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Emerging Two-Dimensional Nanomaterials for Advanced Sensing Applications and Intelligent Systems Integration

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Abstract: Two-dimensional (2D) nanomaterials have emerged as a transformative class of materials, particularly for advancing advanced sensing technologies. The isolation of graphene in 2004, the complex of atomic-level thin materials has expanded rapidly to include MXenes, transition metal dichalcogenides (TMDs), black phosphorus, and crystalline porous frameworks such as metal–organic frameworks (MOFs) and covalent organic frameworks (COFs). These materials show exceptional physicochemical properties, including atomic-scale thickness, very high surface-to-volume ratios, tunable electronic band structures, and extraordinary charge carrier mobility. Such features enable strong interfacial interactions between sensing surfaces and target analytes, helping highly sensitive detection platforms capable of finding ultra-low concentrations of chemical and biological species. The structural characteristics of 2D materials ensure that a huge proportion of atoms are exposed at the surface, promoting efficient adsorption of analyte molecules and inducing pronounced changes in electronic, electrochemical, or optical properties. Therefore, sensing mechanisms based on electrical signal modulation, electrochemical redox reactions, and optical responses can detect minute variations in analyte concentration. Recent advances in synthesis techniques, including liquid-phase exfoliation, electrochemical exfoliation, and chemical vapor deposition, have enabled the fabrication of high-quality 2D nanostructures with controlled thickness and morphology. Also, advanced materials engineering strategies such as heterostructure formation, defect engineering, and surface functionalization have greatly improved sensor sensitivity, selectivity, and stability. This review provides a comprehensive overview of emerging 2D nanomaterials for next-generation sensing technologies. Fundamental sensing mechanisms and recent applications in biomedical diagnostics, environmental monitoring, and chemical detection are systematically discussed. Meanwhile, key challenges related to material stability, large-scale manufacturing, and real-world deployment are detailed, along with future research directions, followed by intelligent sensing systems integrated with artificial intelligence and Internet-of-Things (IoT) technologies.

Keywords: Two-Dimensional Nanomaterials, Graphene, Transition Metal Dichalcogenides, Mxenes, Biosensors, Environmental Sensors, Nanotechnology, Artificial Intelligence, IoT Sensing, Sensor Mechanisms, AI-Enabled Sensing.

1. Introduction

1.1 Increasing Global Demand for Advanced Sensing Technologies

In recent decades, the hasty expansion of modern society has widely increased the demand for advanced sensing technologies capable of monitoring complex chemical, biological, and environmental systems with high accuracy and reliability [1]. Sensitive detection of trace-level analytes is essential for numerous applications, including early disease diagnosis [2], environmental pollution monitoring [3], food safety inspection [4], industrial process control [5], and national security [6]. For instance, the early detection of disease biomarkers in biological fluids can improve treatment outcomes and reduce mortality rates, while continuous monitoring of environmental pollutants like toxic gases, heavy metal ions, and microplastics is critical for productive ecosystems and public health [7]. Consequently, the development of highly sensitive, selective, and rapid sensing platforms has become a major motivation for interdisciplinary research involving materials science, chemistry, physics, and biomedical engineering.

Conventional sensing devices basically rely on bulk materials as their active sensing layers. Although these materials have been successfully implemented in many commercial sensors, they are often affected by intrinsic limitations associated with their relatively small active surface areas and limited interaction with target analytes. In bulk materials, sometimes only a small fraction of atoms is exposed at the surface where analyte adsorption happens, while the majority remain buried within the material lattice and do not contribute directly to sensing processes [8]. As a result, traditional sensors frequently exhibit limited sensitivity, slow response times, and insufficient selectivity when detecting trace concentrations of chemical or biological species. These boundaries have inspired researchers to explore alternative materials with improved surface accessibility and enhanced electronic properties.

Nanotechnology has emerged as a powerful strategy to overcome these challenges by activating the design and fabrication of materials with nanoscale dimensions and unique physicochemical characteristics [9]. Nanomaterials possess much higher surface-to-volume ratios compared with bulk materials, allowing a larger number of active sites to interact with target molecules. Furthermore, nanoscale structures often exhibit tunable electronic, optical, and catalytic properties that can be exactly engineered to optimize sensing performance. Among the various classes of nanomaterials explored to date, two-dimensional (2D) nanomaterials have attracted exceptional attention due to their atomic-thin structures and extraordinary electronic properties [10].

1.2 Emergence of Two-Dimensional Nanomaterials

Two-dimensional nanomaterials represent a unique class of materials in which electrons are confined within a planar structure consisting of a single or a few atomic layers [11]. This reduced dimensionality gives rise to strong quantum confinement effects that significantly influence the electrical, optical, and chemical behaviour of the material. As a result, many two-dimensional materials exhibit properties that are fundamentally different from those of their bulk counterparts. The discovery of graphene in 2004 marked a major milestone in the field of nanoscience and materials engineering [12]. Graphene, a single atomic layer of sp^2-bonded carbon atoms arranged in a hexagonal lattice, demonstrated extraordinary properties including ultrahigh electron mobility, exceptional mechanical strength, remarkable thermal conductivity, and excellent chemical stability. These characteristics immediately attracted widespread interest from researchers seeking to exploit graphene for a wide range of applications, including electronics, energy storage, catalysis, and sensing technologies.

In sensing applications, graphene shows particular promise due to its high electrical conductivity and extremely large specific surface area, which allows efficient interaction with adsorbed molecules [13]. Even small perturbations caused by molecular adsorption can induce measurable changes in graphene's electrical conductivity, making it highly sensitive to various chemical and biological species [14]. However, despite its many advantages, graphene also possesses certain limitations that restrict its applicability in some electronic sensing devices. In particular, the absence of an intrinsic bandgap in graphene results in poor switching behaviour in field - effect transistor (FET) devices, which can limit its sensitivity and selectivity in certain, sensing configurations [15]. These limitations stimulated extensive research aimed at discovering new two-dimensional materials with tunable electronic properties and improved functionality for sensing applications.

1.3 Expansion of the Two-Dimensional Material Family

Following the discovery of graphene, researchers began exploring a wide range of layered materials that could be exfoliated into atomically thin structures. Over the past decade, this effort has led to the emergence of a diverse family of two-dimensional materials with distinct structural, electronic, and chemical characteristics. Among the most extensively studied materials are transition metal dichalcogenides (TMDs), which possess the general chemical formula MX_2, where M represents a transition metal such as molybdenum or tungsten and X represents a chalcogen element such as sulfur, selenium, or tellurium [16]. Unlike graphene, many TMDs exhibit intrinsic semiconducting behaviour with tunable band gaps, making them highly suitable for electronic and optoelectronic sensing applications [17]. Materials such as MoS_2, WS_2, and $MoSe_2$ have demonstrated excellent performance in field-effect transistor sensors and photodetectors due to their high carrier mobility and strong interaction with adsorbed molecules [18].

Another important class of two-dimensional materials is MXenes, which are derived from layered MAX phases through selective chemical etching processes. MXenes consist of transition metal carbides, nitrides, or carbonitrides and typically possess metallic conductivity combined with hydrophilic surfaces rich in functional groups such as hydroxyl, oxygen, and fluorine [19]. These surface functional groups enable strong chemical interactions with analyte molecules, making MXenes particularly attractive for electrochemical and gas sensing applications. Black phosphorus has also emerged as a promising two-dimensional semiconductor with a tunable bandgap and high carrier mobility [20]. Its anisotropic crystal structure provides unique electronic and optical properties that are advantageous for optoelectronic sensing devices. In addition to these inorganic layered materials, researchers have recently begun exploring two-dimensional crystalline porous frameworks, including metal–organic frameworks (MOFs) [21] and covalent organic frameworks (COFs) [22]. These materials possess highly ordered porous architectures and exceptionally large surface areas, allowing selective adsorption of target molecules and enabling the development of highly selective sensing platforms.

1.4 Unique Sensing Advantages of Two-Dimensional Nanomaterials

The exceptional sensing performance of two-dimensional nanomaterials is primarily attributed to their unique structural and electronic characteristics. One of the most important advantages of these materials is their extremely high surface-to-volume ratio [23]. In conventional bulk materials, the majority of atoms are located within the interior of the material and do not directly participate in interactions with analytes. In contrast, in atomically thin two-dimensional materials, nearly all atoms are exposed at the surface, allowing direct interaction with surrounding molecules. This fully exposed surface significantly enhances the adsorption efficiency of analyte molecules and enables even small perturbations in the local chemical environment to induce measurable changes in the electronic or optical properties of the sensing layer. For example, adsorption of gas molecules can alter the charge carrier concentration within the material, leading to detectable variations in electrical conductivity [24]. Similarly, adsorption events can influence electrochemical redox reactions or modify optical properties such as photoluminescence or Raman scattering intensity.

Recent advances in nanofabrication techniques have enabled the integration of two-dimensional materials into a variety of sensing architectures, including field-effect transistor sensors, electrochemical sensors, optical sensors, and surface-enhanced Raman spectroscopy platforms [25]. These devices have demonstrated remarkable sensitivity, rapid response times, and low detection limits for a wide range of chemical and biological analytes. Another important advantage of many 2D materials is their mechanical flexibility and robustness. These characteristics allow the fabrication of flexible and wearable sensing devices capable of continuous monitoring of physiological signals or environmental conditions [26, 27].

1.5 Emerging Role of Intelligent Sensing Systems

In addition to materials innovation, recent advances in digital technologies are transforming the field of sensing through the integration of artificial intelligence (AI) and Internet-of-Things (IoT) systems [28]. AI-based data analysis methods, particularly machine learning algorithms, enable the interpretation of complex sensor signals and the identification of specific analytes in environments containing multiple interfering species. These algorithms can significantly improve sensor selectivity and reliability by recognizing characteristic response patterns. Meanwhile, IoT connectivity enables distributed sensor networks capable of real-time data transmission and remote monitoring. Such systems are particularly valuable in applications such as environmental surveillance, smart healthcare systems, and industrial process monitoring. The combination of advanced 2D nanomaterial sensors with AI and IoT technologies, therefore, represents a promising pathway toward the development of intelligent sensing platforms [29].

1.6 Scope and Organization of This Review

Despite remarkable progress in the development of two-dimensional nanomaterial-based sensors, several challenges remain before these technologies can achieve widespread commercialization. These challenges include scalable synthesis of high-quality materials, long-term stability under practical operating conditions, reproducibility of sensor performance, and integration with existing electronic and data processing systems. This review provides a comprehensive overview of emerging two-dimensional nanomaterials for next-generation sensing technologies. The fundamental sensing mechanisms underlying electrical, electrochemical, and optical detection platforms are first discussed. Subsequently, recent advances in biomedical, environmental, and chemical sensing applications are examined. Finally, key challenges and future research directions are highlighted to guide the continued development and practical implementation of 2D nanomaterial-based sensing systems. Despite extensive research on two-dimensional nanomaterials, existing reviews primarily focus on individual material classes or isolated sensing mechanisms without establishing a unified relationship between material design, sensing principles, and application performance. Furthermore, limited attention has been given to the integration of intelligent data analysis systems with nanoscale sensors. This study addresses these gaps by providing a structured comparative analysis and a unified conceptual framework linking materials, mechanisms, and applications. Figure 1 displays the Conceptual framework illustrating the relationships among two-dimensional nanomaterial classes, structural and surface engineering strategies, fundamental sensing mechanisms, and application domains integrated with artificial intelligence and Internet-of-Things systems.

2. Classification of Two-Dimensional Nanomaterials

Two-dimensional (2D) nanomaterials represent a rapidly expanding class of materials characterized by atomic-scale thickness and lateral dimensions that can extend from nanometers to several micrometers. Their layered structures are typically composed of strongly bonded atoms within the plane and weak van der Waals interactions between adjacent layers, which allows them to be mechanically or chemically exfoliated into ultrathin sheets. Due to their reduced dimensionality and fully exposed surface atoms, these materials exhibit unique electronic, optical, mechanical, and catalytic properties that are fundamentally different from their bulk counterparts [30].

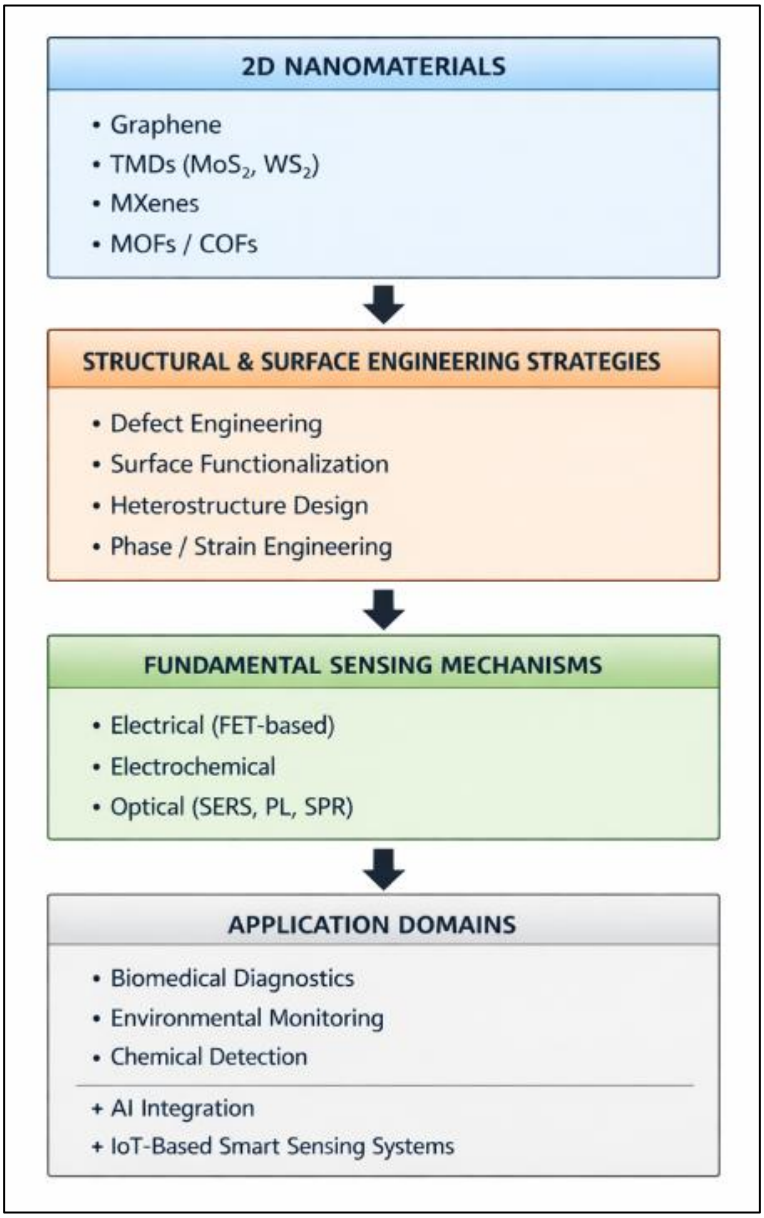

Figure 1. Conceptual Framework

Over the past two decades, extensive research efforts have led to the discovery and development of a wide variety of two-dimensional materials with diverse chemical compositions and electronic structures. These materials can generally be classified into several major categories based on their composition and structural characteristics, including graphene-based materials, transition metal dichalcogenides (TMDs), MXenes, elemental Xenes, and crystalline porous frameworks such as metal–organic frameworks (MOFs) and covalent organic frameworks (COFs). Each category exhibits distinct physicochemical properties that influence its sensing performance and suitability for specific applications.

2.1 Graphene-Based Materials

Graphene-based materials represent the earliest and most extensively studied class of two-dimensional nanomaterials. Graphene itself consists of a single atomic layer of carbon atoms arranged in a hexagonal honeycomb lattice formed through sp^2 hybridization [31]. This unique structure gives rise to exceptional electrical conductivity, extremely high carrier mobility, remarkable mechanical strength, and excellent thermal conductivity. One of the most significant advantages of graphene in sensing applications is its extremely high specific surface area, which theoretically reaches approximately 2630 $m^2\ g^{-1}$ [32]. This large surface area allows efficient adsorption of analyte molecules and facilitates strong interactions between the sensing surface and target species. As a result, even minor changes in surface chemistry can lead to measurable variations in graphene's electrical conductivity or optical properties.

However, pristine graphene exhibits a zero bandgap, which limits its switching behaviour in field-effect transistor (FET) devices. To overcome this limitation, researchers have developed various graphene derivatives, including graphene oxide (GO) and reduced graphene oxide (rGO) [33]. Graphene oxide contains abundant oxygen-containing functional groups such as hydroxyl, carboxyl, and epoxy groups, which enhance its hydrophilicity and provide active sites for chemical functionalization. Reduced graphene oxide, obtained through chemical or thermal reduction of GO, partially restores electrical conductivity while retaining some functional groups that facilitate analyte adsorption. Due to these properties, graphene-based materials have been widely investigated for applications in gas sensing, electrochemical biosensing, and wearable sensor devices. Their high conductivity and rapid charge transfer capabilities make them particularly suitable for detecting gases such as NO_2, NH_3, and volatile organic compounds, as well as biological analytes including glucose, DNA, and proteins [34].

2.2 Transition Metal Dichalcogenides (TMDs)

Transition metal dichalcogenides constitute another important class of two-dimensional nanomaterials with the general chemical formula MX_2, where M represents a transition metal such as molybdenum, tungsten and X represents a chalcogen atoms like sulfur, selenium, or tellurium) [16]. In contrast to graphene, many TMDs exhibit intrinsic semiconducting behaviour with tunable band gaps, which makes them particularly attractive for electronic and optoelectronic sensing applications. The layered structure of TMDs consists of a transition metal atom sandwiched between two chalcogen layers, forming a trigonal prismatic or octahedral coordination geometry. Weak van der Waals forces between adjacent layers allow these materials to be exfoliated into monolayers or few-layer nanosheets [35]. Interestingly, the electronic properties of TMDs often change significantly when the material thickness is reduced to a monolayer. For example, molybdenum disulfide (MoS_2) exhibits an indirect bandgap in its bulk form but transitions to a direct bandgap semiconductor when isolated as a monolayer. This property enables strong optical absorption and enhanced photoluminescence, which are advantageous for optical sensing applications. TMD-based sensors have demonstrated excellent performance in field-effect transistor sensors, photodetectors, and chemical sensors. Their semiconducting nature allows precise modulation of electrical conductivity upon interaction with analyte molecules, enabling highly sensitive detection of gases, biomolecules, and environmental pollutants.

2.3 MXenes

MXenes are a relatively new family of two-dimensional materials derived from layered MAX phases, which have the general formula $M_{n+1}AX_n$ [36]. In this structure, M represents an early transition metal, A represents an element from groups 13 or 14 of the periodic table, and X represents carbon or nitrogen. MXenes are typically produced by selectively etching the A layer from MAX phases using chemical etchants such as hydrofluoric acid. The resulting

MXene nanosheets possess metallic conductivity and surfaces terminated with functional groups such as –OH, –O, and –F. These surface terminations impart strong hydrophilicity and provide numerous active sites for chemical adsorption and functionalization. As a result, MXenes exhibit excellent electrochemical activity and strong interactions with various analytes. Among the different MXene materials, $Ti_3C_2T_x$ is the most extensively studied due to its high electrical conductivity, large surface area, and ease of synthesis [37]. MXene-based sensors have shown outstanding performance in electrochemical sensing, gas detection, and biosensing applications. Their high conductivity facilitates rapid electron transfer, while their surface functional groups enable strong binding with target molecules such as heavy metal ions, gases, and biomolecules.

2.4 Elemental Xenes

Elemental Xenes represent another emerging category of two-dimensional materials composed of single elements arranged in layered structures. Examples include black phosphorus (phosphorene), silicene, germanene, and stanene. These materials exhibit diverse electronic properties ranging from semiconducting to metallic. Black phosphorus is one of the most extensively studied Xenes due to its high carrier mobility and thickness-dependent bandgap, which can vary from approximately 0.3 eV in bulk form to around 2 eV in monolayer phosphorene [38]. This tunable bandgap enables efficient absorption of light across a wide spectral range, making black phosphorus particularly attractive for optoelectronic sensing applications. Silicene and germanene possess honeycomb lattice structures similar to graphene but exhibit stronger spin–orbit coupling and enhanced electronic properties [39]. Although these materials are still in relatively early stages of research, they hold considerable potential for future sensing technologies.

2.5 Two-Dimensional Porous Framework Materials

In addition to inorganic layered materials, porous crystalline frameworks such as metal–organic frameworks (MOFs) and covalent organic frameworks (COFs) have recently been explored as two-dimensional sensing materials. These frameworks consist of metal ions or organic nodes connected through organic linkers to form highly ordered porous structures. One of the most important characteristics of MOFs and COFs is their extremely high surface area and tunable pore size [40]. These properties enable selective adsorption of target molecules based on size, shape, or chemical affinity. Furthermore, the chemical functionality of the framework can be precisely engineered by selecting appropriate metal nodes or organic linkers. Two-dimensional MOF and COF nanosheets exhibit enhanced diffusion of analytes and improved accessibility of active sites compared with their bulk counterparts [41]. As a result, they have been widely investigated for chemical sensing applications, including the detection of volatile organic compounds, toxic gases, and environmental pollutants. Fundamental Properties of Major Two-Dimensional Nanomaterial Classes are listed in table 1.

Table 1. Fundamental Properties of Major Two-Dimensional Nanomaterial Classes

Material Class	Typical Examples	Electronic Property	Key Advantage	Applications
Graphene	Graphene, GO, rGO	Semimetal	High electrical conductivity	Gas sensing, biosensors
TMDs	MoS_2, WS_2, $MoSe_2$	Semiconductor	Tunable bandgap	Photodetectors, FET sensors
MXenes	$Ti_3C_2T_x$, Nb_2C	Metallic	High conductivity, hydrophilic surface	Gas sensors, electrochemical sensors
Xenes	Black phosphorus, silicene	Semiconductor	High carrier mobility	Optoelectronic sensors
MOFs / COFs	ZIF-8, HKUST-1	Porous frameworks	Extremely high surface area	Chemical sensing

A comparative evaluation of existing studies indicates that graphene-based sensors provide high conductivity but limited selectivity due to zero bandgap characteristics. In contrast, transition metal dichalcogenides enable stronger signal modulation but may suffer from lower carrier mobility. MXenes demonstrate excellent electrochemical performance owing to surface functional groups, although stability remains a concern under ambient conditions [42]. Porous frameworks offer high selectivity but face challenges in electrical signal transduction. These trade-offs highlight the necessity of hybrid material systems to balance sensitivity, selectivity, and stability.

3. Advanced Synthesis and Fabrication Strategies of Two-Dimensional Nanomaterials

The performance of sensors based on two-dimensional (2D) nanomaterials is strongly influenced by the synthesis routes used to produce the active materials. Structural quality, crystallinity, thickness uniformity, surface chemistry, and defect density all play critical roles in determining the sensitivity, selectivity, response time, and long-term stability of sensing devices. Consequently, the synthesis and fabrication strategies used to obtain two-dimensional materials are of central importance in the development of next-generation sensing technologies. Over the past two decades, significant progress has been made in developing various methods to synthesize atomically thin materials with controlled structures and properties. In general, the preparation of 2D nanomaterials can be categorized into two major approaches: top-down methods and bottom-up methods. Top-down approaches involve the exfoliation or delamination of layered bulk crystals into ultrathin nanosheets by mechanical, chemical, or electrochemical processes [11]. These techniques are often relatively simple and can produce high-quality materials when appropriate conditions are employed. In contrast, bottom-up approaches rely on the direct growth or assembly of materials from atomic or molecular precursors. These methods typically offer better control over crystal size, layer number, and large-area film formation, which is particularly important for electronic sensor fabrication.

Beyond the initial synthesis, additional fabrication processes such as surface functionalization, heterostructure engineering, and device integration are often necessary to optimize the sensing performance of 2D materials [43]. These strategies allow researchers to tailor the electronic properties and surface reactivity of the materials to enhance analyte adsorption and signal transduction. Therefore, understanding the advantages, limitations, and mechanisms of different synthesis techniques is crucial for designing high-performance sensors based on two-dimensional nanomaterials.

3.1 Top-Down Exfoliation Strategies

Top-down exfoliation approaches are the most commonly used technique to prepare two-dimensional (2D) nanomaterials, as listed in table 2. These strategies are based on the separation of atomically thin layers from bulk layered crystals, which integrally possess strong in-plane covalent bonds and relatively weak interlayer van der Waals forces. The anisotropic bonding nature of such materials triggers individual layers to be isolated through external mechanical, chemical, or electrochemical stimuli without any particular fundamental lattice structure within each layer. As a result, top-down techniques allow the production of ultrathin nanosheets that largely preserve the intrinsic physicochemical properties of their parent materials, including high carrier mobility, unique electronic structures, and large specific surface areas [44]. A key advantage of top-down methods lies in their conceptual simplicity and flexibility. Since many naturally occurring or synthetically produced layered compounds, such as graphite, transition metal dichalcogenides (TMDs), and certain MAX phases already exhibit weak interlayer bonding, they can serve as suitable precursors for exfoliation processes. By applying mechanical force, ultrasonic energy, or electrochemical intercalation, it becomes possible to overcome the weak van der Waals interactions that hold the layers together. Consequently, large quantities of nanosheets can be generated from bulk materials without requiring complex chemical reactions or sophisticated equipment. These characteristics have made top-down exfoliation strategies particularly attractive for exploratory research and laboratory-scale production of two-dimensional materials.

Another important advantage of these techniques is their ability to produce nanosheets that retain the crystallographic structure and chemical composition of the original bulk material [45]. In many cases, the exfoliation process introduces relatively few structural defects compared with certain chemical synthesis routes, thereby preserving desirable electronic and optical properties. This aspect is especially valuable for sensing applications, as the performance of devices often depends strongly on the electrical conductivity and surface reactivity of the sensing layer. Despite these benefits, top-down exfoliation methods also present several challenges that limit their widespread implementation in large-scale industrial applications. Achieving precise control over the thickness, lateral dimensions, and structural uniformity of exfoliated nanosheets remains a significant difficulty [46]. The exfoliation process often produces a heterogeneous mixture of monolayer, few-layer, and multilayer sheets with varying sizes, which may require additional separation or purification steps. Furthermore, certain exfoliation techniques, particularly those involving strong mechanical forces or prolonged ultrasonication, can introduce structural defects, edge damage, or chemical impurities that may influence the electronic properties of the resulting materials.

Scalability is another critical issue related to many top-down synthesis strategies [47]. While some methods are capable of producing large quantities of nanosheets, maintaining consistent quality and uniformity when the large-scale production remains challenging. In practical sensor fabrication, reproducibility and batch-to-batch consistency are essential factors that determine device reliability. Therefore, ongoing research efforts are focused on improving exfoliation efficiency, developing more controlled delamination techniques, and optimizing processing conditions to produce high-quality nanosheets with minimal defects. Overall, top-down exfoliation strategies continue to play a fundamental role in the preparation of two-dimensional nanomaterials. Their relatively straightforward processing, compatibility with a wide range of layered materials, and ability to preserve intrinsic crystal properties make them indispensable tools in both fundamental research and applied materials engineering.

Table 2. Major Top-Down Exfoliation Methods for the Preparation of Two-Dimensional Nanomaterials

Exfoliation Method	Principle	Typical Materials	Key Advantages	Limitations	Sensor-Relevant Features
Mechanical Exfoliation	Physical peeling of layers from bulk crystals using adhesive tape or mechanical force	Graphene, MoS_2, WS_2	Produces extremely high-quality single crystals with minimal defects	Very low yield, poor scalability, small flake size	Ideal for fundamental studies and prototype sensor devices
Liquid-Phase Exfoliation	Ultrasonic energy separates layers in suitable solvents or surfactant solutions	Graphene, TMDs, MXenes	Scalable, low-cost, compatible with solution processing	Broad thickness distribution, possible defect generation	Enables printable sensor inks and flexible devices
Electrochemical Exfoliation	Ion intercalation between layers under applied voltage weakens interlayer forces	Graphene, MoS_2, graphite derivatives	Rapid production, tunable process conditions	Requires electrolyte control and electrochemical setup	Produces functionalized nanosheets suitable for electrochemical sensors
Chemical Intercalation Exfoliation	Intercalation of chemical species (e.g., Li^+, alkali metals) expands layers followed by delamination	Graphene, TMDs	High exfoliation efficiency, large nanosheets	Chemical residues and structural damage possible	Creates active defect sites beneficial for sensing
Ball-Milling Assisted Exfoliation	Mechanical grinding induces shear forces that separate layered structures	Graphite, layered oxides	Simple equipment and scalable production	Structural defects and contamination	Suitable for catalytic and gas sensing materials

Continued advancements in exfoliation technologies are expected to further enhance the scalability, structural control, and reproducibility of these methods, thereby supporting the development of high-performance 2D material–based sensing devices. Table 3 compare the synthesis Techniques for Two-Dimensional Nanomaterials

3.1.1 Mechanical Exfoliation

Mechanical exfoliation represents the earliest and simplest technique used to isolate two-dimensional materials. This method gained widespread attention following the successful isolation of graphene from graphite through the use of adhesive tape. In a typical process, layers are repeatedly peeled from a bulk crystal and transferred onto a suitable substrate such as silicon dioxide or mica. With careful manipulation, it is possible to obtain monolayer or few-layer nanosheets with extremely high crystalline quality. One of the major advantages of mechanical exfoliation is that it produces materials with minimal structural defects and excellent electronic properties [48]. Because the process does not involve harsh chemical reactions or high temperatures, the resulting nanosheets closely resemble ideal single crystals. For this reason, mechanically exfoliated samples are frequently used in fundamental studies aimed at investigating the intrinsic physical properties of two-dimensional materials, including charge transport behaviour and optical characteristics.

Despite these advantages, mechanical exfoliation has significant limitations that restrict its practical applications. The process is labor-intensive, difficult to reproduce consistently, and incapable of producing large quantities of material [49]. Furthermore, the lateral dimensions of exfoliated flakes are typically limited to micrometer-scale sizes, which makes device fabrication challenging. As a result, mechanical exfoliation is primarily used for laboratory-scale research rather than industrial production of sensing devices.

3.1.2 Liquid-Phase Exfoliation

Liquid-phase exfoliation has emerged as one of the most versatile and scalable approaches for producing two-dimensional nanosheets in large quantities [50]. In this method, bulk layered materials are dispersed in an appropriate solvent and subjected to ultrasonic agitation. The ultrasonic waves generate cavitation bubbles that collapse violently within the liquid, producing localized shear forces capable of separating adjacent layers of the material. The efficiency of liquid-phase exfoliation is strongly influenced by the choice of solvent. Ideally, the surface energy of the solvent should closely match that of the layered material to minimize the energy required for exfoliation and to prevent restacking of the nanosheets. Solvents such as N-methyl-2-pyrrolidone (NMP), dimethylformamide (DMF), and certain aqueous surfactant solutions have been widely used for this purpose [51]. One of the key advantages of liquid-phase exfoliation is that it produces stable dispersions of nanosheets that can be processed using solution-based fabrication techniques. For example, these dispersions can be deposited onto substrates through spin coating, spray coating, or inkjet printing, enabling the development of low-cost and flexible sensor devices. However, the intense mechanical forces involved in the exfoliation process can introduce structural defects and produce nanosheets with varying thicknesses and lateral dimensions. Therefore, additional separation techniques such as centrifugation are often required to obtain uniform nanosheets.

3.1.3 Electrochemical Exfoliation

Electrochemical exfoliation has emerged as a highly efficient and scalable strategy for the synthesis of high-quality two-dimensional nanomaterials. This technique utilizes electrochemical reactions to induce the delamination of layered bulk crystals, offering a rapid and controllable alternative to conventional mechanical and liquid-phase exfoliation methods. In a typical electrochemical exfoliation process, a bulk layered material such as graphite or a transition metal dichalcogenide is employed as the working electrode in an electrochemical cell containing an appropriate electrolyte solution [46]. Upon application of an external electrical potential, electrolyte ions migrate toward the electrode surface and subsequently intercalate into the interlayer galleries of the layered crystal.

The intercalation of ions between adjacent layers significantly weakens the van der Waals forces that normally maintain the structural integrity of the layered material. As the electrochemical process continues, several concurrent phenomena contribute to the exfoliation mechanism. First, the insertion of ions increases the interlayer spacing, thereby reducing the cohesive interactions between layers. Second, electrochemical reactions occurring at the electrode surface often generate gaseous species such as oxygen or hydrogen. The evolution of these gases within the interlayer spaces creates additional mechanical pressure, which further promotes layer separation. Additionally, electrostatic repulsion between charged layers induced by the applied potential facilitates the progressive delamination of the material into ultrathin nanosheets [52].

Compared with traditional exfoliation techniques, electrochemical exfoliation offers several significant advantages. One of the most notable benefits is the relatively high production rate, as the process can generate large quantities of nanosheets within a short period of time. Furthermore, the electrochemical parameters such as applied voltage, current density, electrolyte composition, and reaction duration can be precisely tuned to regulate the exfoliation efficiency, nanosheet thickness, and degree of surface functionalization [46]. This level of control enables researchers to tailor the structural and chemical characteristics of the resulting two-dimensional materials according to the requirements of specific sensing applications.

Another important aspect of electrochemical exfoliation is the possibility of introducing functional surface groups during the exfoliation process. Depending on the electrolyte system used, various oxygen-containing or other functional moieties can be incorporated onto the nanosheet surfaces [53]. These functional groups enhance the hydrophilicity and chemical reactivity of the materials, thereby improving their interaction with target analyte molecules. Such surface modifications are particularly advantageous for sensing platforms, where strong adsorption of analytes and efficient charge transfer are essential for achieving high sensitivity. As a result of these advantages, electrochemically exfoliated two-dimensional materials have demonstrated considerable potential in the development of advanced sensing devices, including electrochemical sensors, gas sensors, and biosensors. The combination of scalable production, controllable surface chemistry, and preserved electronic properties makes electrochemical exfoliation a promising technique for the large-scale fabrication of functional nanomaterials suitable for next-generation sensing technologies.

3.2 Bottom-Up Growth Strategies

While top-down approaches rely on separating layers from existing bulk materials, bottom-up methods involve constructing two-dimensional materials from atomic or molecular building blocks. These techniques typically provide greater control over crystal growth, layer number, and large-area film formation, which are essential characteristics for the fabrication of electronic sensing devices.

3.2.1 Chemical Vapor Deposition

Chemical vapor deposition (CVD) is one of the most widely used bottom-up techniques for synthesizing high-quality two-dimensional materials. In this process, gaseous precursor molecules are introduced into a reaction chamber containing a heated substrate. The precursor molecules undergo thermal decomposition or chemical reactions on the substrate surface, leading to the formation of thin crystalline films. CVD has been successfully employed to produce large-area graphene films on metal substrates such as copper and nickel. The method has also been widely used for synthesizing transition metal dichalcogenides, including MoS_2, WS_2, and WSe_2 [54]. By carefully controlling the growth conditions such as temperature, gas flow rate, and precursor concentration, it is possible to achieve precise control over film thickness and crystal morphology. The ability of CVD to produce wafer-scale films with high crystallinity makes it particularly attractive for the fabrication of electronic and optoelectronic sensor devices. However, the technique requires sophisticated equipment and high-temperature processing conditions, which can increase production costs and limit its accessibility.

3.2.2 Hydrothermal and Solvothermal Synthesis

Hydrothermal and solvothermal synthesis methods represent solution-based approaches that have been widely used for preparing various two-dimensional nanomaterials [55]. In these processes, precursor materials are dissolved in a solvent and sealed within a high-pressure autoclave. The reaction mixture is then heated to elevated temperatures, which promotes crystal nucleation and growth. These methods offer several advantages, including relatively low equipment costs and the ability to control material morphology by adjusting reaction parameters such as temperature, pressure, and precursor concentration. Hydrothermal synthesis has been particularly effective for producing nanosheets of transition metal dichalcogenides and metal oxide materials. Another advantage of these techniques is their compatibility with doping and heterostructure formation. By introducing additional precursor species during the synthesis process, researchers can modify the electronic structure of the resulting materials to improve sensing performance.

3.2.3 Molecular Self-Assembly

Molecular self-assembly represents an important bottom-up strategy for constructing two-dimensional porous frameworks such as metal–organic frameworks (MOFs) and covalent organic frameworks (COFs) [56]. In these systems, metal ions or organic molecules spontaneously organize into ordered structures through coordination interactions or covalent bonding. This approach enables precise control over pore size, structural topology, and chemical functionality. As a result, MOF and COF nanosheets can be designed to selectively adsorb specific molecules based on their size or chemical properties. Such selectivity is highly advantageous for chemical sensing applications.

3.3 Surface Engineering and Functionalization

Although the intrinsic properties of two-dimensional materials play a crucial role in determining sensing performance, surface engineering strategies are often required to enhance analyte interactions further. Functionalization techniques can introduce catalytic nanoparticles, polymer coatings, or biomolecular recognition elements onto the surface of 2D nanosheets [57]. For instance, noble metal nanoparticles such as gold, platinum, or palladium are frequently deposited onto graphene or transition metal dichalcogenides to enhance catalytic activity and facilitate charge transfer. Similarly, biomolecules such as antibodies, enzymes, or DNA strands can be immobilized on the surface of nanosheets to create highly selective biosensors. Another widely used approach is defect engineering, which involves deliberately introducing structural defects such as vacancies or dopant atoms. These defects can create additional active sites for analyte adsorption and significantly modify the material's electronic properties.

3.4 Device Fabrication and Sensor Integration

The final step in developing practical sensing devices involves integrating synthesized two-dimensional materials into functional device architectures. Various deposition techniques, including spin coating, spray deposition, inkjet printing, and layer-by-layer assembly, have been used to fabricate sensor films [58]. Printed electronics technologies are particularly promising for large-scale sensor production because they enable the fabrication of flexible and wearable devices at relatively low cost. In addition, the development of 2D material heterostructures, in which multiple nanosheets are stacked together, has opened new possibilities for enhancing sensing performance through synergistic interactions between different materials. Figure 2 displays Device Fabrication and Sensor Integration of Two-Dimensional MoS_2/WSe_2 Heterostructure-Based Sensor.

Table 3. Comparison of Synthesis Techniques for Two-Dimensional Nanomaterials

Method	Principle	Advantages	Limitations
Mechanical exfoliation	Peeling layers from bulk crystals	High crystal quality	Not scalable
Liquid-phase exfoliation	Ultrasonic delamination in solvent	Scalable, solution-processable	Defects and thickness variation
Electrochemical exfoliation	Ion intercalation between layers	Rapid production	Requires electrolyte control
Chemical vapor deposition	Vapor-phase growth on a heated substrate	Large-area high-quality films	Expensive equipment
Hydrothermal synthesis	High-pressure solution growth	Controlled morphology	Limited film size
Molecular self-assembly	Coordination-driven assembly	Tunable porous structures	Complex synthesis

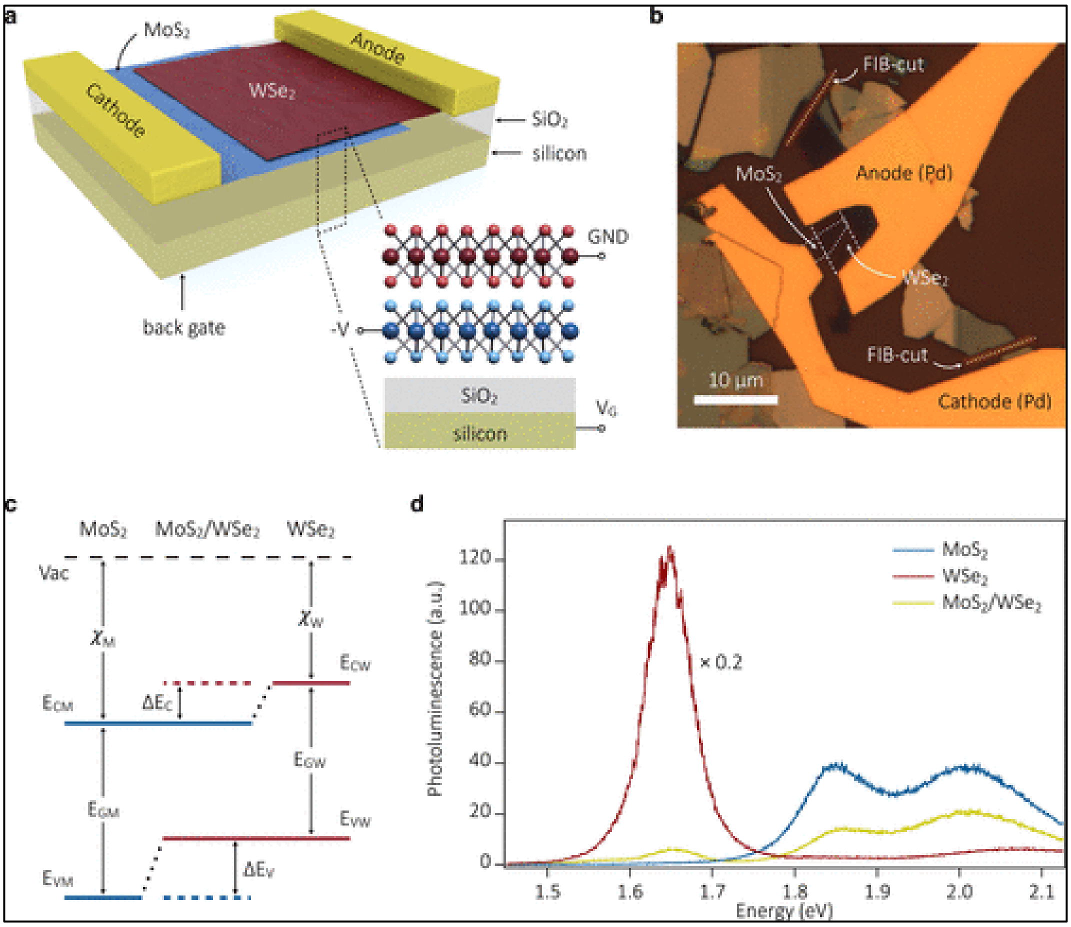

Figure 2. Device Fabrication and Sensor Integration of Two-Dimensional MoS_2/WSe_2 Heterostructure-Based Sensor [59]

4. Structural and Surface Engineering of Two-Dimensional Nanomaterials for Advanced Sensing Platforms

The sensing performance of two-dimensional (2D) nanomaterials is fundamentally governed by their structural configuration, electronic band structure, and surface chemistry. Unlike bulk materials, atomically thin 2D crystals have a high fraction of surface atoms, making their electronic states highly sensitive to perturbations from adsorbed molecules or environmental changes. Consequently, structural and surface engineering strategies have emerged as critical tools for tailoring the physicochemical properties of 2D materials to achieve highly sensitive, selective, and stable sensing platforms. In pristine form, many 2D materials exhibit limited sensing performance due to insufficient active adsorption sites, weak analyte binding energies, or inadequate charge transfer interactions. Therefore, rational modification of the material structure at the atomic, nanoscale, and mesoscale levels is required to optimize sensor response characteristics. Advanced engineering approaches such as defect engineering, heterostructure design, surface functionalization, phase engineering, and strain modulation enable fine control over carrier density, band alignment, catalytic activity, and adsorption energetics [60].

Structural engineering typically focuses on manipulating the lattice architecture of 2D materials by intentionally introducing vacancies, dopant atoms, edge defects, or structural distortions. These modifications create localized electronic states that enhance the adsorption and activation of target analytes. Meanwhile, surface engineering strategies involve chemical modification of the exposed basal plane or edge sites using functional groups, biomolecules, nanoparticles, or catalytic species [61]. Such surface modifications significantly improve selectivity toward specific molecules, including biomarkers, toxic gases, heavy metals, and organic pollutants. Another promising strategy involves constructing van der Waals heterostructures, where multiple 2D materials are stacked or integrated to create new electronic interfaces with tunable band alignment [62]. Structural Engineering Strategies for Enhancing 2D Material Sensor Performance are listed in table 4

Table 4. Structural Engineering Strategies for Enhancing 2D Material Sensor Performance

S.No	Material System	Engineering Strategy	Synthesis Technique	Target Analyte / Application	Detection Limit	Sensitivity / Performance	Operating Condition	Key Performance Improvement	Ref.
1	Graphene-based electrodes	Surface functionalization	Chemical exfoliation	Environmental pollutants	ppb (typical)	High electrochemical sensitivity	Room temp	Large surface area, fast electron transfer	[63]
2	P3HT/ZnO nanorods OTFT	Hybrid composite	Solution + nanorod growth	NO_2 gas	—	Sensitivity ↑ 40.2%	Ambient	Improved charge mobility & Vth modulation	[64]
3	HPLC-CD system	Signal enhancement strategy	Multiplexing technique	Chiral compounds	—	S/N ↑ ~10×	Lab conditions	Improved analytical sensitivity	[65]
4	MoS_2/WSe_2 heterostructure	van der Waals heterojunction	Layer stacking	Optoelectronics / sensing potential	—	Tunable charge transport	Electrical bias	Enhanced carrier separation	[66]
5	Ti_3C_2Tx MXene electrode	Nanoarchitectonics	HCl + LiF etching	Energy storage (indirect sensing relevance)	—	299 F/g capacitance	Electrochemical	High conductivity & ion transport	[67]
6	Atomic-layer MoS_2	Charge-transfer sensing	CVD growth	NO_2, NH_3	ppb-level	High selectivity	Room temp	Strong adsorption & PL mechanism	[68]
7	N-doped rGO	Heteroatom doping	Hydrothermal	NO gas	~400 ppb	Sensitivity 1.7 (>> rGO)	Room temp	Enhanced active sites & conductivity	[69]
8	MXene composites	Surface termination tuning	Etching + compositing	Gas sensing (flexible devices)	ppb–ppm	High sensitivity & flexibility	Room temp	Tunable surface groups & conductivity	[70]
9	Few-layer MoS_2 transistor	Thickness engineering	Mechanical exfoliation	NO_2, NH_3, humidity	—	High sensitivity & recovery	Gate/light-assisted	Bandgap tuning improves sensing	[71]
10	Graphene Quantum Dots (GQDs)	Surface/edge modification	Bottom-up/top-down	Biomolecules	nM–μM	Strong fluorescence response	Aqueous	High stability & optical tunability	[72]
11	Pt-decorated MoS_2 nanosheets	Noble metal decoration	Hydrothermal + ALD	Catalysis (HER, sensing relevance)	—	Low overpotential (31 mV)	Electrochemical	Activated basal planes	[73]
12	MoS_2 layered transistor	Layer-dependent tuning	Exfoliation	Gas sensing	—	Improved sensitivity (few-layer > monolayer)	Bias/light	Optimized carrier transport	[74]
13	MXene/DNA/Pd/Pt nanocomposite	Bio-template + metal NP	In-situ growth	Dopamine	30 nM	Wide linear range	Electrochemical	High electrocatalytic activity	[75]
14	MoS_2/WSe_2 heterojunction	Photovoltaic effect tuning	Layer stacking	Photodetection/sensing	—	High EQE (~55%)	Light-assisted	Efficient charge separation	[60]
15	Strained MoS_2	Strain engineering	Mechanical strain	Optoelectronic sensing	—	Bandgap shift ~70 meV/% strain	Flexible substrate	Tunable electronic structure	[76]

These heterostructures facilitate efficient charge separation and interfacial electron transfer, thereby amplifying sensor signals. Additionally, emerging approaches such as strain engineering and phase modulation further expand the design space for next-generation sensing materials by modifying electronic band structures and catalytic properties. The integration of these structural and surface engineering techniques enables the development of multifunctional sensing architectures with enhanced detection limits, rapid response times, and improved environmental stability. The following subsections discuss the major engineering strategies employed to optimize the sensing performance of 2D nanomaterials.

4.1 Defect Engineering for Enhanced Sensitivity

Defect engineering has emerged as one of the most powerful approaches for improving the sensing performance of two-dimensional nanomaterials. In atomically thin materials, even a small concentration of structural defects can dramatically influence electronic properties, adsorption energetics, and charge transport characteristics. Defects introduce localized electronic states within the band structure, which can act as highly reactive sites for molecular adsorption and charge transfer interactions with analytes [77]. In pristine graphene, for example, the chemically inert basal plane limits strong interaction with gas molecules. However, the introduction of vacancy defects, Stone–Wales defects, or heteroatom dopants significantly enhances adsorption affinity and charge transfer processes. Similarly, defect creation in transition metal dichalcogenides (TMDs) such as MoS_2 or WS_2 generates sulfur vacancies that act as catalytically active sites capable of interacting strongly with gas molecules, including NO_2, NH_3, and CO.

4.1.1 Several Types of Defects Can Be Intentionally Introduced Into 2D Materials

Vacancy defects are among the most commonly engineered structural modifications. These defects arise when atoms are removed from the lattice during synthesis or post-treatment processes. In MoS_2, sulfur vacancies create localized mid-gap states that facilitate electron donation or withdrawal upon analyte adsorption, thereby modulating the electrical conductivity of the sensing layer [78]. Substitutional doping involves replacing host atoms with foreign elements that possess different electronegativity or valence states. For example, nitrogen-doped graphene introduces electron-rich sites that enhance interactions with electron-acceptor molecules such as NO_2 [79]. Similarly, transition metal doping in TMDs can improve catalytic activity and charge transfer efficiency, which significantly enhances electrochemical sensor performance.

Edge defects are another important category of structural imperfections. Because the edges of 2D materials contain unsaturated bonds and dangling orbitals, they serve as highly reactive adsorption sites. Increasing the density of edge sites through nanostructuring or exfoliation processes can therefore substantially enhance sensor response. Advanced fabrication methods have been developed to precisely control defect concentration in 2D materials. Techniques such as plasma treatment, ion irradiation, thermal annealing, and chemical etching enable controlled creation of defects without significantly damaging the overall lattice structure. For instance, oxygen plasma treatment has been widely used to introduce vacancies in graphene and TMDs for gas-sensing applications [80]. From a sensing perspective, defect engineering enhances performance through several mechanisms. First, defects increase the density of adsorption sites, thereby improving analyte capture efficiency. Second, defect-induced electronic states facilitate stronger charge-transfer interactions between the analyte and the sensing layer. Third, defects often reduce activation barriers for surface reactions, enabling faster response and recovery times. However, excessive defect concentrations may lead to undesirable effects such as increased noise, structural instability, or reduced carrier mobility. Therefore, optimizing defect density is essential to achieve the best trade-off between sensitivity and electronic transport properties. Recent studies have demonstrated that defect-engineered 2D materials can achieve detection limits in the parts-per-billion (ppb) or even parts-per-trillion (ppt) range, highlighting their potential for next-generation chemical and biological sensing platforms [81, 82].

4.2 Heterostructure Engineering and van der Waals Interfaces

Heterostructure engineering represents another transformative strategy for improving the sensing performance of two-dimensional materials. In this approach, multiple atomically thin materials are combined to form van der Waals heterostructures, where individual layers interact through weak interlayer forces without requiring lattice matching. This unique architecture allows the integration of materials with distinct electronic, optical, and catalytic properties into a single functional system. The formation of heterostructures introduces new electronic interfaces that can significantly modify charge-transport pathways and energy-band alignment [83]. These interfacial effects often lead to enhanced charge separation, increased carrier mobility, and improved sensitivity toward target analytes. One widely studied example is the graphene–MoS_2 heterostructure, in which graphene serves as a highly conductive charge-transport layer, while MoS_2 provides strong adsorption sites for gas molecules. When analyte molecules adsorb onto the MoS_2 surface, charge transfer occurs across the heterointerface and is efficiently transported through the graphene layer, resulting in amplified electrical signals.

Similarly, MXene–TMD heterostructures have shown exceptional performance in electrochemical sensing. MXenes possess metallic conductivity and abundant surface functional groups, while TMDs provide catalytically active sites for redox reactions [84]. The combination of these materials enhances electron transfer kinetics and increases electrochemical sensitivity. Another promising class of heterostructures comprises MOF/COF–2D material composites, in which porous crystalline frameworks are integrated with conductive 2D nanosheets. In such architectures, MOFs or COFs function as molecular sieves that selectively capture analytes, whereas the 2D material serves as the signal-transduction layer.

4.2.1 Heterostructures Can Be Fabricated Using Several Techniques

1. Layer-by-layer stacking.
2. Chemical vapor deposition growth.
3. Solution-phase self-assembly.
4. Electrostatic layer deposition.

These methods enable precise control over interface quality, layer thickness, and structural orientation.

The sensing advantages of heterostructures arise from multiple synergistic effects. First, heterointerfaces create built-in electric fields that promote efficient charge separation. Second, band alignment between different materials can facilitate directional electron transfer upon analyte adsorption. Third, heterostructures often exhibit enhanced catalytic activity due to interfacial electronic coupling. Additionally, heterostructures can enhance sensor selectivity by combining materials with complementary adsorption affinities. For example, graphene provides a rapid electrical response while TMDs or metal oxides selectively interact with specific gas molecules [85]. Recent advances in nanoscale characterization techniques, such as scanning tunneling microscopy and Kelvin probe force microscopy, have provided deeper insights into the electronic properties of heterostructure interfaces, enabling rational design of high-performance sensing platforms.

4.3 Surface Functionalization for Selective Detection

While defect engineering and heterostructure design primarily enhance sensitivity, surface functionalization plays a crucial role in improving sensor selectivity toward specific analytes. Surface functionalization involves modifying the exposed surface of 2D materials with chemical groups, nanoparticles, polymers, enzymes, antibodies, or other molecular recognition elements. The large surface-to-volume ratio of 2D materials makes them particularly suitable for surface functionalization. Nearly every atom in these materials is exposed to the surrounding environment, enabling efficient interaction with functional molecules and target analytes. Chemical functionalization can occur through covalent or non-covalent interactions. Covalent functionalization involves forming strong chemical bonds between functional groups and the 2D material surface. For example, graphene can be functionalized with carboxyl, hydroxyl, or amine groups through oxidation reactions, creating active sites for biomolecule immobilization [86].

Non-covalent functionalization, on the other hand, relies on weaker interactions such as π–π stacking, van der Waals forces, or electrostatic attraction. This approach preserves the intrinsic electronic properties of the 2D material while enabling attachment of functional molecules [87]. In biosensing applications, 2D materials are often functionalized with enzymes, antibodies, or DNA probes to enable selective detection of biomarkers such as glucose, cancer markers, or pathogenic microorganisms. For example, graphene oxide functionalized with glucose oxidase has been widely used in electrochemical glucose sensors due to its high electron transfer efficiency and strong enzyme immobilization capability.

Metal nanoparticles such as Au, Pt, or Pd are frequently deposited onto 2D materials to enhance catalytic activity and signal amplification [88]. These nanoparticles provide additional adsorption sites and facilitate rapid electron transfer during electrochemical sensing reactions. Polymer functionalization is another effective strategy for improving sensor stability and selectivity. Conducting polymers such as polyaniline or polypyrrole can be integrated with 2D materials to create hybrid sensing layers with improved environmental stability and mechanical flexibility. Surface functionalization also plays a crucial role in environmental sensing, where selective detection of pollutants such as heavy metal ions, pesticides, or volatile organic compounds is required. Functional groups can be designed to specifically bind target molecules, thereby minimizing interference from other species. However, excessive functionalization may block active sites or disrupt charge transport pathways, reducing sensor sensitivity. Therefore, careful optimization of functionalization density is essential to maintain a balance between selectivity and electronic conductivity.

5. Fundamental Sensing Mechanisms of Two-Dimensional Nanomaterial-Based Sensors

The exceptional sensing performance of two-dimensional (2D) nanomaterials arises from their unique electronic structure, atomic thickness, and high surface-to-volume ratio, which collectively enable strong interactions with adsorbed analyte molecules. Unlike conventional bulk sensing materials, atomically thin nanostructures expose a large proportion of surface atoms directly to the environment, allowing even subtle molecular adsorption events to induce pronounced changes in electrical, electrochemical, or optical properties. Consequently, 2D materials have emerged as powerful transduction platforms capable of converting molecular recognition events into measurable signals with extremely high sensitivity.

The fundamental sensing mechanisms of 2D material-based sensors rely on the modulation of physical or chemical properties of the sensing layer upon interaction with target analytes. These mechanisms generally involve charge transfer processes, modulation of carrier density, alteration of surface potential, catalytic redox reactions, or optical signal amplification. Because the electronic states of atomically thin materials are highly sensitive to external perturbations, even minute interactions between analytes and the sensing surface can produce measurable variations in conductivity, electrochemical current, or optical intensity [89]. Among the various sensing strategies, field-effect transistor (FET)-based sensors, electrochemical sensors, and optical sensors represent the most extensively investigated transduction platforms for 2D nanomaterials. Each sensing approach exploits distinct physical principles but benefits from the intrinsic advantages of 2D materials, including high carrier mobility, tunable band structures, and abundant surface adsorption sites. Structural and Surface Engineering Strategies for 2D Material Sensors listed in table 5.

Table 5. Structural and Surface Engineering Strategies for 2D Material Sensors

Engineering Strategy	**Modification Type**	**Key Advantages**	**Typical Materials**	**Representative Applications**
Defect Engineering	Vacancies, dopants, edge defects	Increased adsorption sites and charge transfer	Graphene, MoS_2, WS_2	Gas sensing, chemical detection
Heterostructure Engineering	van der Waals layered interfaces	Enhanced charge separation and signal amplification	Graphene/MoS_2, MXene/TMD	Electrochemical and gas sensors
Surface Functionalization	Chemical groups, biomolecules, nanoparticles	Improved analyte selectivity	Graphene oxide, MXenes	Biosensors and environmental sensors
Phase Engineering	Crystal phase modulation	Improved catalytic activity	MoS_2 (1T/2H phases)	Electrochemical sensing
Strain Engineering	Mechanical deformation	Tunable band structure	TMDs, graphene	Flexible wearable sensors

In electrical sensing devices such as FET sensors, adsorption of analyte molecules onto the 2D material surface induces charge transfer or dipole interactions that modulate the carrier concentration within the conductive channel [90]. This process results in measurable changes in electrical conductivity or threshold voltage. Electrochemical sensors, on the other hand, rely on redox reactions occurring at the interface between the analyte and the sensing electrode.

The high conductivity and catalytic activity of many 2D materials significantly accelerate electron transfer kinetics, leading to enhanced electrochemical signals. Optical sensing techniques provide another powerful detection platform by exploiting light–matter interactions in 2D materials. Methods such as surface-enhanced Raman scattering (SERS), photoluminescence modulation, and surface plasmon resonance (SPR) enable ultra-sensitive detection by amplifying optical signals generated by adsorbed molecules [91, 92]. The integration of plasmonic nanoparticles with 2D materials further enhances electromagnetic fields near the sensing surface, dramatically improving optical detection limits. Understanding these fundamental sensing mechanisms is essential for designing high-performance sensors with optimized sensitivity, selectivity, response time, and operational stability. The following subsections discuss the major sensing transduction mechanisms employed in 2D nanomaterial-based sensors.

5.1 Field-Effect Transistor (FET)-Based Sensing Mechanisms

Field-effect transistor (FET) sensors represent one of the most powerful electronic sensing platforms utilizing two-dimensional nanomaterials. In these devices, the 2D material acts as the conductive channel connecting the source and drain electrodes, while the gate electrode modulates the carrier concentration within the channel. Because the conductive channel consists of an atomically thin material, any adsorption of analyte molecules on its surface can strongly influence its electronic properties. The sensing principle of FET devices is based on the modulation of carrier density and surface potential caused by analyte adsorption [93]. When molecules interact with the 2D material surface, charge transfer occurs between the analyte and the sensing layer. Depending on the electron-donating or electron-withdrawing nature of the molecule, this interaction can either increase or decrease the carrier concentration within the channel.

For example, adsorption of electron-withdrawing molecules such as NO_2 on graphene or MoS_2 surfaces results in p-type doping, where electrons are withdrawn from the channel, leading to increased hole concentration [94]. Conversely, electron-donating molecules such as NH_3 induce n-type doping, increasing electron density in the channel. These changes in carrier concentration directly affect the electrical conductivity of the device and can be detected as variations in drain current or threshold voltage. Two-dimensional materials provide several advantages for FET sensing compared with traditional semiconductor materials. First, the atomically thin nature of 2D materials ensures that the entire channel is exposed to the environment, enabling extremely efficient analyte interaction.

Second, many 2D materials exhibit exceptionally high carrier mobility, allowing rapid signal transduction and fast response times. Third, the band structures of 2D materials can be tuned through doping, strain engineering, or heterostructure formation, enabling precise control over sensor sensitivity. Among the various 2D materials investigated for FET sensors, graphene, MoS_2, WS_2, black phosphorus, and MXenes have demonstrated remarkable performance. Graphene-based FET sensors are particularly attractive due to their high conductivity and low electrical noise, enabling detection of analytes at extremely low concentrations. However, the absence of an intrinsic bandgap in graphene can limit its sensitivity in certain applications [95].

Semiconducting TMDs such as MoS_2 offer an advantage because of their finite bandgap, which enables stronger modulation of channel conductivity upon analyte adsorption. Consequently, MoS_2-based FET sensors have shown exceptional sensitivity for detecting gases, biomolecules, and environmental pollutants. Another important feature of FET-based sensors is their ability to operate in liquid environments, making them highly suitable for biosensing applications [96]. Functionalization of the 2D material surface with antibodies, enzymes, or DNA probes enables selective detection of specific biomolecules, including proteins, nucleic acids, and disease biomarkers.

5.2 Electrochemical Sensing Mechanisms

Electrochemical sensors represent another widely explored platform for 2D nanomaterial-based detection systems. These sensors operate through electrochemical reactions occurring at the interface between the analyte and the sensing electrode, typically involving oxidation–reduction (redox) processes [97]. The resulting changes in electrical current, potential, or impedance serve as measurable signals corresponding to analyte concentration. Two-dimensional nanomaterials offer several unique advantages for electrochemical sensing. Their large surface area provides abundant active sites for analyte adsorption, while their excellent electrical conductivity facilitates rapid electron transfer between the analyte and the electrode surface. Additionally, many 2D materials exhibit intrinsic catalytic activity, further enhancing electrochemical reaction kinetics.

The electrochemical sensing process generally involves three key steps:

1. Adsorption of analyte molecules onto the sensing surface
2. Electron transfer between the analyte and electrode material
3. Generation of measurable electrical signals such as current or potential

Because of their high electrical conductivity and tunable surface chemistry, materials such as graphene, MXenes, and transition metal dichalcogenides have been widely employed in electrochemical sensing applications. MXenes, for example, possess metallic conductivity and abundant surface functional groups such as hydroxyl, oxygen, and fluorine terminations. These surface groups enhance analyte adsorption and provide additional catalytic sites for electrochemical reactions. As a result, MXene-based sensors have demonstrated excellent performance for detecting heavy metal ions, pesticides, and biomolecules [98].

Graphene-based electrochemical sensors are also widely used due to their exceptional electron mobility and chemical stability. When combined with metal nanoparticles such as gold or platinum, graphene-based electrodes exhibit enhanced catalytic activity and signal amplification. Transition metal dichalcogenides such as MoS_2 also show strong catalytic properties for electrochemical reactions. Their layered structure exposes edge sites that serve as highly active catalytic centers for redox processes. Electrochemical sensors based on 2D materials are particularly valuable in biomedical diagnostics, where they can detect biomolecules such as glucose, dopamine, uric acid, and cancer biomarkers with high sensitivity. Their ability to operate in aqueous environments and their compatibility with microfabrication technologies make them ideal for point-of-care diagnostic devices [99].

5.3 Optical Sensing Mechanisms

Optical sensing techniques provide another powerful detection strategy utilizing the unique light–matter interactions of two-dimensional nanomaterials. In optical sensors, analyte detection is achieved by monitoring changes in optical signals such as Raman scattering intensity, photoluminescence emission, or refractive index variations. One of the most widely used optical sensing techniques is surface-enhanced Raman scattering (SERS). In SERS-based sensors, electromagnetic fields generated near plasmonic nanostructures dramatically amplify Raman signals from molecules adsorbed on the sensing surface. When 2D materials such as graphene or MoS_2 are integrated with plasmonic nanoparticles, the resulting hybrid structures exhibit synergistic enhancement effects that significantly improve Raman signal intensity [100].

Graphene, in particular, has been shown to enhance Raman signals through a mechanism known as chemical enhancement, where charge transfer interactions between graphene and the analyte modify the polarizability of molecular vibrations. When combined with plasmonic metals such as gold or silver nanoparticles, graphene-based SERS substrates can achieve detection limits down to the single-molecule level [101]. Schematic Illustration of Evanescent Wave Optical Fiber Sensor for Surface-Based Molecular Detection is shown figure 3 [102].

Another important optical sensing technique is surface plasmon resonance (SPR), which relies on changes in the refractive index near a metal surface when analyte molecules bind to the sensing interface. Integration of 2D materials with SPR sensors improves sensitivity by increasing analyte adsorption efficiency and enhancing electromagnetic field confinement. Photoluminescence-based sensing is also widely explored in semiconducting 2D materials such as MoS_2 and WS_2 [103]. In these materials, adsorption of analyte molecules can modify exciton recombination processes, leading to measurable changes in photoluminescence intensity or wavelength. Optical sensing methods offer several advantages, including label-free detection, real-time monitoring, and ultra-high sensitivity. Furthermore, optical sensors can often detect multiple analytes simultaneously by monitoring spectral signatures. Fundamental Sensing Mechanisms of Two-Dimensional Material-Based Sensors are listed in table 6.

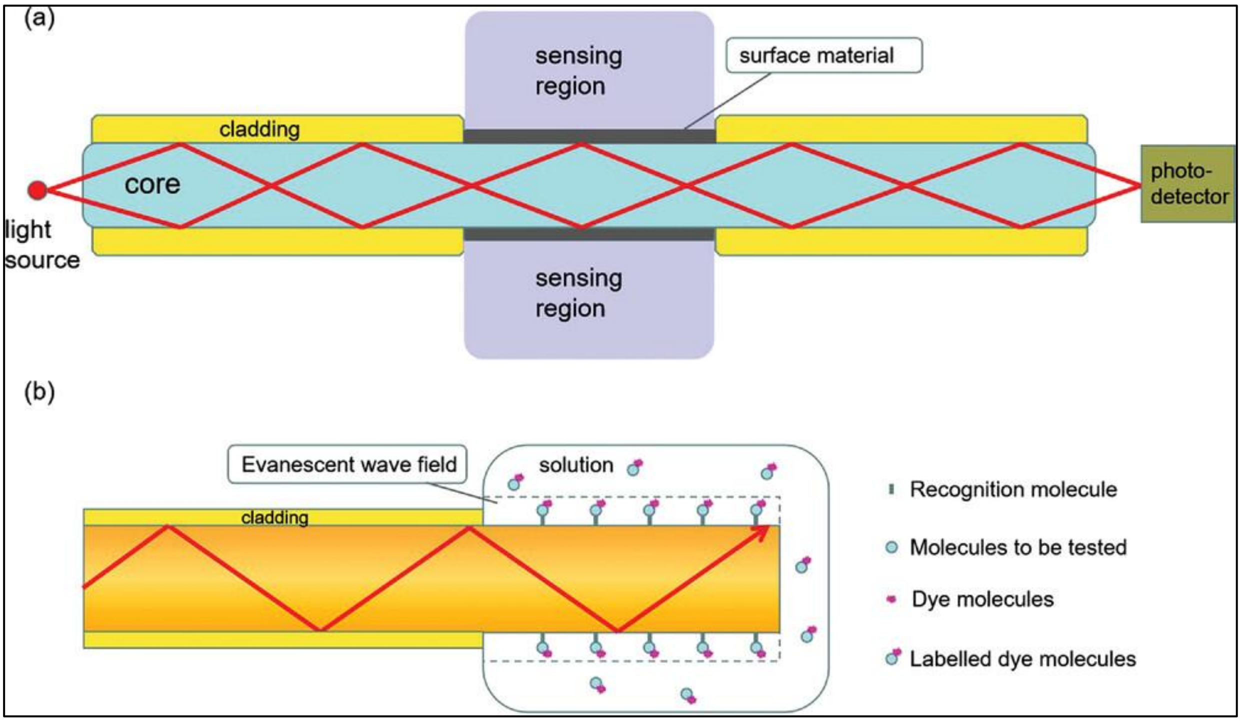

Figure 3. Schematic Illustration of Evanescent Wave Optical Fiber Sensor for Surface-Based Molecular Detection. [102]

Table 6. Fundamental Sensing Mechanisms of Two-Dimensional Material-Based Sensors

Sensing Mechanism	Operating Principle	Typical 2D Materials	Key Advantages	Representative Applications
Field-Effect Transistor (FET)	Carrier density modulation due to analyte adsorption	Graphene, MoS_2, WS_2	High sensitivity, rapid response	Gas sensors, biosensors
Electrochemical Sensing	Redox reactions at the electrode interface	Graphene, MXenes, MoS_2	High catalytic activity, fast electron transfer	Biomedical and environmental monitoring
Optical Sensing	Raman enhancement, plasmon resonance, photoluminescence modulation	Graphene, TMDs	Ultra-sensitive detection	Chemical and biomolecular detection

6. Biomedical Sensing Applications of Two-Dimensional Nanomaterials

The rapid evolution of nanotechnology has significantly transformed modern biomedical diagnostics, particularly through the development of highly sensitive and selective biosensors. Among emerging nanomaterials, two-dimensional (2D) nanomaterials have attracted tremendous interest due to their exceptional physicochemical characteristics, including atomic-scale thickness, large specific surface area, tunable electronic properties, and superior charge transport capabilities. These features enable efficient interaction between biological molecules and the sensing surface, making 2D materials highly promising platforms for next-generation biomedical sensing technologies. Early disease diagnosis often requires the detection of biomarkers at extremely low concentrations in complex biological environments such as blood, saliva, urine, or interstitial fluid. Conventional diagnostic techniques such as enzyme-linked immunosorbent assays (ELISA) or polymerase chain reaction (PCR) offer high accuracy but often require complex instrumentation, lengthy processing times, and centralized laboratory facilities [104]. In contrast, 2D material-based biosensors enable rapid, label-free, and real-time detection of biomolecules, making them highly suitable for point-of-care diagnostics and personalized healthcare [105, 106]. Table 7 lists the Comparative Performance of 2D Nanomaterial-Based Biosensors for Biomedical Detection.

Table 7. Comparative Performance of 2D Nanomaterial-Based Biosensors for Biomedical Detection

S.No	2D Material	Synthesis Method	Target Biomarker	Detection Technique	Detection Limit	Linear Range	Response Time	Ref.
1	Graphene nanosheets	CVD	SARS-CoV-2 spike protein	FET	1 fg mL^{-1}	1 fg–1 ng mL^{-1}	5 s	[107]
2	MoS$_2$ nanosheets	Liquid exfoliation	PSA	Electrochemical	0.8 pg mL^{-1}	1 pg–100 ng mL^{-1}	8 s	[108]
3	MXene (Ti$_3$C$_2$Tx)	HF etching	Glucose	Electrochemical	0.23 nM	0.5 nM–5 mM	6 s	[109]
4	rGO	Hydrothermal	Dopamine	Electrochemical	0.5 nM	1 nM–10 μM	4 s	[110]
5	MoS$_2$–AuNP	Solvothermal	DNA biomarker	SERS	10 fM	10 fM–1 μM	7 s	[111]
6	Graphene oxide	Modified Hummers	Cholesterol	Electrochemical	0.2 μM	0.5 μM–10 mM	6 s	[112]
7	WS$_2$ nanosheets	Hydrothermal	Glucose	Electrochemical	1 nM	2 nM–2 mM	9 s	[113]
8	MoS$_2$ nanosheets	Liquid exfoliation	Cancer antigen (CA-125)	Electrochemical	0.5 pg mL^{-1}	1 pg–50 ng mL^{-1}	8 s	[71]
9	Graphene–MoS$_2$ hybrid	Layer stacking	DNA	FET	5 fM	10 fM–1 μM	5 s	[66]
10	MXene–AuNP composite	Chemical reduction	Dopamine	Electrochemical	0.1 nM	1 nM–10 μM	4 s	[114]
11	Black phosphorus	Mechanical exfoliation	miRNA	FET	2 fM	5 fM–1 μM	6 s	[115]
12	MoS$_2$–PtNP hybrid	Hydrothermal	Glucose	Electrochemical	0.05 μM	0.1 μM–5 mM	5 s	[116]
13	Graphene quantum dots	Solvothermal	Uric acid	Fluorescence	0.3 μM	1 μM–5 mM	7 s	[117]
14	MXene–polymer composite	In-situ polymerization	Lactate	Electrochemical	0.4 μM	1 μM–2 mM	8 s	[118]
15	MoS$_2$ nanosheets	CVD	PSA	FET	0.2 pg mL^{-1}	1 pg–100 ng mL^{-1}	6 s	[119]

The outstanding sensing performance of 2D nanomaterials arises from their ability to transduce biochemical interactions into measurable electrical, electrochemical, or optical signals. Because most atoms in these materials are exposed at the surface, adsorption of biomolecules such as proteins, nucleic acids, or metabolites can induce significant modulation in their electronic or electrochemical properties. Furthermore, the surfaces of 2D materials can be easily functionalized with antibodies, enzymes, aptamers, or DNA probes, enabling selective recognition of specific biomarkers [106]. Recent advances in nanofabrication techniques have enabled the development of diverse biomedical sensing platforms based on graphene, transition metal dichalcogenides (TMDs), MXenes, black phosphorus, and other emerging 2D materials. These sensors have demonstrated remarkable capabilities in detecting viral pathogens, cancer biomarkers, metabolic indicators, and neurological signaling molecules. Additionally, flexible and wearable biosensors based on 2D materials are gaining increasing attention for continuous health monitoring and early disease detection. In the following subsections, the major biomedical sensing applications of 2D nanomaterials are discussed, including viral and pathogen detection, metabolic biomarker monitoring, and cancer diagnostics.

6.1 Viral and Pathogen Detection

Rapid and accurate detection of viral pathogens is essential for controlling infectious diseases and preventing global health crises. The COVID-19 pandemic highlighted the urgent need for rapid diagnostic technologies capable of detecting viral biomarkers with high sensitivity and specificity [120]. In this context, biosensors based on two-dimensional nanomaterials have demonstrated extraordinary potential for detecting viral proteins, nucleic acids, and other pathogen-associated molecules. Graphene-based field-effect transistor (FET) biosensors represent one of the most prominent examples of 2D material-enabled viral detection platforms. Due to its exceptional electrical conductivity and high carrier mobility, graphene can efficiently transduce molecular binding events occurring at its surface into measurable electrical signals. When the graphene surface is functionalized with specific antibodies or receptor molecules, binding of viral antigens can induce significant modulation in channel conductance.

One notable example is the graphene FET biosensor developed for detecting the SARS-CoV-2 spike protein, the key surface antigen responsible for viral entry into host cells [121]. In such devices, antibodies specific to the spike protein are immobilized on the graphene surface. When the viral antigen binds to these antibodies, local electrostatic interactions alter the carrier density in the graphene channel, producing a measurable electrical signal. Remarkably, these sensors have demonstrated detection limits in the femtogram per milliliter range, enabling ultra-sensitive detection of viral particles even in early infection stages. Beyond graphene, other 2D materials such as MoS_2 and black phosphorus have also been investigated for viral detection. Semiconducting TMDs possess intrinsic band gaps that enable strong modulation of electrical conductivity upon analyte adsorption, which can further enhance sensor sensitivity.

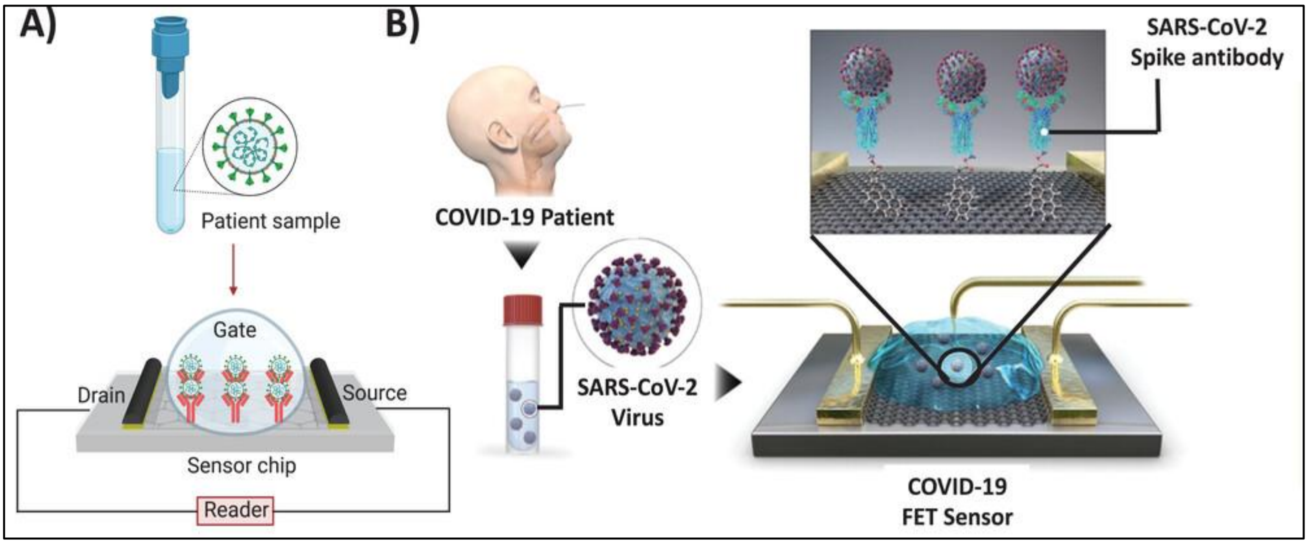

Figure 4. Design and Working Principle of an Antibody-Functionalized FET Biosensor for SARS-CoV-2 Detection [122]

Figure 4 shows the design and working principle of an antibody-functionalized FET biosensor for SARS-CoV-2 detection Additionally, MoS_2-based FET biosensors have demonstrated excellent stability and selectivity for detecting viral RNA fragments and protein biomarkers.

Another promising approach involves integrating plasmonic nanoparticles with 2D materials to enhance optical sensing methods such as surface-enhanced Raman scattering (SERS). In these hybrid systems, plasmonic metals amplify electromagnetic fields near the sensing surface, enabling highly sensitive detection of viral components. These advances demonstrate that 2D nanomaterials can serve as powerful platforms for rapid and accurate viral diagnostics. Importantly, many of these sensors can be integrated into portable devices, enabling point-of-care detection in clinical and field settings. Table 8 examples Two-Dimensional Material-Based Biosensors for Biomedical Diagnostics.

6.2 Metabolic Biomarker Monitoring

Monitoring metabolic biomarkers is essential for diagnosing and managing chronic diseases such as diabetes, cardiovascular disorders, and neurological conditions. Biosensors capable of continuously measuring biochemical indicators in bodily fluids can provide valuable insights into physiological health and enable personalized disease management. Two-dimensional nanomaterials have emerged as highly promising materials for developing electrochemical biosensors capable of detecting metabolic molecules with exceptional sensitivity and rapid response times [123]. Among the various metabolic biomarkers, glucose monitoring is one of the most extensively studied applications of 2D nanomaterial-based biosensors. Diabetes mellitus affects millions of individuals worldwide, and continuous monitoring of blood glucose levels is critical for effective disease management [124]. Traditional glucose sensors often rely on enzyme-based electrochemical detection systems; however, these devices can suffer from limited stability and slow response times.

MXene-based electrochemical sensors have demonstrated outstanding performance in glucose detection due to their metallic conductivity and abundant surface functional groups. MXenes, typically represented by the formula Mn+1XnTx, possess hydrophilic surfaces terminated with functional groups such as hydroxyl, oxygen, or fluorine. These surface groups enhance enzyme immobilization and promote strong interactions with glucose molecules, thereby improving sensor sensitivity. In a typical MXene-based glucose sensor, glucose oxidase enzymes are immobilized on the MXene surface. When glucose molecules interact with the enzyme, they undergo oxidation reactions that generate electrons [125]. The excellent electrical conductivity of MXenes facilitates rapid electron transfer from the enzyme to the electrode, resulting in measurable electrochemical signals proportional to glucose concentration.

Beyond glucose monitoring, 2D material-based electrochemical sensors have also been widely explored for detecting neurotransmitters such as dopamine, serotonin, and acetylcholine, which play crucial roles in neural communication and neurological disorders. For example, graphene and MoS_2 electrodes have demonstrated remarkable sensitivity for detecting dopamine at nanomolar concentrations due to their strong adsorption affinity and fast electron transfer kinetics [126]. The development of flexible and wearable biosensors incorporating 2D nanomaterials further expands their potential for continuous health monitoring. Such devices can be integrated into wearable patches or electronic textiles capable of measuring biomarkers in sweat, saliva, or interstitial fluid. These wearable biosensors offer a non-invasive approach for real-time monitoring of physiological health parameters.

6.3 Cancer Biomarker Detection

Early detection of cancer significantly improves treatment outcomes and patient survival rates. However, many conventional diagnostic methods rely on imaging techniques or invasive biopsy procedures that may not detect cancer at its earliest stages. Biosensors based on two-dimensional nanomaterials offer a powerful alternative by enabling highly sensitive detection of cancer biomarkers, including proteins, nucleic acids, and circulating tumor cells. Among widely studied cancer biomarkers, prostate-specific antigen (PSA) is commonly used for diagnosing prostate cancer. Detection of PSA at very low concentrations is essential for early-stage diagnosis. MoS_2-based biosensors have shown excellent performance in PSA detection due to their semiconducting properties and high surface reactivity [127]. In these sensors, the MoS_2 surface is typically functionalized with antibodies specific to PSA molecules. When PSA molecules bind to these antibodies, the resulting biochemical interaction alters the electrical or electrochemical properties of the sensing layer.

Table 8. Examples of Two-Dimensional Material-Based Biosensors for Biomedical Diagnostics

Material System	Target Biomarker	Detection Limit	Detection Technique	Biomedical Application
Graphene FET	SARS-CoV-2 spike protein	fg mL^{-1}	Electrical (FET) sensing	Viral infection detection
MXene electrochemical sensor	Glucose	nM	Electrochemical sensing	Diabetes monitoring
MoS_2 biosensor	Prostate-specific antigen (PSA)	pg mL^{-1}	Electrochemical/FET	Cancer diagnosis
Graphene oxide biosensor	Dopamine	nM	Electrochemical sensing	Neurological monitoring
MoS_2–Au nanoparticle hybrid	DNA mutations	fM	Optical/SERS sensing	Genetic cancer screening

Because MoS_2 possesses a high density of reactive edge sites and strong adsorption capabilities, even extremely low concentrations of PSA can induce detectable signals [128]. Another promising approach involves using graphene oxide or reduced graphene oxide platforms functionalized with DNA probes for detecting cancer-related genetic mutations. These sensors can identify specific nucleic acid sequences associated with tumor development, enabling early diagnosis through genetic analysis. Furthermore, hybrid nanostructures combining 2D materials with metal nanoparticles or quantum dots have demonstrated enhanced sensitivity for cancer biomarker detection through optical sensing techniques such as SERS or fluorescence quenching. These developments highlight the enormous potential of 2D nanomaterials in advancing cancer diagnostics. With further optimization and clinical validation, such biosensors could enable rapid, non-invasive cancer screening technologies suitable for routine healthcare applications.

7. Environmental and Chemical Detection Using Two-Dimensional Nanomaterials

The escalating levels of environmental pollution resulting from rapid industrialization, urbanization, and intensive agricultural activities have created an urgent need for advanced sensing technologies capable of monitoring pollutants with high sensitivity, selectivity, and real-time responsiveness [129]. Conventional environmental monitoring techniques often rely on sophisticated analytical instruments such as gas chromatography–mass spectrometry (GC–MS), inductively coupled plasma mass spectrometry (ICP–MS), or high-performance liquid chromatography (HPLC). Although these methods offer excellent analytical precision, they typically require complex sample preparation, centralized laboratory facilities, and trained personnel, which limits their applicability for continuous field-based monitoring.

In recent years, two-dimensional (2D) nanomaterials have emerged as powerful sensing platforms for environmental and chemical detection due to their extraordinary physicochemical properties. Atomically thin structures such as graphene, transition metal dichalcogenides (TMDs), MXenes, black phosphorus, and layered metal–organic frameworks expose an exceptionally high fraction of active surface atoms that interact directly with surrounding chemical species. This structural characteristic dramatically enhances analyte adsorption and facilitates efficient charge transfer interactions between pollutant molecules and the sensing surface. The sensing capabilities of 2D nanomaterials arise primarily from their high surface-to-volume ratio, tunable electronic band structure, superior carrier mobility, and chemically modifiable surfaces. These properties enable efficient transduction of analyte interactions into measurable electrical, electrochemical, or optical signals. Furthermore, the surfaces of 2D materials can be readily engineered through defect introduction, heterostructure construction, or chemical functionalization to enhance selectivity toward specific pollutants. Environmental pollutants of particular concern include toxic gases, volatile organic compounds (VOCs), heavy metal ions, pesticides, and emerging contaminants such as microplastics and pharmaceutical residues. Exposure to these pollutants can pose severe risks to ecosystems and human health, making their detection and monitoring critically important [130].

Table 9. Comparative Analysis of 2D Nanomaterial Gas Sensors for Environmental Monitoring

S.No	2D Material	Synthesis Method	Target Gas	Detection Mechanism	Detection Limit	Sensitivity	Operating Temp.	Ref.
1	Graphene	CVD	NO_2	Chemiresistive	20 ppb	15%	RT	[130]
2	MoS_2	Hydrothermal	NH_3	FET	50 ppb	18%	RT	[121]
3	MXene	HF etching	VOCs	Electrochemical	30 ppb	22%	RT	[131]
4	WS_2	Two-step deposition technique	H_2S	Chemiresistive	10 ppb	20%	50°C	[132]
5	Black phosphorus	Mechanical exfoliation	NO_2	FET	5 ppb	25%	RT	[133]
6	Graphene oxide	Hummers method	CO_2	Resistive	40 ppb	14%	RT	[134]
7	$MoSe_2$	Hydro thermal	CO	FET	60 ppb	16%	RT	[71]
8	MXene–graphene hybrid	Chemical synthesis	VOCs	Chemiresistive	25 ppb	23%	RT	[135]
9	WS_2–AuNP	Solvothermal	H_2	Resistive	15 ppb	21%	RT	[136]
10	MoS_2–ZnO	Hydrothermal	NO_2	Hybrid sensor	8 ppb	24%	75°C	[137]
11	Graphene–SnO_2	Sol-gel	CO	Resistive	30 ppb	19%	RT	[138]
12	MoS_2 nanosheets	CVD	SO_2	FET	12 ppb	22%	RT	[139]
13	MXene–polymer composite	In-situ polymerization	Acetone	Electrochemical	18 ppb	20%	RT	[140]
14	rGO–TiO_2	Hydrothermal	VOCs	Resistive	22 ppb	17%	60°C	[141]
15	Graphene–MoS_2 heterostructure	Layer stacking	NO_2	FET	6 ppb	26%	RT	[66]

Recent studies have demonstrated that sensors based on 2D nanomaterials can detect environmental pollutants at extremely low concentrations, often reaching parts-per-billion (ppb) or even parts-per-trillion (ppt) levels [82]. Comparative Analysis of 2D Nanomaterial Gas Sensors for Environmental Monitoring are listed in table 9. Moreover, the integration of 2D materials with flexible substrates and wireless electronics enables the development of portable environmental monitoring devices capable of real-time data acquisition. The following subsections discuss the major environmental sensing applications of 2D nanomaterials, including toxic gas detection, volatile organic compound monitoring, and heavy metal ion sensing in water systems. Table 10 lists the Environmental Sensing Using Two-Dimensional Nanomaterials.

7.1 Gas Sensing for Air Quality Monitoring

Air pollution is one of the most pressing environmental challenges facing modern society. Toxic gases such as nitrogen dioxide (NO_2), ammonia (NH_3), carbon monoxide (CO), and sulfur dioxide (SO_2) are commonly released from industrial processes, vehicle emissions, and agricultural activities [142]. These pollutants can have severe impacts on human health, contributing to respiratory diseases, cardiovascular disorders, and environmental degradation. Consequently, the development of highly sensitive gas sensors capable of detecting trace concentrations of these pollutants is essential for effective air quality monitoring. Two-dimensional nanomaterials have emerged as exceptional candidates for gas sensing applications due to their atomically thin structure and high adsorption capacity [143]. Because nearly all atoms in 2D materials are exposed to the surrounding environment, adsorption of gas molecules can induce substantial changes in their electronic properties. These changes are typically detected through variations in electrical conductivity, resistance, or field-effect transistor characteristics. Graphene-based gas sensors are among the most extensively investigated systems for detecting atmospheric pollutants. Graphene possesses remarkable electrical conductivity and extremely high carrier mobility, which allows even minor perturbations caused by gas adsorption to produce measurable electrical signals. Figure 5 shows the Metal Oxide Semiconductor (MOS)-Based Gas Sensors for Air Quality Monitoring: Synthesis, Mechanisms, and Performance Parameters. When electron-withdrawing gases such as NO_2 adsorb onto graphene surfaces, they extract electrons from the graphene lattice, leading to increased hole concentration and measurable changes in electrical resistance. In contrast, electron-donating molecules such as NH_3 can transfer electrons to graphene, producing an opposite modulation in carrier concentration. These charge transfer interactions form the fundamental sensing mechanism of graphene-based chemiresistive gas sensors [145].

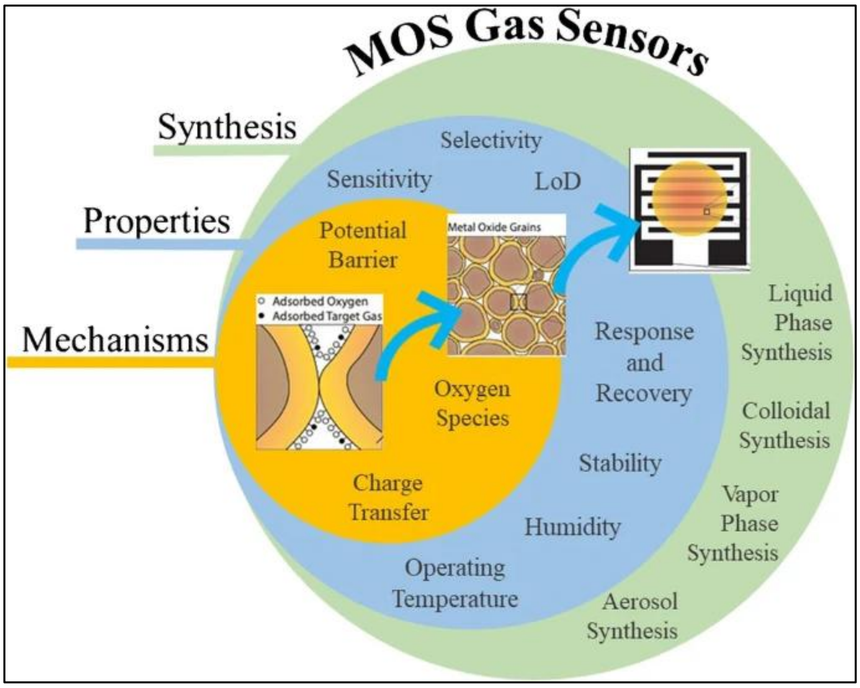

Figure 5. Metal Oxide Semiconductor (MOS)-Based Gas Sensors for Air Quality Monitoring: Synthesis, Mechanisms, and Performance Parameters. [144]

However, pristine graphene often exhibits relatively weak interactions with gas molecules due to its chemically inert basal plane. To address this limitation, various structural engineering strategies have been developed to enhance graphene's sensing performance. For example, defect engineering, metal nanoparticle decoration, and heterostructure formation with semiconducting materials such as MoS_2 or ZnO have been shown to significantly improve adsorption affinity and sensitivity [146]. Transition metal dichalcogenides (TMDs) such as MoS_2 and WS_2 also demonstrate excellent gas sensing properties. These materials possess intrinsic band gaps that enable stronger modulation of electrical conductivity upon analyte adsorption. Additionally, the presence of sulfur vacancies in MoS_2 creates highly reactive adsorption sites capable of strongly interacting with gas molecules. Recent research has also explored hybrid structures combining graphene with metal oxide nanoparticles to create highly sensitive and selective gas sensors. These hybrid materials benefit from the high conductivity of graphene and the strong catalytic activity of metal oxides, resulting in enhanced sensor response.

7.2 Detection of Volatile Organic Compounds

Volatile organic compounds (VOCs) represent a major class of environmental pollutants that originate from industrial emissions, fuel combustion, household chemicals, and various manufacturing processes. Common VOCs such as benzene, toluene, formaldehyde, and acetone are known to pose significant health risks, including carcinogenic effects and neurological damage. Therefore, sensitive detection of VOCs is crucial for environmental safety and occupational health monitoring [147].

Two-dimensional nanomaterials have demonstrated exceptional capabilities in VOC detection due to their large adsorption surface area and tunable surface chemistry. Among these materials, MXenes have attracted considerable attention as promising sensing platforms for VOC monitoring. MXenes are a class of two-dimensional transition metal carbides and nitrides typically represented by the general formula Mn+1XnTx, where M denotes a transition metal, X represents carbon or nitrogen, and Tx corresponds to surface termination groups such as hydroxyl, oxygen, or fluorine. These surface functional groups significantly enhance chemical interactions between MXenes and VOC molecules. One of the most distinctive features of MXenes is their metallic electrical conductivity, which facilitates rapid electron transfer during analyte adsorption. When VOC molecules interact with MXene surfaces, they induce changes in the local electronic structure, resulting in measurable variations in electrical resistance or electrochemical current [148].

MXene-based electrochemical sensors have demonstrated remarkable sensitivity toward various VOCs, including ethanol, acetone, and formaldehyde. The high density of surface functional groups on MXenes enables strong adsorption of VOC molecules, while their excellent electrical conductivity ensures efficient signal transduction. Recent research has also explored hybrid materials combining MXenes with polymers or metal oxide nanoparticles to improve selectivity toward specific VOC species. For example, MXene–polymer composites have shown enhanced sensitivity toward formaldehyde due to synergistic interactions between polymer functional groups and VOC molecules [149]. Furthermore, the integration of MXene-based sensors into flexible substrates enables the development of wearable environmental monitoring devices capable of detecting harmful VOCs in indoor environments.

7.3 Heavy Metal Ion Detection in Water Systems

Water contamination by heavy metal ions represents a major environmental and public health concern worldwide. Toxic metals such as mercury (Hg^{2+}), lead (Pb^{2+}), cadmium (Cd^{2+}), and arsenic (As^{3+}) can accumulate in aquatic ecosystems and enter the human food chain through contaminated drinking water or agricultural irrigation. Even at extremely low concentrations, these heavy metals can cause severe health effects, including neurological damage, kidney dysfunction, and developmental disorders. Two-dimensional nanomaterials have shown remarkable potential for detecting heavy metal ions in water due to their strong adsorption affinity and tunable surface functionalization capabilities. Among these materials, transition metal dichalcogenides such as MoS_2 have been extensively studied for heavy metal sensing applications. MoS_2 possesses a layered structure with abundant edge sites and sulfur atoms capable of strongly interacting with metal ions through coordination bonding. These interactions can significantly alter the electrical properties of MoS_2, enabling detection of heavy metal ions through field-effect transistor (FET) or electrochemical sensing mechanisms [150].

For example, MoS_2-based FET sensors have demonstrated exceptional sensitivity for detecting Hg^{2+} ions [151]. In these devices, adsorption of mercury ions onto the MoS_2 surface induces significant changes in carrier concentration within the semiconducting channel, resulting in measurable modulation of drain current. Graphene oxide and reduced graphene oxide have also been widely employed for heavy metal detection due to their abundant oxygen-containing functional groups, which can chelate metal ions. These materials can be integrated into electrochemical sensing platforms for detecting lead and cadmium ions with extremely low detection limits. Additionally, hybrid nanostructures combining 2D materials with metal nanoparticles or conductive polymers have shown enhanced sensitivity for heavy metal detection through synergistic catalytic and adsorption effects. The development of portable water monitoring devices based on 2D nanomaterials offers significant advantages for environmental surveillance. Such devices can enable real-time detection of water pollutants directly in field environments, eliminating the need for complex laboratory analysis.

8. Artificial Intelligence and Intelligent Sensing in Two-Dimensional Nanomaterial-Based Sensors

The rapid advancement of sensing technologies over the past decade has generated vast amounts of multidimensional data, particularly from high-performance nanoscale sensors capable of detecting multiple chemical and biological analytes simultaneously. While these sensors offer unprecedented sensitivity and selectivity, interpreting the complex datasets produced by such systems presents significant analytical challenges. In this context, artificial intelligence (AI) and machine learning (ML) have emerged as transformative tools for enhancing the performance and functionality of modern sensing platforms. The integration of AI with two-dimensional (2D) nanomaterial-based sensors represents a paradigm shift toward intelligent sensing systems capable of autonomous decision-making and adaptive sensing strategies [27, 152]. Machine learning algorithms can analyze complex sensor responses, identify hidden patterns in large datasets, and differentiate between analytes even in environments containing multiple interfering species. This capability significantly enhances sensor selectivity and reliability, particularly in real-world applications where environmental noise and signal overlap often complicate detection processes. Two-dimensional nanomaterials such as graphene, transition metal dichalcogenides (TMDs), MXenes, and black phosphorus generate highly sensitive electrical, electrochemical, and optical responses upon interaction with analyte molecules. However, these signals are often influenced by external factors including humidity, temperature fluctuations, and cross-reactive species. AI-based data analysis enables sophisticated pattern recognition that can distinguish genuine analyte signals from background noise, thereby improving detection accuracy. Another key development in intelligent sensing is the integration of Internet of Things (IoT) technologies, which allow distributed sensor networks to collect and transmit real-time environmental or biomedical data to centralized computational platforms [153].

Table 10. Environmental Sensing Using Two-Dimensional Nanomaterials

2D Material	Target Pollutant	Detection Method	Typical Detection Limit	Environmental Application
Graphene	NO_2 gas	Chemiresistive sensing	ppb	Air quality monitoring
MXene	Volatile organic compounds (VOCs)	Electrochemical sensing	ppb	Industrial emission monitoring
MoS_2	Hg^{2+} ions	Field-effect transistor (FET) sensing	nM	Water quality monitoring
Graphene oxide	Pb^{2+} ions	Electrochemical sensing	nM	Drinking water safety
MXene–polymer hybrid	Formaldehyde	Chemiresistive sensing	ppb	Indoor air monitoring

When combined with AI algorithms, these networks can perform advanced data analytics, predictive modeling, and automated response generation. The convergence of 2D nanomaterial sensors, artificial intelligence, and IoT technologies has led to the emergence of smart sensing ecosystems capable of continuous monitoring and real-time decision-making. Such systems hold immense potential for applications in healthcare diagnostics, environmental surveillance, industrial safety monitoring, and smart city infrastructure. The following subsections discuss key aspects of AI-enabled sensing technologies, including machine learning algorithms for sensor data analysis, intelligent sensor networks, AI-assisted sensor design, and emerging autonomous sensing platforms.

8.1 Machine Learning Algorithms for Sensor Data Analysis

Machine learning algorithms play a central role in extracting meaningful information from complex sensor datasets generated by two-dimensional nanomaterial-based sensing devices. Unlike traditional analytical methods that rely on predefined signal thresholds or simple calibration curves, machine learning approaches can identify nonlinear relationships and multidimensional patterns within sensor signals. In many sensing applications, particularly gas detection or biomolecular sensing, sensor responses may be influenced by multiple environmental variables such as humidity, temperature, or cross-reactive analytes. These factors can produce overlapping signals that are difficult to interpret using conventional signal-processing techniques. Machine learning algorithms provide powerful tools for resolving these challenges by identifying unique patterns associated with specific analytes.

Machine learning models such as support vector machines and artificial neural networks have demonstrated measurable improvements in sensor selectivity by distinguishing overlapping signal patterns in multi-analyte environments. For instance, classification accuracy improvements exceeding conventional threshold-based methods have been reported in gas sensing arrays [154]. Deep learning architectures further enable nonlinear mapping between sensor responses and analyte concentrations, improving predictive performance in complex environments. Principal component analysis is commonly used as a dimensionality reduction technique that transforms high-dimensional sensor datasets into a smaller set of orthogonal variables while preserving the most significant variations in the data. This approach enables visualization of sensor responses and identification of clusters corresponding to different analytes. Artificial neural networks and deep learning models offer even greater capabilities for pattern recognition. These algorithms can learn complex nonlinear relationships between sensor signals and analyte concentrations, enabling highly accurate classification and quantitative prediction. Recent studies have demonstrated that AI-assisted analysis of sensor arrays based on graphene or MXene materials can accurately identify multiple gas species in mixed environments with significantly improved selectivity compared with traditional methods [155]. Such AI-enabled electronic nose systems are particularly promising for environmental monitoring and industrial safety applications.

8.2 AI-Assisted Sensor Design and Materials Discovery

Beyond data analysis, artificial intelligence is increasingly being used to accelerate the discovery and design of advanced sensing materials. Traditional materials discovery processes often rely on time-consuming experimental trial-and-error approaches. AI-driven computational methods offer a more efficient strategy by predicting material properties and guiding experimental design [156]. Machine learning algorithms can analyze large datasets derived from theoretical calculations, experimental measurements, and materials databases to identify correlations between material structure and sensing performance. These models can predict key parameters such as adsorption energies, charge transfer characteristics, and electronic band structures, which are critical factors influencing sensor sensitivity. For example, density functional theory (DFT) calculations combined with machine learning models have been used to predict the adsorption behavior of gas molecules on graphene derivatives and transition metal dichalcogenides [157]. These predictions enable researchers to identify promising material candidates before conducting experimental synthesis, thereby significantly reducing research time and cost. AI-assisted materials discovery has also been applied to the design of heterostructures and hybrid nanomaterials with optimized sensing properties. Machine learning models can evaluate numerous combinations of materials and structural configurations to determine the most effective architectures for specific sensing applications.

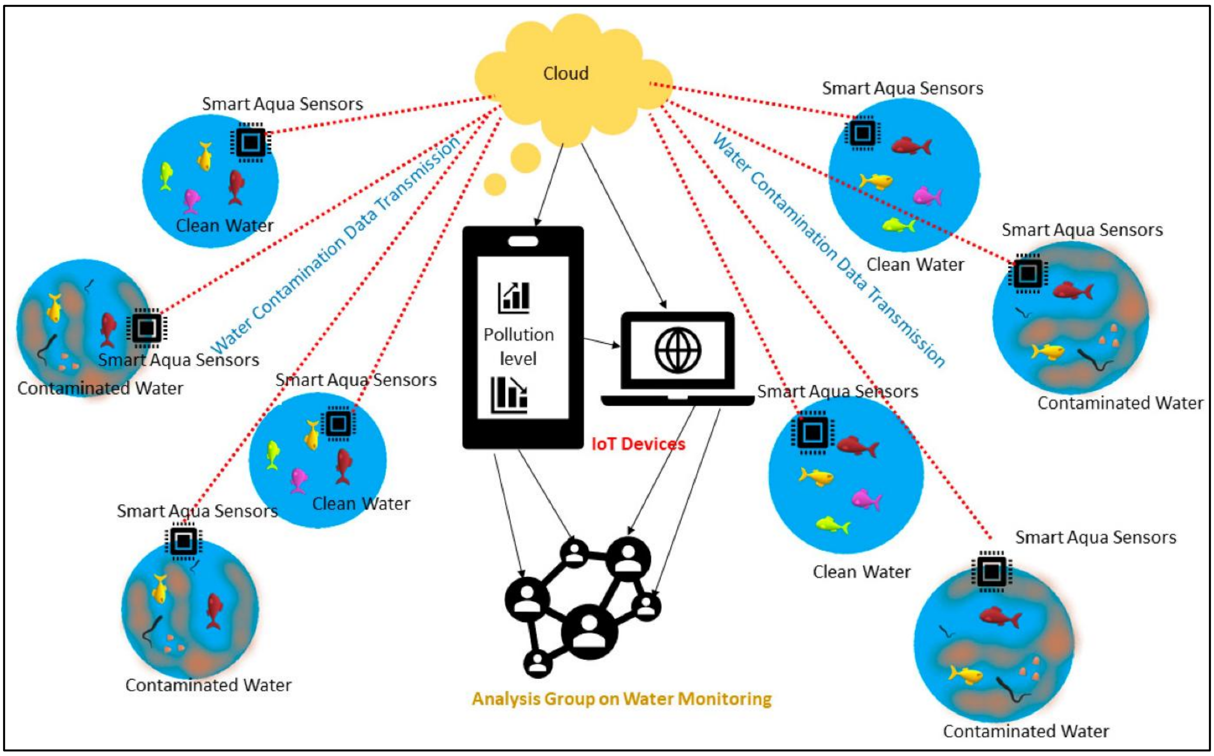

Figure 6. Conceptual Framework of IoT-Based Smart Water Monitoring Using Distributed Aqua Sensors. [160]

Furthermore, AI algorithms can optimize synthesis parameters such as temperature, precursor concentration, and reaction time to achieve desired material characteristics. This capability is particularly valuable for scalable production of high-quality 2D nanomaterials used in sensor fabrication.

8.3 Intelligent Sensor Networks and IoT Integration

The integration of 2D nanomaterial-based sensors with Internet of Things (IoT) technologies has enabled the development of distributed sensor networks capable of real-time environmental and biomedical monitoring. These networks consist of multiple interconnected sensing nodes that continuously collect data and transmit it to centralized cloud-based platforms for analysis. When combined with artificial intelligence algorithms, IoT-enabled sensor networks can perform advanced data analytics and predictive modeling. For example, environmental monitoring systems equipped with arrays of graphene-based gas sensors can detect fluctuations in air pollutant concentrations across urban areas [158]. AI algorithms can then analyze these data streams to identify pollution sources and predict future air quality trends. In healthcare applications, wearable biosensors incorporating 2D materials can continuously monitor physiological biomarkers such as glucose levels, lactate concentration, or stress hormones. These sensors transmit data to mobile devices or cloud platforms, where machine-learning algorithms analyze trends and detect potential health anomalies. The integration of intelligent sensing systems with wireless communication technologies enables real-time alerts and automated responses. For instance, industrial safety systems equipped with AI-enabled gas sensors can automatically trigger ventilation systems or safety alarms when hazardous gases are detected [159]. Such intelligent sensing platforms represent a key component of emerging smart city infrastructures, where interconnected sensor networks monitor environmental conditions, public health indicators, and industrial processes. Conceptual Framework of IoT-Based Smart Water Monitoring is shown in figure 6.

8.4 Autonomous and Self-Learning Sensing Systems

One of the most exciting developments in intelligent sensing technologies is the emergence of autonomous sensing systems capable of self-learning and adaptive operation. In these systems, AI algorithms continuously analyze incoming sensor data and update their predictive models based on new information. Self-learning sensor systems can adapt to changing environmental conditions or evolving analyte compositions without requiring manual recalibration

[161]. This capability is particularly valuable in dynamic environments such as industrial process monitoring or environmental surveillance. Deep learning algorithms are especially well-suited for autonomous sensing applications because they can automatically extract complex features from raw sensor data. These algorithms enable sensors to recognize subtle patterns associated with specific analytes even when signals are partially obscured by noise or interference. For instance, AI-enabled gas sensing arrays based on graphene and metal oxide nanomaterials have demonstrated the ability to distinguish between multiple VOCs with high accuracy using deep learning classification models [162]. Over time, these systems improve their predictive accuracy as they are exposed to larger datasets. Autonomous sensing systems also have the potential to perform predictive diagnostics, identifying early warning signals that precede environmental hazards or medical conditions. Such predictive capabilities could significantly enhance preventive healthcare and environmental risk management.

8.5 Future Perspectives of AI-Driven Smart Sensing Platforms

The convergence of two-dimensional nanomaterials, artificial intelligence, and IoT technologies is expected to revolutionize the field of sensing technologies in the coming years. AI-driven smart sensing platforms have the potential to transform traditional sensors into intelligent analytical systems capable of continuous monitoring, automated data interpretation, and predictive decision-making. Future research efforts are likely to focus on the development of multi-analyte sensor arrays, often referred to as electronic noses or electronic tongues, which mimic biological sensory systems. These sensor arrays generate complex response patterns that can be interpreted using machine learning algorithms to identify specific analytes with high accuracy.

Another promising direction involves integrating AI-enabled sensors with edge computing technologies, allowing data processing to occur directly at the sensor node rather than in centralized cloud servers [163]. This approach reduces data transmission latency and improves system responsiveness, which is particularly important for real-time monitoring applications. Additionally, advances in flexible electronics and wearable technologies are expected to enable the development of intelligent biosensing devices capable of continuous health monitoring. These devices could provide personalized health insights by combining sensor data with AI-based predictive analytics. Table 11 lists the AI Techniques Applied to Two-Dimensional Nanomaterial-Based Sensors. Despite these promising developments, several challenges remain, including data security, sensor calibration, and the development of standardized protocols for AI-enabled sensing systems. Addressing these challenges will be essential for translating intelligent sensing technologies from laboratory research to practical real-world applications.

9. Challenges and Future Perspectives of Two-Dimensional Nanomaterial-Based Sensors

Despite the remarkable progress achieved in the development of two-dimensional (2D) nanomaterial-based sensors over the past decade, several fundamental and technological challenges remain before these systems can be fully translated from laboratory-scale demonstrations to practical real-world applications, as listed in table 12.

Table 11. Artificial Intelligence Techniques Applied to Two-Dimensional Nanomaterial-Based Sensors

AI Technique	Function in Sensing Systems	Typical Application	Advantages
Principal Component Analysis (PCA)	Dimensionality reduction and signal visualization	Gas sensor arrays	Identifies analyte clusters
Support Vector Machines (SVM)	Classification of sensor responses	VOC detection	High classification accuracy
Artificial Neural Networks (ANN)	Pattern recognition and prediction	Biosensor signal analysis	Handles nonlinear relationships
Deep Learning	Feature extraction from complex datasets	Electronic nose systems	High predictive capability
Random Forest	Ensemble learning for classification	Environmental monitoring	Robust against noise

While materials such as graphene, transition metal dichalcogenides (TMDs), MXenes, black phosphorus, and porous 2D frameworks exhibit extraordinary sensing performance under controlled experimental conditions, the scalability, stability, reproducibility, and integration of these materials into reliable sensing devices continue to pose significant obstacles. One of the most prominent challenges lies in the large-scale synthesis of high-quality 2D nanomaterials with controlled structural and electronic properties. Many of the high-performance sensors reported in the literature rely on materials produced through laboratory-scale methods such as mechanical exfoliation or small-batch chemical synthesis. These techniques often yield materials with excellent crystallinity and minimal defects but are difficult to scale up for industrial production.

Another critical limitation concerns the chemical and environmental stability of certain 2D materials. For example, black phosphorus, despite its exceptional electronic properties and strong analyte interactions, undergoes rapid oxidation when exposed to oxygen and moisture [20]. Similarly, some MXenes can experience surface oxidation during long-term operation, which may degrade sensor performance. Device reproducibility and standardization represent additional challenges. Variations in synthesis methods, defect density, layer thickness, and surface functionalization can lead to significant differences in sensor response across different research groups or production batches. Achieving consistent performance across large numbers of devices is therefore essential for commercialization. Furthermore, integrating 2D nanomaterial sensors with existing electronic platforms, wireless communication systems, and intelligent data analysis frameworks remains an active area of research [164]. Figure 7 shows future perspectives of Smart Sensing: Role of Two-Dimensional Nanomaterials in Health, Environment, and IoT Applications.

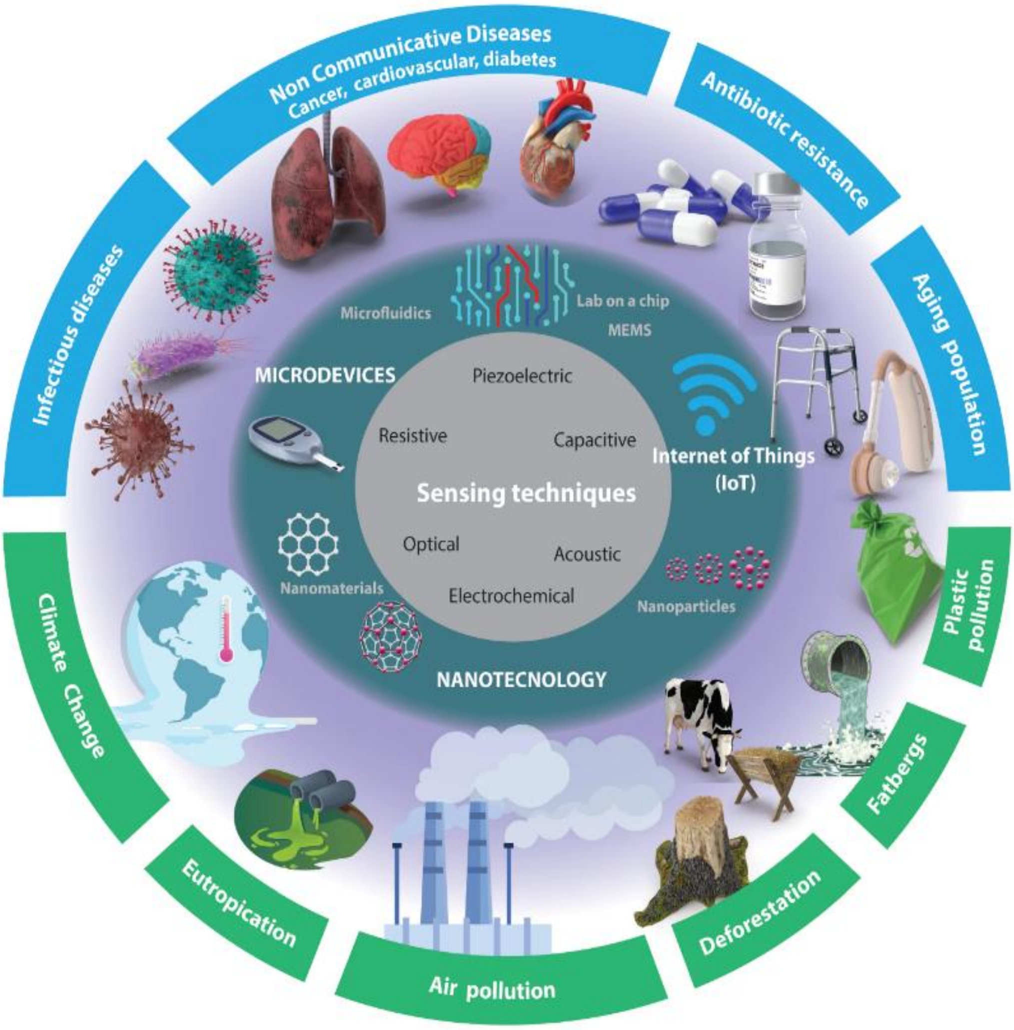

Figure 7. Future Perspectives of Smart Sensing: Role of Two-Dimensional Nanomaterials in Health, Environment, and IoT Applications. [165]

The convergence of nanomaterials, electronics, and artificial intelligence presents exciting opportunities for next-generation sensing technologies but also requires interdisciplinary collaboration across materials science, chemistry, electrical engineering, and data science.

The following subsections discuss the major challenges and emerging future directions in the development of 2D nanomaterial-based sensing systems.

9.1 Large-Scale Synthesis and Material Uniformity

One of the most critical barriers to the widespread adoption of two-dimensional nanomaterials in sensing technologies is the lack of scalable synthesis techniques capable of producing high-quality materials with consistent structural properties. Laboratory-scale methods such as mechanical exfoliation, although capable of producing pristine monolayers with minimal defects, are inherently unsuitable for large-scale manufacturing due to their low throughput and lack of reproducibility.

Chemical vapor deposition (CVD) has emerged as one of the most promising approaches for producing large-area 2D materials with controlled thickness and crystallinity. CVD techniques have been successfully used to synthesize wafer-scale graphene and TMD films suitable for electronic device fabrication. However, achieving uniform layer thickness, minimizing grain boundaries, and controlling defect densities remain significant challenges. Liquid-phase exfoliation methods provide another scalable route for producing 2D nanosheets in large quantities. This technique involves ultrasonic or chemical exfoliation of layered bulk materials in liquid solvents. Although liquid-phase exfoliation is attractive for mass production, the resulting materials often exhibit broad size distributions and structural defects that can affect sensor performance. Recent advances in bottom-up synthesis techniques and continuous flow reactors have shown promise for producing high-quality 2D materials with improved scalability [166]. Additionally, machine learning-assisted optimization of synthesis parameters is emerging as a powerful strategy for improving reproducibility and material quality. Future research should focus on developing cost-effective, scalable synthesis methods capable of producing uniform 2D nanomaterials with controlled structural properties suitable for industrial sensor manufacturing.

9.2 Stability and Environmental Durability

The long-term stability of two-dimensional nanomaterials under operational conditions is another major challenge that must be addressed before these materials can be widely used in sensing technologies. Many 2D materials exhibit high chemical reactivity due to their large surface area and exposed atomic structure, which can lead to degradation under ambient conditions. Black phosphorus is a notable example of a highly promising 2D material that suffers from poor environmental stability [167]. Exposure to oxygen and moisture can rapidly oxidize black phosphorus, leading to structural degradation and loss of electronic conductivity. Similar stability concerns have also been reported for certain MXenes, which can undergo oxidation during prolonged exposure to air or aqueous environments.

Various strategies have been proposed to improve the environmental stability of these materials. Surface passivation techniques, such as coating with protective polymer layers, atomic layer deposition of oxide films, or encapsulation with graphene or hexagonal boron nitride, have shown significant potential for preventing oxidation and preserving material integrity [168]. Another promising approach involves chemical functionalization of the 2D material surface, which can enhance stability while simultaneously improving selectivity toward target analytes. For example, functionalizing graphene with oxygen-containing groups or metal nanoparticles can protect the underlying lattice while enhancing sensing performance. Future efforts should focus on developing robust passivation strategies that maintain high sensitivity while ensuring long-term environmental stability.

9.3 Device Reproducibility and Sensor Calibration

Achieving reliable and reproducible sensor performance remains a critical challenge for 2D nanomaterial-based sensing technologies. Variations in material synthesis, device fabrication processes, and environmental conditions can lead to significant differences in sensor response across devices. For example, variations in layer thickness, defect density, or surface functionalization can alter adsorption energetics and charge transfer interactions between analytes and the sensing material [169]. As a result, sensors fabricated using nominally identical materials may exhibit different sensitivities or response times.

Standardized fabrication protocols and calibration methods are therefore essential for ensuring consistent sensor performance. Advances in microfabrication technologies, including photolithography and inkjet printing, have enabled more precise control over sensor architecture and electrode design [170]. Additionally, the development of self-calibrating sensors using artificial intelligence algorithms offers a promising approach for improving device reproducibility. Machine learning models can analyze sensor response patterns and compensate for variations caused by environmental factors such as humidity or temperature. Future research should aim to establish standardized protocols for sensor fabrication, calibration, and performance evaluation to facilitate comparison between different sensing platforms.

9.4 Integration with Electronic and Intelligent Systems

For practical deployment in real-world applications, 2D nanomaterial sensors must be integrated with electronic circuitry, wireless communication modules, and data processing systems. This integration presents several technological challenges related to device architecture, power consumption, and data management. Flexible and wearable sensing devices represent a particularly promising application area for 2D materials due to their mechanical flexibility and lightweight nature. However, integrating these materials into flexible electronic systems requires careful engineering of substrate materials, electrode interfaces, and encapsulation layers. The incorporation of artificial intelligence and Internet of Things (IoT) technologies into sensing platforms offers exciting opportunities for intelligent environmental and biomedical monitoring systems [171]. AI algorithms can analyze large datasets generated by sensor networks and identify patterns associated with specific chemical or biological events. Future sensing systems may consist of distributed networks of nanoscale sensors connected through wireless communication technologies, enabling continuous monitoring of environmental pollutants, industrial emissions, or physiological biomarkers.

9.5 Emerging Future Research Directions

Looking ahead, several emerging research directions are expected to shape the future of two-dimensional nanomaterial-based sensing technologies. One promising area is the development of multi-functional heterostructure sensors, where multiple 2D materials are combined to exploit complementary electronic and catalytic properties [172]. Another exciting direction involves the creation of self-powered sensing systems based on energy harvesting technologies such as triboelectric nanogenerators or photovoltaic devices. These systems could enable autonomous sensor operation in remote environments without external power sources.

Advances in nanofabrication and materials engineering may also lead to the development of single-molecule detection platforms, capable of identifying extremely low concentrations of analytes with unprecedented sensitivity. Finally, the integration of AI-driven predictive analytics with nanoscale sensors could enable early detection of environmental hazards or disease biomarkers, transforming sensing technologies into proactive monitoring systems.

Table 12. Major Challenges and Future Research Directions for 2D Nanomaterial Sensors

Challenge	Description	Potential Solutions	Future Outlook
Large-scale synthesis	Difficulty producing uniform materials at an industrial scale	CVD growth, liquid-phase exfoliation optimization	Scalable manufacturing technologies
Environmental stability	Oxidation and degradation of sensitive materials	Surface passivation and encapsulation	Long-term stable sensors
Device reproducibility	Variations in sensor response due to fabrication differences	Standardized fabrication protocols	Commercial device reliability
System integration	Challenges in integrating sensors with electronics and IoT systems	Flexible electronics and wireless networks	Smart sensing platforms
Data interpretation	Complex datasets generated by sensor arrays	AI-assisted data analysis	Intelligent autonomous sensors

Continued interdisciplinary collaboration between materials scientists, chemists, engineers, and data scientists will be essential for overcoming existing challenges and unlocking the full potential of two-dimensional nanomaterials in next-generation sensing technologies.

The analysis reveals a clear convergence toward hybrid material systems combining multiple two-dimensional nanomaterials to overcome intrinsic limitations of individual materials [173]. Studies consistently demonstrate that defect engineering enhances sensitivity, while surface functionalization improves selectivity. However, The relationship between sensitivity and stability remain unresolved. Comparison with conventional sensing materials indicates that while metal oxide sensors offer robustness, they lack the ultra-low detection limits achieved by two-dimensional materials. Similarly, polymer-based sensors provide flexibility but exhibit lower signal stability. This positions two-dimensional nanomaterials as highly competitive candidates for next-generation sensing systems, particularly when integrated with intelligent data processing frameworks.

10. Conclusion

Two-dimensional (2D) nanomaterials have emerged as a transformative class of materials that are significantly advancing modern sensing technologies. Since the discovery of graphene, the expanding family of 2D materials, including transition metal dichalcogenides (TMDs), MXenes, black phosphorus, and porous crystalline frameworks such as metal–organic frameworks (MOFs) and covalent organic frameworks (COFs) has created new opportunities for developing highly sensitive and selective sensing platforms. Their atomically thin structures, large surface-to-volume ratios, tunable electronic properties, and excellent charge transport characteristics enable strong interactions with target analytes, allowing even subtle adsorption events to generate measurable electrical, electrochemical, or optical signals.

This review has summarized recent progress in emerging 2D nanomaterials for next-generation sensors, highlighting advanced design strategies, fundamental sensing mechanisms, and key application areas. Structural and surface engineering approaches such as defect engineering, heterostructure construction, and surface functionalization play a critical role in tailoring the electronic structure and adsorption behavior of 2D materials, thereby enhancing sensor sensitivity, selectivity, and response dynamics. Diverse sensing mechanisms, including field-effect transistor (FET) sensing, electrochemical detection, and optical transduction, further demonstrate the versatility of these materials as multifunctional sensing platforms.

Applications of 2D material-based sensors have expanded rapidly across biomedical diagnostics, environmental monitoring, and chemical detection. In biomedical systems, these sensors enable ultra-sensitive detection of disease biomarkers and viral proteins, supporting rapid point-of-care diagnostics and wearable health monitoring technologies. In environmental monitoring, 2D material sensors have demonstrated excellent performance in detecting toxic gases, volatile organic compounds, and heavy metal ions. Moreover, the integration of artificial intelligence (AI) and Internet of Things (IoT) technologies is enabling intelligent sensing systems capable of real-time monitoring and automated data analysis.

This review establishes a structured relationship between material properties, sensing mechanisms, and application performance in two-dimensional nanomaterial-based sensors. The findings demonstrate that engineering strategies such as defect tuning, heterostructure formation, and surface functionalization significantly influence sensing efficiency. The integration of artificial intelligence further enhances analytical capability and real-time decision-making. Future research should prioritize scalable synthesis, long-term stability, and standardized performance evaluation to enable practical deployment of intelligent sensing systems.

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