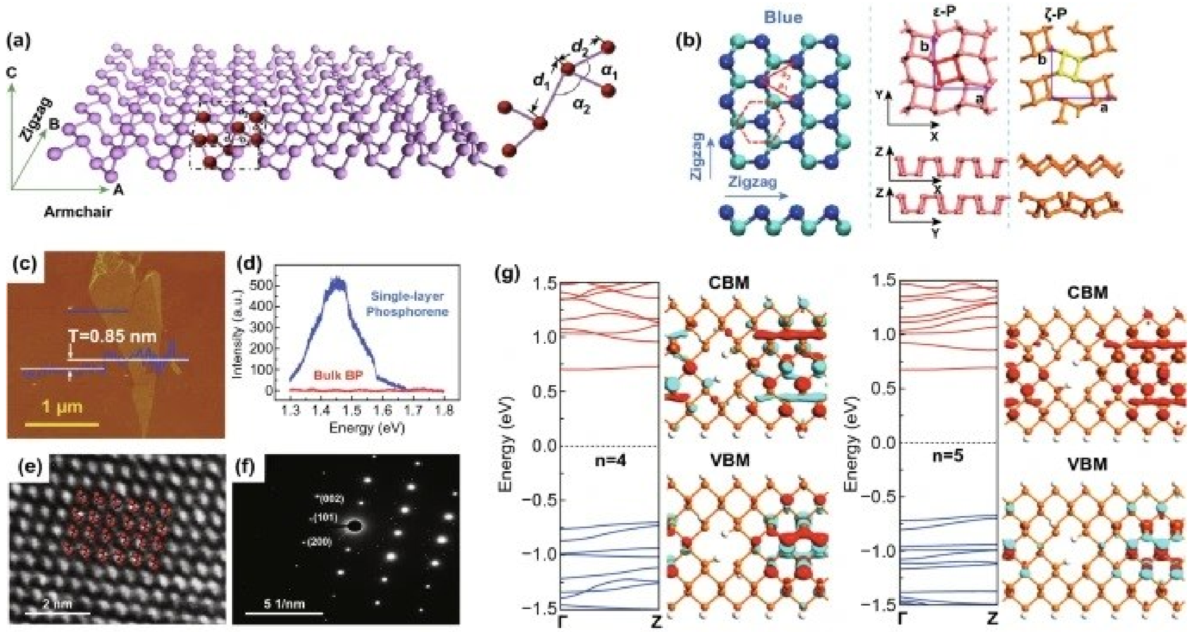


Fig. 8. Structural and physical characterization of black phosphorus (BP) and phosphorene nanoribbons [59]. (a) Crystal structure of monolayer black phosphorus, highlighting the zigzag and armchair directions (green axes). The dashed-dotted lines indicate the unit cell [60]. (b) Predicted structures of three polymorphs of phosphorene [61] (c) Atomic force microscopy (AFM) image of monolayer BP. (d) Raman spectra comparing monolayer and bulk BP [62]. (e, f) Selected area electron diffraction (SAED) patterns of few-layer 2D BP [63]. (g) Schematic models of phosphorene nanoribbons: *n* denotes the neck width, and *W* the overall nanoribbon width. The top two models depict zigzag-edged nanoribbons with nanoholes at the center and near the edge, while the bottom model shows an armchair-edged nanoribbon. The calculated electronic band structures for zigzag and armchair nanoribbons are shown above and below, respectively [64].

Fig. 8 provides a detailed overview of the structural, optical, and electronic properties of BP and its derivatives. **Fig. 8(a)** displays the atomic structure of BP, highlighting its puckered orthorhombic lattice and anisotropic armchair and zigzag directions. The right inset shows atomic bond lengths and angles, reflecting the unique geometry responsible for BP's directional-dependent properties. **Fig. 8(b)** contrasts BP with blue phosphorus, showing the differences in top view and side view atomic arrangements. While BP adopts a puckered structure, blue phosphorus features a buckled honeycomb lattice, significantly altering its electronic and mechanical characteristics. **Fig. 8(c)** shows an AFM image of a single-layer BP sheet with a thickness of approximately 0.85 nm, confirming monolayer formation. **Fig. 8(d)** presents photoluminescence spectra comparing bulk BP with single-layer phosphorene, revealing a significant bandgap increase from ~0.3 eV (bulk) to ~1.73 eV (monolayer), indicating strong quantum confinement. **Fig. 8(e)** shows a high-resolution TEM image, while **Fig. 8(f)** displays selected area electron diffraction (SAED), validating the crystalline nature of BP. Finally, **Fig. 8(g)** illustrates the evolution of electronic band structures and wavefunction distributions (conduction band minimum - CBM, and valence band maximum - VBM) with layer number (n=4 and n=5), showing band dispersion and orbital contributions. Altogether, the figure demonstrates the tunable properties of BP, critical for optoelectronic applications [**59**].

The synthesis of BP and its exfoliation into monolayers or few-layer flakes can be achieved through mechanical exfoliation, liquid-phase exfoliation, or more advanced chemical vapor transport techniques. While mechanical exfoliation yields high-quality flakes suitable for fundamental research, scalable synthesis remains a bottleneck for commercial deployment. Nevertheless, recent progress in bottom-up growth approaches, such as chemical vapor deposition, is paving the way for large-area BP film production. In addition to electronics and optoelectronics, BP is being explored for applications in flexible electronics, thermoelectric devices, gas sensing, and biomedical imaging. Its biocompatibility and photothermal properties have made it a candidate for photothermal therapy and bio-imaging in the near-infrared region. In summary, black phosphorus offers a rare combination of a tunable direct bandgap, high mobility, and in-plane anisotropy, making it an exceptional platform for next-generation electronic and optoelectronic systems. Continued research focused on improving its environmental stability and scalable synthesis will be crucial for realizing its full technological potential [**65,66**].

MXenes

MXenes are an emerging class of 2D transition metal carbides, nitrides, or carbonitrides with the general chemical formula $M_{n+1}X_nT_x$, where M represents an early transition metal, X is carbon and/or nitrogen, and T_x denotes surface terminations such as -OH, -O, and -F introduced during synthesis. Discovered in 2011, MXenes are typically derived from layered MAX phases ternary carbides or nitrides—by selectively etching out the A layer (usually a group 13 or 14 element like aluminum) using fluoride-containing acidic solutions such as HF or in-situ generated etchants. The resulting MXenes possess a layered structure with metallic conductivity and hydrophilic surfaces, allowing for easy dispersion in aqueous solutions. This combination of electrical conductivity and surface functionalization makes MXenes highly attractive for a broad range of applications [**73,74**]. In energy storage, MXenes exhibit excellent capacitance, fast charge/discharge rates, and good cyclic stability, making them prime candidates for supercapacitors and batteries. Their 2D morphology and tunable surface chemistry enable high ion intercalation capacity, while the mechanical flexibility supports flexible and wearable energy storage devices [**75–80**].

Fig. 9 illustrates the diverse structural configurations of MXenes, a family of two-dimensional transition metal carbides, nitrides, or carbonitrides. The top row shows standard MXene compositions in the form of $M_{n+1}X_nT_x$ (where M is a transition metal, X is carbon or nitrogen, and T_x represents surface terminations like –O, –OH, or –F), ranging from M_2XT_x to $M_5X_4T_x$. These variations represent an increasing number of atomic layers, influencing mechanical, electrical, and chemical properties. The second row introduces out-of-plane ordered double transition metal MXenes (e.g., $M'_2M''X_2T_x$), which exhibit layered ordering of two different metals, and in-plane ordered double transition metals, where metals are arranged laterally within the same layer (e.g., $(M'_{2/3}M''_{1/3})_2XT_x$). Another variation shown is the in-plane ordered vacancy MXene ($M'_{4/3}X_n$), where certain metal sites are vacant, further tuning electronic and catalytic behavior. Subsequent rows explore MXenes with solid solutions on either the M-site or the X-site. These allow fine-tuning of material properties by incorporating different atomic species (M′, M″, M‴, etc.) or varying carbon and nitrogen ratios in X-sites (e.g., $M_2(C_{1-x}N_x)T_x$). The figure provides a comprehensive landscape of structural tunability, crucial for tailoring MXenes for applications in energy storage, catalysis, and electronic devices. The included color legend clarifies the assignment of different transition metal oxidation states and surface terminations [**81**].

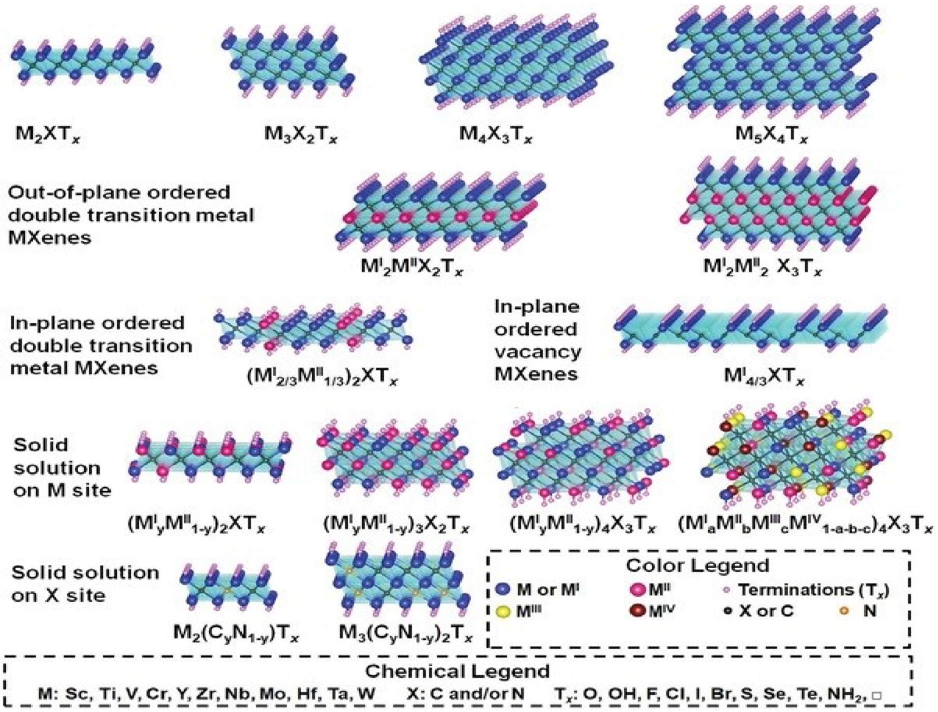


Fig. 9. Representative structures and compositions of typical MXenes. MXenes are generally represented by the formula $M_{n+1}X_nT_x$, where M denotes an early transition metal, X is carbon and/or nitrogen, and T_x refers to surface terminations such as –OH, –O, or –F. The integer n ranges from 1 to 4. The M sites can be occupied by one or multiple transition metals, resulting in solid solutions or structurally ordered phases. Ordered double transition metal MXenes can form as: In-plane ordered structures (i-MXenes), e.g., $(Mo_{2/3}Y_{1/3})_2CT_x$, In-plane vacancy-ordered structures, e.g., $Mo_{2/3}CT_x$, and Out-of-plane ordered structures (o-MXenes), where one or more layers of a secondary metal (MII) are sandwiched between layers of a primary metal (MI), e.g., $Cr_2TiC_2T_x$ or $Mo_2Ti_2C_3T_x$ [81].

MXenes also show significant promise in electromagnetic interference (EMI) shielding due to their high conductivity and layered architecture, which facilitates the absorption and reflection of electromagnetic waves. In addition, their ability to interact with various chemical species through surface functional groups makes them highly effective for chemical and biosensing applications. Their conductive nature enhances signal transduction in sensors, enabling sensitive and rapid detection of gases, ions, and biomolecules. The physical and chemical properties of MXenes can be tuned by varying the transition metal and the type of surface terminations, offering a customizable platform for targeted functionalities. For instance, $Ti_3C_2T_x$, one of the most widely studied MXenes, exhibits outstanding performance in electrochemical applications and has been incorporated into hybrid materials to further enhance conductivity and mechanical strength.[75,82–86]

Synthesis methods are evolving to reduce the use of hazardous chemicals and enable scalable production. New etching techniques, such as electrochemical and molten salt-based methods, are being explored to achieve more environmentally friendly and controllable MXene synthesis. However, challenges remain in controlling the thickness, defect density, and surface chemistry of MXenes for consistent performance across applications. In summary, MXenes represent a highly versatile and rapidly expanding family of 2D materials. Their exceptional electrical conductivity, surface functionality, and chemical versatility position them at the forefront of research in energy storage, sensing, catalysis, and EMI shielding. Ongoing research efforts aim to enhance synthesis scalability, environmental stability, and integration with other materials, thereby unlocking the full potential of MXenes for next-generation technological applications [**87–98**].

Other Emerging 2D Materials

Emerging 2D materials beyond graphene continue to attract significant research interest due to their unique properties and wide-ranging applications. One notable class includes 2D transition metal oxides (TMOs) such as MoO_3 and V_2O_5, which are known for their fascinating electrical, optical, and catalytic properties. These materials often exhibit high ionic conductance, making them suitable for energy storage and conversion applications, such as supercapacitors and lithium-ion batteries. Moreover, their ability to catalyze reactions, including electrochemical processes like oxygen evolution and reduction, positions them as promising candidates for renewable energy technologies. 2D organic-inorganic hybrid materials, such as metal-organic frameworks (MOFs) and perovskite-like structures, offer exciting prospects due to their tunable bandgaps, chemical versatility, and ease of fabrication. These materials have been explored for applications in optoelectronics, photocatalysis, and gas sensing, with particular attention given to their high surface area and ability to host guest molecules for selective catalysis. 2D polymers are another emerging class, where the introduction of covalent bonds within 2D lattices leads to materials with extraordinary mechanical properties, chemical stability, and electrical conductivity. These materials can be tailored for molecular electronics, sensors, and flexible devices. Finally, 2D halide perovskites, which have garnered significant attention in the field of optoelectronics, offer promising applications in solar cells, light-emitting diodes and photodetectors. Their high photoluminescence and tunable optical properties make them versatile material for various light-based technologies. Together, these diverse 2D materials expand the horizon for next-generation devices, enabling innovations across a range of fields from energy storage and conversion to flexible electronics, catalysis, and quantum computing. Their ability to be engineered at the atomic level allows for the precise control of properties, opening up new opportunities for both fundamental research and practical applications. However, challenges such as scalable production, environmental stability, and integration into existing technologies must be overcome to realize their full potential. Ongoing research is focused on addressing these issues by developing new synthesis techniques, improving material stability, and exploring novel applications that can take advantage of the unique characteristics of these 2D materials. As the understanding of these materials continues to grow, they are expected to play an increasingly important role in shaping the future of advanced technologies [**1,87,99–101**].

APPLICATIONS

The diverse and tunable properties of 2D materials, ranging from semiconducting to metallic and insulating behaviors, have opened exciting new pathways for a broad range of applications across various technological fields. These materials have proven to be valuable candidates for applications in electronics, optoelectronics, energy storage, catalysis, sensing and biomedicine, where their unique characteristics such as high surface area, mechanical flexibility, and quantum effects at reduced dimensions can be harnessed to create high-performance devices. In electronics, the ability of 2D materials to exhibit high charge mobility, coupled with their intrinsic tunability, has led to the development of advanced electronic components such as FETs and logic circuits. For instance, transition metal dichalcogenides like MoS_2 and WS_2 have shown promising performance as channel materials in FETs due to their direct bandgap properties in monolayer form, which allows for efficient switching and low-power operation. Unlike traditional semiconductors, many 2D materials can be scaled down to the atomic level, offering devices that are ultra-thin and flexible, which is critical for modern flexible electronics. These materials can be integrated into flexible, stretchable, and transparent electronics, opening up applications in wearable devices, flexible displays, and advanced circuit integration. Moreover, 2D materials' potential for quantum effects and spintronic properties, such as in valleytronics, further expands their utility in next-generation electronics, allowing for the development of ultra-low-power, high-speed transistors that could revolutionize computing technologies [**103–109**].

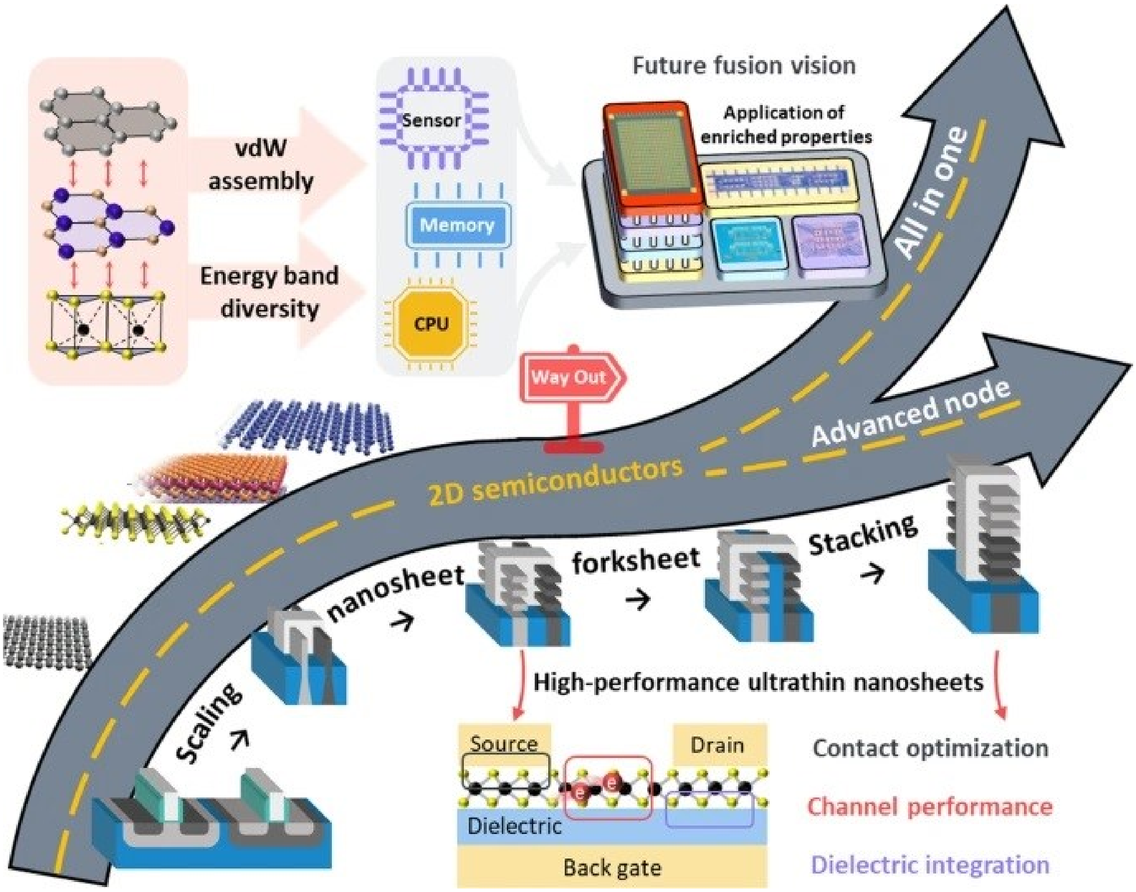
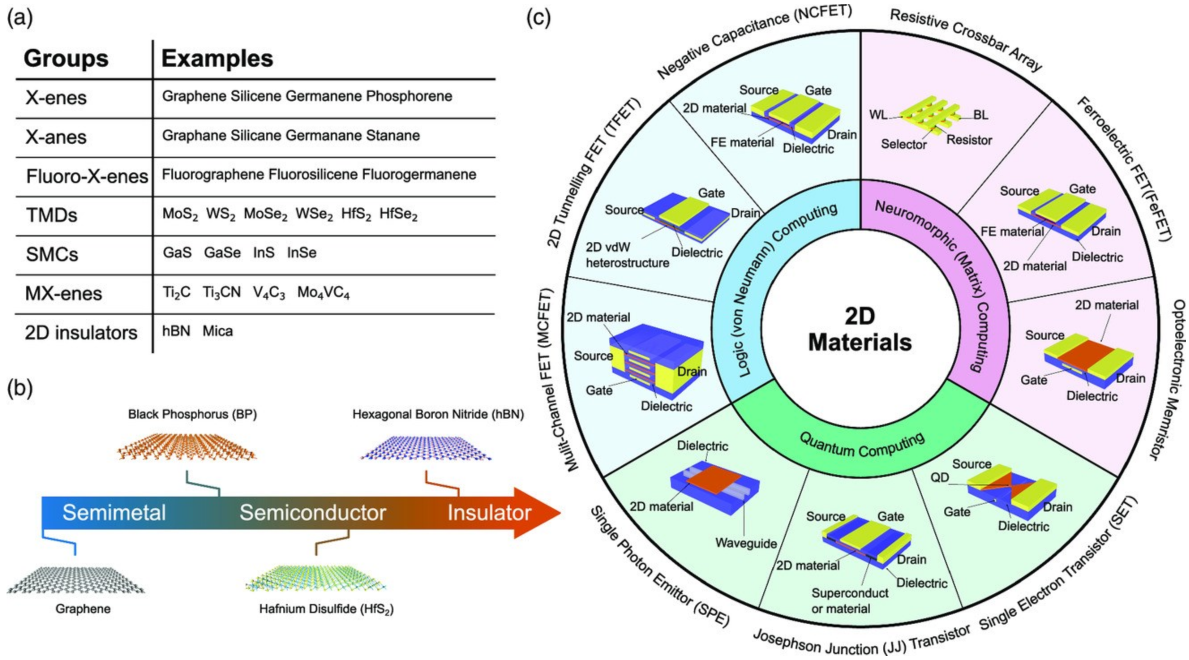


Fig. 10. A schematic diagram of the potential road of specific electrical applications for 2D semiconductors [102].

Fig. 10 presents a visionary roadmap for the application and integration of 2D semiconductors in next-generation electronics, emphasizing their potential as a "way out" of the scaling limitations faced by traditional semiconductor technologies. The illustration begins with van der Waals assembly and energy band diversity —key attributes of 2D materials that fundamentally differentiate them from conventional semiconductors. Van der Waals assembly leverages weak interlayer bonding to construct artificial heterostructures without lattice matching constraints, enabling unprecedented freedom in material combination and bandgap engineering. The diversity of available 2D materials—spanning direct bandgap semiconductors (TMDs), indirect bandgap materials (black phosphorus), tunable-bandgap systems, and metallic conductors (MXenes)—provides customizable electronic characteristics enabling application-specific optimization. These properties position 2D materials as ideal candidates for ultrathin, high-performance devices with engineered transport and optical properties. As the technology development pathway progresses from these fundamental material concepts through scaling stages, it transitions through progressively more complex device architectures. The roadmap illustrates this progression through: (1) nanosheet stage, where individual high-quality 2D monolayers or few-layers form the fundamental active channel material; (2) forksheet architecture, where parallel-aligned 2D nanosheets are arranged in controlled geometric configurations enabling enhanced gate control and reduced short-channel effects; (3) stacking designs, where distinct 2D materials are layered to create van der Waals heterostructures with engineered interlayer coupling and optimized band alignment; (4) high-performance ultrathin nanosheets, representing the culmination of this progression—optimized devices combining atomically thin channels, engineered interfaces, and superior electrostatics. Each stage of this progression represents increased structural complexity and enhanced electronic functionality while maintaining the fundamental advantages of 2D geometry: reduced short-channel effects, improved gate control, and potential for 3D integration. The roadmap also includes a schematic of a typical 2D FET, highlighting the flow of electrons from source to drain through a 2D channel modulated by a back gate, with dielectric layers ensuring insulation and stability. This device architecture demonstrates how 2D materials' exceptional electrostatic properties enable improved gate control at scaled dimensions, potentially extending Moore's Law scaling beyond silicon's fundamental limits. The culmination of this development trajectory is the "all-in-one" advanced node concept, where sensors, memory, CPUs, and other components are unified using enriched 2D material properties. This integration facilitates multifunctional chip designs with reduced footprint, improved speed, and lower power consumption hallmarks of future electronics. The overarching message of the figure is that 2D semiconductors offer a compelling alternative path to continue Moore's Law, unlocking new avenues in miniaturization and multifunctionality. The transformative potential of 2D semiconductors derives from their fundamental advantages: (1) three-dimensional stacking capability exploiting van der Waals bonding to create vertically integrated circuits without lattice matching constraints; (2) bandgap engineering through material selection and heterostructure design enabling application-specific optimization; (3) superior electrostatics enabling scaled gate lengths below silicon's practical limits through naturally reduced short-channel effects in ultrathin channels; (4) flexibility in device architecture enabling innovations like gate-all-around geometries and vertical transistor designs. Their ability to overcome current limitations in traditional silicon-based technologies by enabling 3D stacking, bandgap engineering, and superior electrostatics positions them as the cornerstone of next-generation computing platforms and integrated circuits, unlocking new avenues in miniaturization, performance enhancement, and multifunctional device integration [102]



Groups	Examples
X-enes	Graphene Silicene Germanene Phosphorene
X-anes	Graphane Silicane Germanane Stanane
Fluoro-X-enes	Fluorographene Fluorosilicene Fluorogermanene
TMDs	MoS_2 WS_2 $MoSe_2$ WSe_2 HfS_2 $HfSe_2$
SMCs	GaS GaSe InS InSe
MX-enes	Ti_2C Ti_3CN V_4C_3 Mo_4VC_4
2D insulators	hBN Mica

Fig. 11. Overview of two-dimensional (2D) materials and their applications, (a) A selection of widely studied 2D materials, (b) The diverse electronic properties of 2D materials, ranging from zero-bandgap semimetals like graphene to wide-bandgap insulators such as h-BN and (c) Representative devices utilizing 2D materials for various emerging technologies, including logic circuits, neuromorphic computing, and quantum computing [110].

Fig. 11 comprehensively outlines the classification, electronic spectrum, and application domains of 2D materials in modern and emerging electronic technologies. **Fig. 11(a)** categorizes 2D materials into several distinct groups, including X-enes (e.g., graphene, silicene), X-anes and Fluoro-X-enes (hydrogenated or fluorinated counterparts), transition metal dichalcogenides, semiconducting monochalcogenides (SMCs), MXenes, and 2D insulators like hexagonal boron nitride and mica. This classification showcases the vast chemical and functional diversity of 2D materials, enabling tailored properties for specific applications. **Fig. 11(b)** visually places these materials along an electronic spectrum, ranging from semimetals (e.g., graphene) through semiconductors (e.g., HfS_2) to insulators (e.g., hBN), highlighting their tunable bandgap properties critical for electronic and optoelectronic devices. **Fig. 11(c)** presents a circular schematic that illustrates the diverse technological applications of 2D materials, divided into four major computing paradigms: Logic (von Neumann) computing, Neuromorphic (matrix) computing, Quantum computing, and Optoelectronic systems. For logic computing, configurations such as 2D tunneling field-effect transistors (TFETs), van der Waals heterostructures, and multi-channel FETs (MCFETs) are shown. Quantum computing applications include single-photon emitters, Josephson junction transistors, and single-electron transistors, leveraging the quantum properties of 2D materials. Neuromorphic computing utilizes resistive crossbar arrays and ferroelectric FETs (FeFETs) to emulate synaptic behaviors. Optoelectronic memristors and ferroelectric-based devices underline the role of 2D materials in future memory and sensory systems. This figure highlights how 2D materials bridge conventional and next-generation computing by offering unique mechanical flexibility, high carrier mobility, and tunable electro-optical properties, enabling compact, multifunctional device architectures. [110]

In optoelectronics, 2D materials are gaining significant attention due to their excellent light-matter interaction, tunable optical properties, and high efficiency. For example, light-emitting diodes and photodetectors based on monolayers of TMDs such as MoS_2, WS_2, and $MoSe_2$ are being actively researched. These materials are capable of emitting light across a broad spectrum, from the visible to the infrared range, depending on their composition and thickness. This makes them ideal for use in next-generation LEDs and lasers, where highly efficient light emission is required. In addition, 2D materials are being explored for use in solar cells, particularly in the form of heterostructures, where layers of different 2D materials are stacked to enhance the efficiency of photovoltaic devices. The combination of a high absorption coefficient, direct bandgap, and efficient charge carrier mobility in materials like TMDs and halide perovskites allows for the potential of ultra-thin, flexible, and highly efficient solar cells that could surpass the efficiency limits of conventional silicon-based photovoltaics. The ability to tune the optical properties of these materials with atomic precision also enables the development of photodetectors with high sensitivity and fast response times, making them highly suitable for applications in optical communication, imaging, and sensing technologies [**103,104,111–123**].

For energy storage, the application of 2D materials has significantly impacted the development of next-generation supercapacitors and lithium-ion batteries. Supercapacitors, which store energy through electrostatic charges, benefit from the high surface area and conductivity of 2D materials, enabling fast charge and discharge rates, as well as high capacitance. Materials such as MXenes and graphene are extensively used in the development of supercapacitors due to their excellent electrical conductivity and large surface area. MXenes, in particular, are capable of facilitating high charge density and quick ion movement, making them ideal candidates for high-performance supercapacitors. In lithium-ion batteries, 2D materials like graphene, TMDs, and black phosphorus can be used to enhance the performance of both anodes and cathodes by providing higher charge storage capacity, better conductivity, and structural stability. The high surface area of 2D materials increases the number of active sites for lithium-ion storage, improving the energy density and cycle life of the batteries. Additionally, the flexibility of 2D materials opens possibilities for the development of flexible batteries, crucial for wearable electronics and portable devices [**116,125–134**]. **Fig. 12** presents a comprehensive overview of the promising roles that 2D materials play in energy-related technologies, emphasizing their unique physicochemical properties. At the center of the schematic is a triangular framework that highlights three key attributes of 2D materials: larger specific surface area, more active catalytic sites, and faster transfer of electrons and ions. These features stem from the atomically thin nature, high aspect ratios, and tunable surface chemistry of 2D materials, making them highly advantageous for energy conversion and storage applications. Surrounding this core are six major applications. Solar cells benefit from 2D materials' high transparency and conductivity, which improve charge separation and light absorption. In thermoelectric devices, their tunable band structures and low thermal conductivity make them efficient for converting heat into electricity. For rechargeable batteries, 2D materials enhance electrode performance through increased ion mobility and surface reactivity. Supercapacitors gain improved charge/discharge rates and cycle stability due to the large surface area and high conductivity of 2D nanosheets. In oxygen electrochemistry, 2D materials serve as efficient catalysts for the oxygen reduction reaction (ORR) and oxygen evolution reaction (OER), essential for fuel cells and metal-air batteries. Finally, for the hydrogen evolution reaction (HER), critical to green hydrogen production, 2D catalysts facilitate rapid proton reduction due to abundant edge sites and optimized electronic structures. Overall, this figure underscores how the integration of 2D materials across diverse energy domains can drive the development of high efficiency, miniaturized, and sustainable energy technologies. Their multifunctionality and customizable nature position them as a cornerstone of next-generation energy systems [**124**].

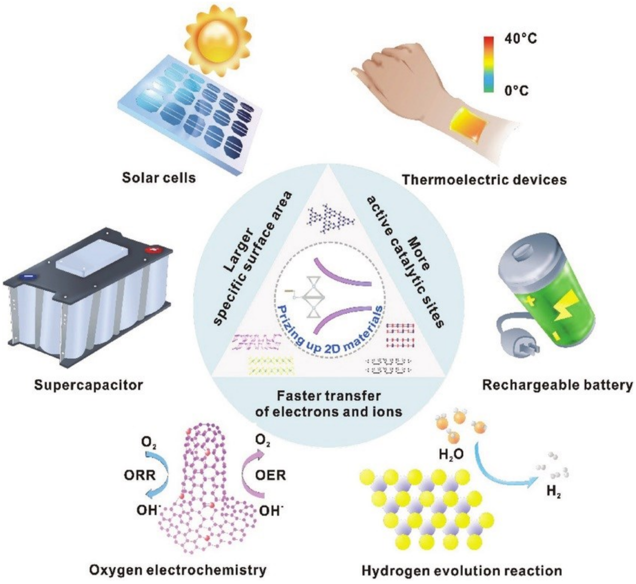


Fig. 12. Opening 2D materials for energy conversion and storage [124].

In catalysis, 2D materials are playing a crucial role in electrocatalysis and photocatalysis. Electrocatalysis involves the acceleration of electrochemical reactions, such as in fuel cells and water splitting, and 2D materials offer excellent catalytic activity due to their high surface area and the ability to modify their electronic properties through surface functionalization and doping. For example, TMDs, particularly MoS_2 and WS_2, have shown remarkable performance in the hydrogen evolution reaction for water splitting, a key reaction for hydrogen fuel production. These materials, when properly engineered, can exhibit low overpotentials and high catalytic efficiency, making them attractive alternatives to expensive platinum-based catalysts. Additionally, graphene oxide and MXenes have been investigated for oxygen reduction and evolution reactions (ORR and OER), both critical for fuel cells. Photocatalysis, the use of light to drive chemical reactions, is another area where 2D materials have demonstrated great promise. Graphene-based materials and TMDs have been explored as photocatalysts for the degradation of organic pollutants and the production of valuable chemicals from sunlight. The high surface area and tunable optical properties of 2D materials enhance their ability to absorb light and facilitate photocatalytic processes, enabling more efficient energy conversion and environmental remediation [**19,135–146**].

In sensing, the exceptional surface-to-volume ratio and tunable electronic properties of 2D materials make them ideal candidates for gas and biosensors. These sensors work by detecting changes in the electrical properties of the material upon exposure to target molecules, which adsorb onto the surface of the 2D material and alter its conductivity. Graphene and MXenes are among the most widely studied materials for gas sensors due to their high surface area and sensitivity to small amounts of adsorbed gas molecules. 2D materials can be functionalized with various chemical groups to selectively target specific gases, such as nitrogen dioxide (NO_2), ammonia (NH_3), and carbon monoxide (CO), making them useful for environmental monitoring, industrial safety, and medical diagnostics. In biosensing, the ability of 2D materials to interact with biological molecules such as proteins, DNA, and cells is being leveraged for the development of highly sensitive and specific biosensors. The integration of TMDs and graphene with biomolecular recognition elements allows for the detection of low concentrations of biomolecules, opening up applications in point-of-care diagnostics, early disease detection, and personalized medicine [**135,147–158**].

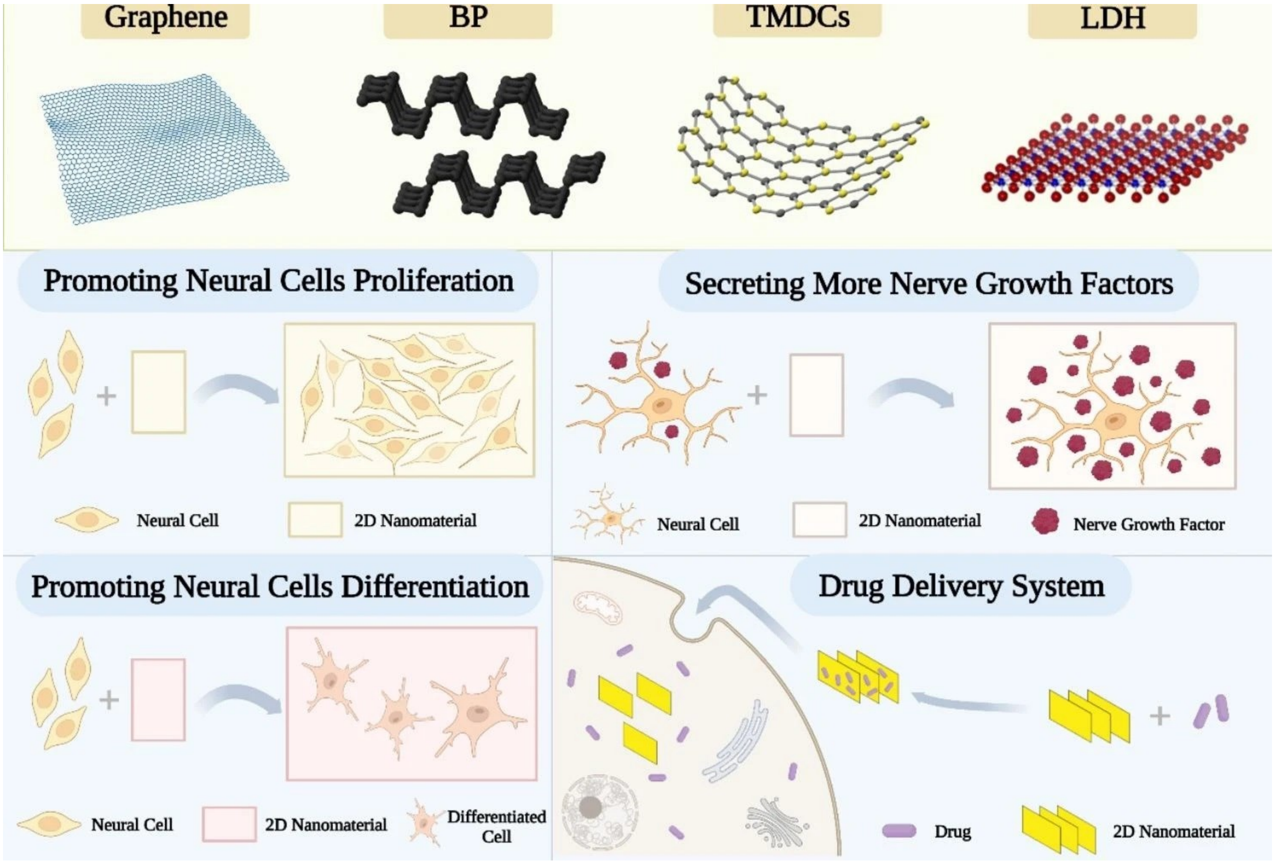


Fig. 13. Applications of 2D nanomaterials in neural repair and regeneration. Two-dimensional nanomaterials, such as graphene, BP, TMDCs, and layered double hydroxides (LDHs) play multifaceted roles in neural tissue engineering. These include promoting neuronal cell proliferation and differentiation, enhancing the secretion of neurotrophic factors, and serving as carriers for targeted drug delivery in the treatment of neurological disorders (NDs) [159].

The diverse properties of 2D materials offer a wide range of possibilities for applications across multiple fields, including electronics, optoelectronics, energy storage, catalysis, and sensing. Their unique ability to be tailored at the atomic level allows for the design of high-performance, multifunctional devices that can address challenges in energy, communication, environmental monitoring, and healthcare. As research continues to explore new materials and applications, the full potential of 2D materials is only beginning to be realized, promising revolutionary advances in technology and industry. However, challenges related to large-scale synthesis, stability, and integration with existing technologies remain, and continued research will be needed to overcome these barriers.

Industrialization Cases of 2D Materials

Graphene and 2D materials have begun transitioning from laboratory demonstrations to real-world commercial applications across multiple sectors, though at early market stages. Graphene was the first 2D material to enter the market, with over 350 companies now producing related products, and commercial applications including composites with enhanced mechanical or thermal properties, batteries, inks for printable electronics, photodetectors, and chemical and biological sensors. The next wave of products, such as solar cells, flexible devices, supercapacitors, water filters/desalinators, and neural interfaces, is expected to emerge in the following years.[160]

One of the most advanced commercialization examples is Skeleton Technologies, an Estonian-based company established in 2009 that has achieved significant market penetration with graphene-enhanced supercapacitors. Skeleton Technologies produces graphene-based supercapacitors for use in trains that can recover up to 30% of energy lost during braking. This technology has been selected for use in new trains for the Granada metro system in Spain, which entered service by summer of 2024 (CAS Insights 2023). Additionally, in August 2015, Skeleton entered the commercial truck fleet market with a graphene-based device that helps truck drivers start engines after long periods of inactivity or in cold weather. In September 2020, Skeleton signed a billion-euro letter of intent with a leading automotive manufacturer for the Super Battery technology. More recently, Skeleton launched Graphene GPU, a peak-shaving power shelf for data centers using graphene-based supercapacitors. Initial shipments from Skeleton's German facility were scheduled for June 2025, with US manufacturing expansion planned for Q1 2026. The company secured strategic partnerships with ZPUE in Poland for 200 MW of energy storage for rail systems (2023–2025), with commercial value exceeding €30 million.

In energy storage applications, multiple companies have progressed graphene-enhanced batteries beyond research stages. The Korea Electrotechnology Research Institute (KERI) announced preparation to move silicon-graphene composite anode material for lithium-ion batteries into mass production, with potential to extend electric vehicle range by storing roughly 10 times more energy than conventional graphite anodes. Solidion Technology (established through the 2024 merger of Honeycomb Battery Technology and Nubia Brand International) began trading on NASDAQ in February 2024, focused on graphene-enhanced battery materials addressing supply shortages for EV and energy storage systems applications. 2D Fab, a Swedish company established in 2013 as a spin-off from Mid Sweden University, closed a €700,000 share issue in June 2020 to commercialize graphene-based battery anode material theoretically capable of increasing storage capacity 8 times compared to graphite, with collaboration projects underway for development and commercialization of paper-based battery anodes.

The broader commercialization landscape indicates that 2D materials are entering rapid growth phases in multiple sectors. IDTechEx forecasts graphene market growth to US$2.7 billion by 2036, with significant applications observed in polymer composites for automotive, heat spreaders for smartphones, industrial elastomers, anti-corrosion coatings, sensors, and optoelectronic applications, with manufacturing improvements driving commercial successes particularly in sensors and optoelectronic applications. Graphene nanoplatelets (GNP), graphene oxide (GO), and reduced graphene oxide (rGO) show the closest forms to significant commercial uptake, with increasing indications of rapid growth phase, particularly following development of ISO graphene standards in 2021.

Despite commercial progress, significant barriers to widespread adoption remain. The lab-to-fab transition lags behind expectations with slow commercial uptake. Academia and industry continue developing reproducible and scalable synthesis methods for 2D materials, as well as standardized characterization, processing, and integration protocols. Unified standardization of quality and performance with application-specific grading systems remains essential. Progress also requires sustained cooperation between academic labs, standardization institutes, supplier and end-user companies, and government agencies [**160**].

CHALLENGES IN RESEARCH OF 2D MATERIALS

Scalable and Reproducible Synthesis

Despite the remarkable advances in the development of 2D materials, achieving scalable and reproducible synthesis remains a significant challenge. Although methods such as chemical vapor deposition, liquid-phase exfoliation, and mechanical cleavage have been successful in laboratory settings, scaling these processes to industrial levels while maintaining high material quality and uniformity is a difficult task. Current techniques often suffer from issues like low yield, difficulty in controlling layer thickness, and the production of defect-laden materials. To enable the widespread use of 2D materials in devices, it is essential to develop scalable synthesis methods that produce large quantities of high-quality materials. Achieving reproducibility across different production batches and facilities is crucial for ensuring consistent material properties, which is vital for commercial applications in electronics, energy storage, and more [**5,6,15,161–163**].

Stability under Ambient Conditions

The stability of 2D materials under ambient conditions is another major hurdle. Many 2D materials, particularly black phosphorus and some transition metal dichalcogenides, are highly sensitive to environmental factors such as oxygen, moisture, and heat. For example, BP rapidly degrades in air, severely limiting its practical applications in electronic and optoelectronic devices. TMDs can also degrade over time due to oxidation or the formation of unwanted surface defects. To make these materials viable for real-world applications, particularly in outdoor or harsh environments, it is necessary to develop strategies for stabilizing these materials. Researchers are exploring methods such as encapsulation techniques, surface passivation, and the development of protective coatings to address this issue. Understanding the degradation mechanisms is vital for ensuring long-term performance in devices [**70,164–168**].

Integration with Existing Technologies

Another significant challenge is the integration of 2D materials with existing technologies. While 2D materials offer exciting properties, integrating them into conventional devices and manufacturing processes is not straightforward. Current semiconductor fabrication processes are not optimized for 2D materials, which require precise control over material thickness and unique handling techniques. Moreover, the compatibility of 2D materials with traditional substrates such as silicon and glass must be carefully engineered to ensure efficient charge transfer and mechanical stability. Issues like poor contact resistance, lattice mismatch, and interfacial defects must be addressed to enable efficient integration with conventional materials. Researchers are exploring hybrid devices that combine 2D materials with traditional materials, but overcoming the challenges associated with material deposition, patterning, and interface engineering will be crucial to the successful integration of 2D materials into existing technologies [**1,50,70,104,146,165,169–174**].

Understanding Interfacial and Quantum Phenomena

As 2D materials are reduced to atomic thickness, interfacial and quantum phenomena begin to play an increasingly significant role in determining their properties. The behavior of charge carriers, for example, can be drastically different at the interface between a 2D material and a substrate compared to within the bulk material. Quantum effects, strong spin-orbit coupling, and modified electron-electron interactions can lead to novel electronic and optical behaviors that are not yet fully understood. The complexity of these phenomena is particularly evident at material interfaces, where the interactions between different 2D materials or between a 2D material and its environment can lead to unexpected results. To fully harness the potential of 2D materials, it is crucial to develop a deeper understanding of these quantum effects and interfacial physics. Advanced characterization techniques, theoretical modeling, and experimental studies are needed to explore how these phenomena affect the performance of 2D materials in devices like spintronic devices, quantum computing systems, and sensors [**1,103,106,175–183**].

FUTURE DIRECTIONS FOR RESEARCH OF 2D MATERIALS

Heterostructure Engineering

One promising future direction is the development of heterostructures, which involve stacking layers of different 2D materials to create new materials with enhanced or tailored properties. By combining materials with different bandgaps, optical properties, or catalytic activities, researchers can design devices with improved performance or entirely new functionalities. Heterostructures can offer greater control over the electronic and optical properties of 2D materials, enabling innovations in photodetectors, solar cells, and transistors. This approach can also help in overcoming the limitations of individual 2D materials, leading to the creation of more efficient devices [**177,184,185**].

Doping Strategies

Doping strategies represent another promising avenue for enhancing the properties of 2D materials. By introducing specific atoms or molecules into the structure of 2D materials, it is possible to modify their electronic structure, charge carrier concentration, and chemical reactivity. For example, doping TMDs with nitrogen or sulfur can improve their catalytic properties, while doping graphene with elements like boron or nitrogen can enhance its electronic performance. Research in precise doping techniques and the ability to control doping levels will be crucial for designing 2D materials optimized for applications in energy storage, electronics, and catalysis [**174,186–193**].

AI-Guided Material Discovery

Finally, AI-guided material discovery is expected to play a significant role in advancing the development of 2D materials. Machine learning and artificial intelligence can be leveraged to predict the properties of new 2D materials, guide the discovery of novel compositions, and optimize synthesis processes. AI algorithms can process vast amounts of data from experimental studies to identify trends and correlations, speeding up the discovery of materials with specific desired characteristics. Combining AI-driven analysis with high-throughput experimental techniques will accelerate the design and testing of 2D materials for specific functions, such as ultra-fast transistors, highly efficient solar cells, and sensitive sensors [**194–200**].

CONCLUSION

The discovery and development of 2D materials beyond graphene represents a fundamental paradigm shift in materials science, transitioning from bulk material constraints to atomically engineered designs that decouple electronic, mechanical, and optical properties. The field has reached a critical inflection point where technological maturation, substantial capital investment, and proven device prototypes converge to enable transition from fundamental research to commercial deployment—a trajectory evidenced by projected market growth of 18–22% CAGR through 2030, substantially exceeding conventional materials markets. However, realizing this commercial potential demands coordinated progress across systemic challenges that extend beyond materials science alone: standardization and metrology frameworks comparable to semiconductor industries, long-term reliability protocols under operational conditions, and manufacturing integration pathways compatible with existing industrial infrastructure. Strategic research priorities must emphasize heterostructure engineering principles, inverse design approaches leveraging artificial intelligence, and sustainability-first synthesis methodologies that embed circular economy considerations from inception. Success ultimately depends not on isolated materials innovations but on robust interdisciplinary ecosystems integrating materials scientists, device engineers, manufacturers, and regulatory bodies—a collaborative framework essential for translating the scientific foundation established over two decades of intensive research into scalable, cost-competitive technologies addressing global imperatives in clean energy, healthcare diagnostics, environmental remediation, and advanced computing. The trajectory of 2D materials science will be determined by the collective effectiveness of this integrated research community in bridging the gap between laboratory demonstration and widespread technological implementation.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Avadhesh K. Yadav: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Visualization, Writing – Original Draft, Writing – Review & Editing, Validation.

DECLARATION OF COMPETING INTEREST

The author declares that there are no known financial or personal conflicts of interest that could have appeared to influence the work reported in this article.

DATA AVAILABILITY STATEMENT

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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