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REVIEW ARTICLE

2D Materials for Environment, Energy, and Biomedical Applications

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ABSTRACT

Recently 2D materials are booming in the field of energy, environment, and biomedical application. Incorporation of metal/non-metal within 2D materials significantly influences the physical and chemical properties, making them intriguing materials for various applications. The advancement of 2D material requires strategic modification by manipulating the electronic structure, which remains a challenge. Herein, we describe 2D materials for the environment, energy, and biomedical application. A predominant aim of this short communication is to summarize the literature on the advanced 2D materials for environment, energy, and biomedical application (especially COVID-19).

INTRODUCTION

Two Dimensional (2D) materials have appeared as a novel material platform due to their unique properties such as high surface area, large reactive sites, flexibility, tunable configuration to change the band gap, thickness at the atomic level, high conductivity, magnetic and fluorescence. These unique characteristic of the 2D materials make them an exceptional candidate for various end application mainly environmental remediation, energy, and biomedical application. Since, the discovery of single-layer graphene using mechanical exfoliation method by Andre Geim and Kostya Novoselov [1-3], a new era of 2D materials has lead that aided advantages in developing a next-generation innovative device with miniaturization and flexibility by assembling a single nanosheet. Moreover, high surface area with enormous active sites to move electrons, and mechanical stability are incorporated advantage of 2D materials. Numerous 2D materials such as Transition Metal Chalcogenides (TMDs), MXene, WS2, silicene, germanene, and phosphorene are another class of 2D materials having a surge of scientific and engineering interest as these materials are fulfilling the demand of advanced materials for energy, environmental, and biomedical application [4-6]. Additionally, their cutting edge properties such as reduction/oxidation ability in-plane electric conductivity, high reactivity, and high biocompatibility significantly aided advantages for energy and biomedical applications [7-10]. In this concern, electronic structure modulation with changes in the design and synthesis process of 2D materials to create feature-rich functional micro-architectures for sustainable energy, clean technologies, and biomedical applications remain a challenge. In this context, researchers continue to develop newer strategies to synthesize 2D materials that efficiently improve applicability in end applications.

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Various synthesis methods such as mechanical/liquid exfoliation, microwave synthesis, Chemical Vapor Deposition (CVD), hydrothermal, and self-assembly etc., have been used for the development of 2D materials. CVD is the most widely used method to synthesize the high-quality 2D material without defects or vacancy in the electronic structure. Moreover, the self-assembly method has attracted other methods for the synthesis of 2D materials because 2D-nano-architecture lacks intermolecular interaction such as hydrogen bonding or hydrophobic interaction during layer assembly that reduces agglomeration and restacking, thereby well-defined nano-architecture [11,12]. The process of self-assembling is different in the case of 2D material as this material exhibits wide distributed in-plane shape, and size. However, the other process is limited by their severe restacking and irreversible aggregation [13-16]. In this regard, tailoring the geometry of nano-architecture with exploiting the material properties is one of the significant tasks to design several nano-composite materials for next-generation materials for energy, environment, and biomedical application.

Recently, several researchers focusing synthesizing 2D materials mainly AgBiP2Se6 monolayer, BiOCl based nanosheet, Cu nanosheets, 2D-NiO, 2D/2D Z-scheme SnNb2O6/Bi2WO6 system, MOS2, MOSe2, WS2, WO3, graphene, and Graphene Oxide (GO) for various end applications such as environment, energy, and biomedical [17-28]. These studies are in good agreement with the use of 2D materials as an effective charge transport layer to apply as environment, energy, and biomedical application. Figure 1 shows the schematic representation of different 2D materials and their application. In this context, we devote attention towards various end application of 2D materials.

PROPERTIES OF 2D MATERIALS

The interaction of the analyte with 2D materials is essential in removing several contaminants from water, subsequently environmental protection. The most common properties of 2D material to deal with the environment is their large surface-to-volume ratio compared to other nanomaterials. A large surface-to-volume ratio creates a large interaction site, which subsequently helps create a strong force for removing analytes from contaminated water. Next, 2D materials are flexible to configurationally tuning, which supports modulating the band gap of these materials by playing in their electronic structure. These modifications require simple metal or non-metal doping or creating defects in their structure. The lower the band gap of 2D materials, the higher is the probability of oxidation and reduction reaction within the water to degrade contaminants. Further, these layered materials' atomic thickness significantly contributes to various inherent properties, mainly conductivity, reactivity, fluorescence, and magnetic permeability [29-35]. Such unique characteristic of the 2D materials makes

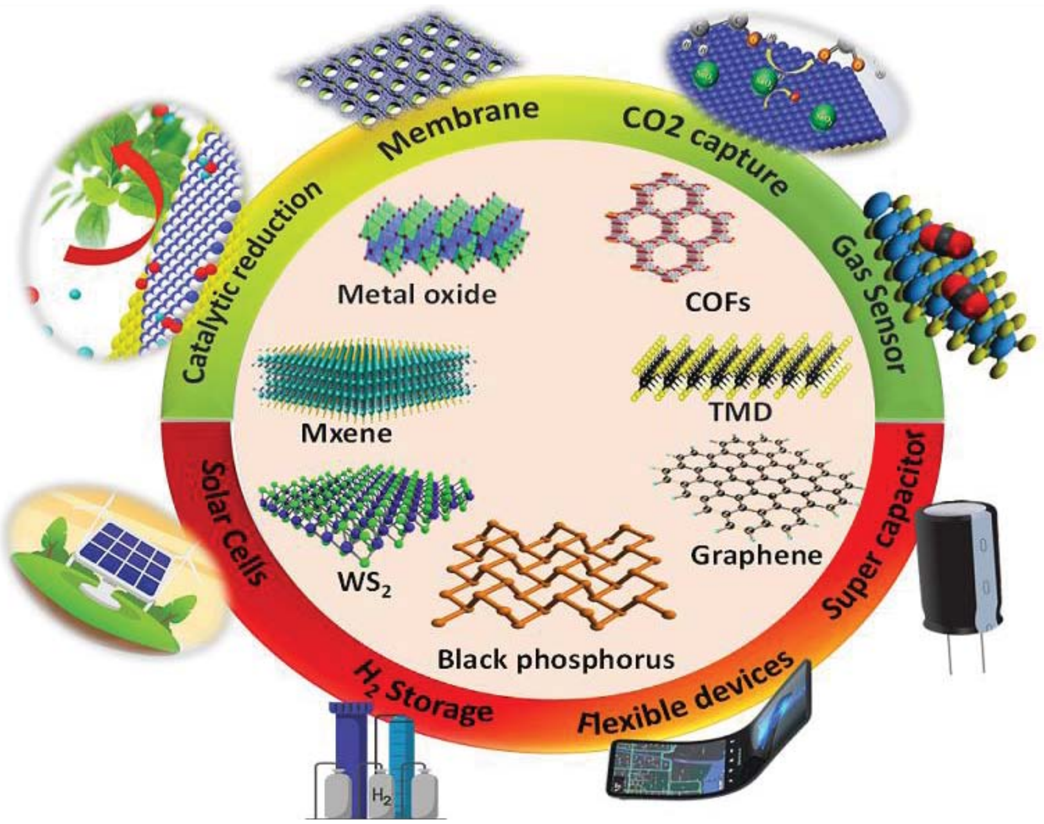

Figure 1 A schematically representation of different 2D materials and their applications.

them exceptional candidate for environmental remediation, energy, and biomedical applications.

APPLICATION OF 2D MATERIALS

2D materials for environmental remediation

2D materials offer a new avenue to explore high-performance filtration materials with high permeability and selectivity compared to other nanomaterials. Controlled pore size distribution, functional sites, and creation of heterojunction to lower the band gap can be utilized in separation process using 2D materials. Numerous studies focused on synthesizing several 2D materials for environmental remediation application; for example, Ikram, et al. [36] synthesized MoS2 nano petals for dye degradation. Iqbal, et al. [37] synthesized La and Mn-co-doped Bismuth Ferrite/Ti3C2 based composites for photodegradation of congo red dye. Another study by Zhu, et al. [38] synthesized MOF on BiOBr based 2D-nanosheet to degrade rhodamine, methylene blue, and methyl orange dye. These studies are based on 2D-nanosheet, and their composite for efficient degradation of various organic contaminants attributed active sites of the 2D materials binds with analyte and also create heterojunction. The heterojunction reduce the band gap position of CB and VB that improve photoelectron adsorption in visible range and degrade organic contaminants by taking part in redox reactions, subsequently support in the removal of contaminants from water.

Additionally, band gap modulation depends on various doping element as geometry and crystal shape efficiently helps to tune the chemical potential results in band gap modulation of 2D-2D heterojunction. Doping and organic functionalization introduce new density of state near fermi level leads to affect carrier density and new lattice constants, which are fundamental properties of 2D materials. The mechanical properties including high in plane stiffness and tensile strength with low flexible rigidity makes 2D materials an impressive candidate in various advance devices. These properties can also be modulated by incorporating various heteroatom doping as modification in these properties alter bond strength and geometry, subsequently lattice constant. Several examples of these modifications are Liu, et al. [39] synthesized 2D-ZnO based single-crystal nanosheets consist of mesoporous structure synthesized using an intriguing colloidal templating approach. The single synthesized crystal shows exposed polar facets, supporting selective adsorption and rhodamine B photodegradation. Another study by Monga, et al. [40] synthesized single-crystalline 2D-BiOCl nanorods decorated with 2D-MoS2 nanosheets. Incorporating MoS2 in BiOCl nanorods modulates the band gap supporting MB degradation and Cr(VI). The GO incorporated ZnO-based photocatalyst materials efficiently degrade dye molecules [41] (Figure 2). The photocatalytic activity of GO incorporated ZnO-based photocatalyst material. This literature shows that tunning and crystal modification provide high degradation efficiency for photodegradation of various pollutants due to change in their electronic structure followed by bandgap lowering so that it can absorb visible light radiation and work under the normal environmental condition reduce contaminants from environments.

2D materials for energy applications

2D materials possess several unique properties such as mechanical robustness, high surface area, functional sites, and mass transport in advanced electronic devices. The working mechanism behind the success of 2D material in energy storage is based on their ability to capture charge and effectively transport or store it inside the structure or migrate through the ions on the surface [42-45]. Researchers found several ways, such as doping, intercalation, altering the chemical composition, etc., to enhance the spacing of the layers of 2D materials to store or transport charge to control charge effectively. To synthesize a promising electrode material, foreign ions can be intercalated between the layers of 2D materials as the layers are stacked together through weak interactions, which allow ions or molecules to pass through them or store inside them to form active sites [46,47]. The particle size and morphology are also significant to enhance charge storage performance. For example, Feng et al. synthesize MoS2 nanoflake having curves to form nanotube-like morphology. This morphology allows Li+ to intercalate easily and increase the battery performance compared to MoS2 nanosheets [48]. Another study by Teng, et al. [49] synthesized MoS2 nanosheet grown over graphene. The MoS2 is grown vertically over graphene using the hydrothermal method. This creates an enormous oxygen functional group on the surface result in enhance charge transport, subsequent high-rate performance, and cycling stability as lithium-ion battery electrodes. Liu synthesized V2C MXene by self-discharge method for hybrid batteries that allows Li ions to pass through the interlayer space and increase the spacing between the layers, which provides ample space for ion diffusion [50]. These studies suggest that the intercalation of foreign ions enhances battery performance by increasing the gap between layers to facilitate ions' transport in advance battery performance.

Similarly, 2D material has an advantage when combined with other nanomaterials as interfacial transfer significantly affects the performance of 2D materials. For example, Wen, et al. [51] synthesized nitrogen (N)-doped MXene (N-MXene). N-MXene increases the c-lattice parameters of MXene. Post etching annealing method with ammonia was used to synthesize MXene. The N-MXene increased gravimetric capacitance performance and is considered a promising candidate in supercapacitor application. Similarly, pseudo-capacitance can be improved by incorporating oxygen functional group in MXene surface to initiate redox reaction over the surface of MXene subsequently increase performance. For example, Zhang, et al. [52] synthesized

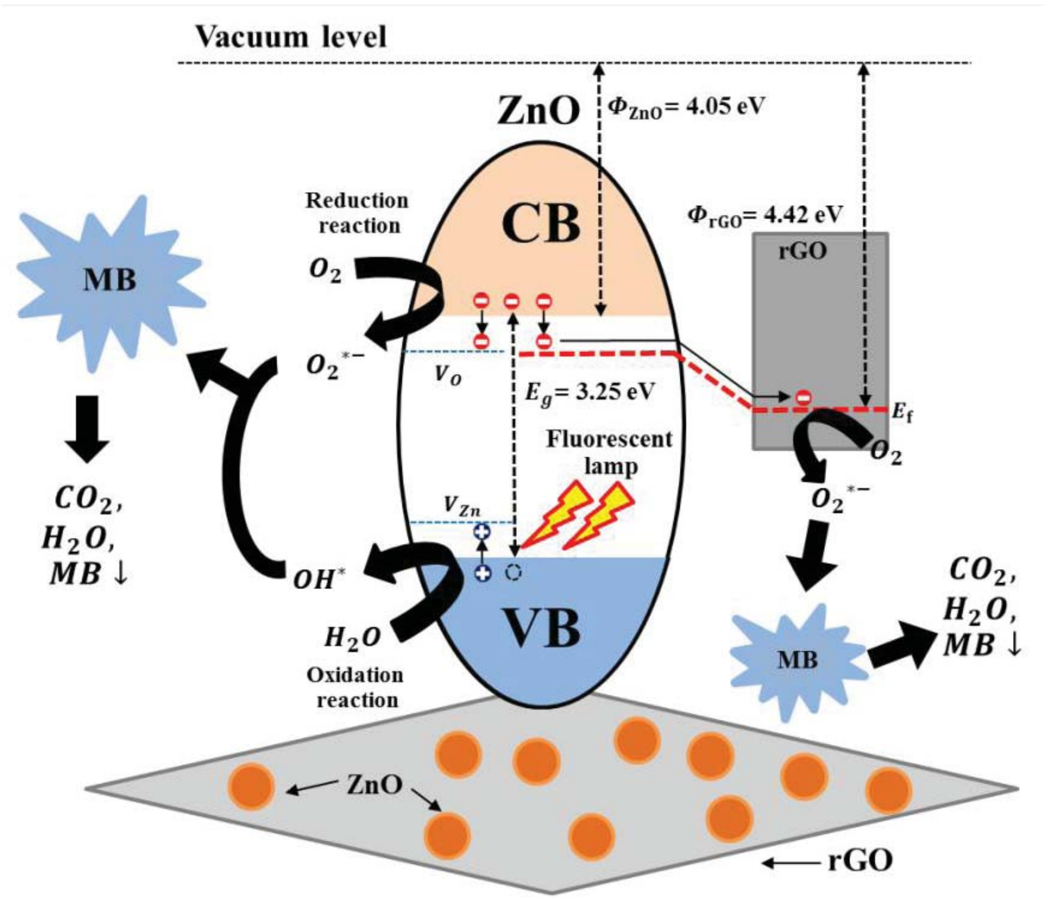

Figure 2 The photocatalytic activity of GO incorporated ZnO-based photocatalyst material. The image was taken with permission [41]. Creative Commons Attribution 2019.

Ti3C2Tx by controlled oxidation using ammonium persulfate, which changes F terminals into O terminals results in high capacitance performance. Jiang, et al. [53] synthesized MXene-RuO2 composite for the supercapacitor application. The material works as an asymmetric electrode by the following pseudocapacitance, significantly increasing the device's performance.

Recently flexible micro-supercapacitors are designed to fulfill the next-generation foldable electronic devices. In this aspect, MXene based 2D materials are considered promising due to their high mechanical stability and ability to store or transport charges within the interlayer space. These flexible devices exhibit high volumetric capacitance, such as Yan et al. synthesized MXene/GO based electrode using electrostatic self-assembly method. In this, rGO was modified with poly(diallyl dimethylammonium chloride) and then inserted between the MXene layer space to design a free-standing electrode with large ion diffusion, which subsequently increases the volumetric capacitance [54]. Another study by Yang et al. reported free-standing MXene as a current collector free electrode for supercapacitor application [55]. The GO-MoS2-WS2 based ternary materials for efficiently used in supercapacitor applications [56] (Figure 3). Synthesis of 2D materials for supercapacitors application. All these studies suggest the applicability of 2D materials in advanced electronic devices.

2D materials for Coronavirus

Material science and engineering are imperative for antiviral research, such as the morphology of the viral structure and biology, diagnosis, and treatment. Usually, the development of practical approaches to protecting, diagnosing, and treating viral diseases requires a detailed study of structure, transmission, and viral sequence.

Importance of structure and viral sequence: With the help of confocal microscopy, individual viruses can be tracked in cells, thereby quickly understanding the mode of action. Nanotechnology or nanopore sequencing has contributed in next-generation sequencing platforms. With the help of nanopore sequencing/gene sequencing, researchers can synthesize the viral protein, and their 3D-structure can be rebuilt by using electron microscopy, X-ray crystallography, and NMR spectroscopy. However, a higher concentration of protein and stability are required for X-ray crystallography and NMR spectroscopy analysis. In this context, single-particle cryo-electron microscopy

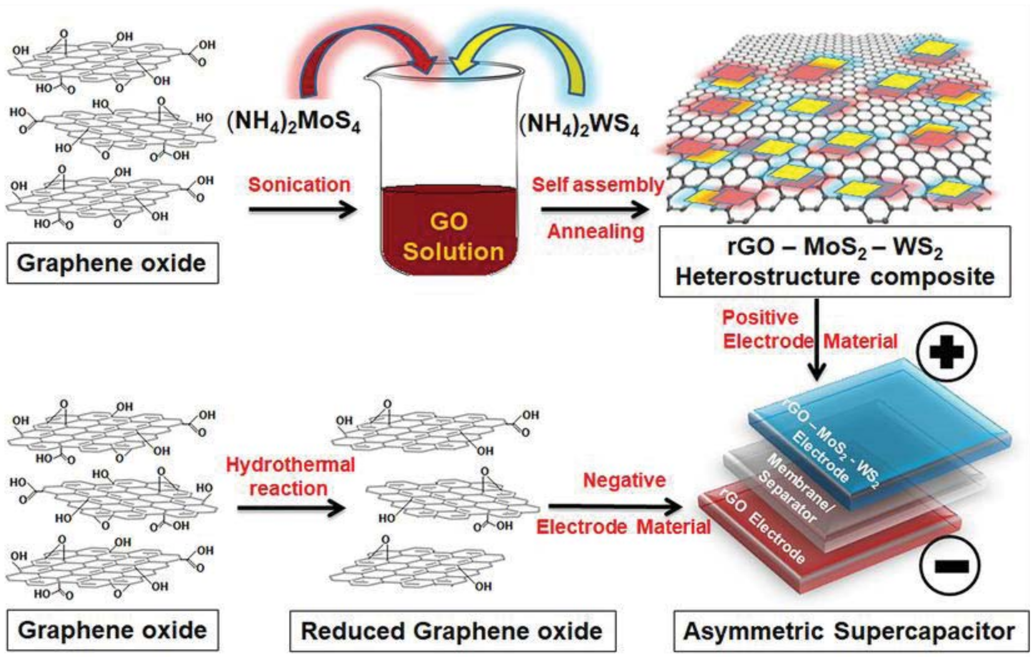

Figure 3 Synthesis of 2D materials for supercapacitors application. The image was taken with permission [56].

has the potential ability to ascertaining the morphology of the viruses. Single-particle cryo-electron microscopy quickly determined the structure of viruses, including SARS-CoV-2. Interestingly, the understanding of material science and viruses has played an essential role in enhancing the sensitivity and selectivity of the particular biomolecules, including SARS-CoV-2 [57,58].

Protection against infection: Usually, viruses replicate within the living cells and are transmitted through air, blood, bloodsucking insects, mucus, anal, vaginal fluid, semen, saliva, and direct contact. Initially, SARS-CoV-2 binds with the host cell using the binding of S protein to the angiotensin-converting enzymes-2 (ACE-2) receptor that allows it to enter the cell and release viral RNA. In other words, the virus captures the host cell to synthesize RNA and produce structural protein that gathers into the new virus, which is released from the host cell. This process is repetitive; thereby SARS-CoV-2 infects human as well as animal. Usually, gloves, masks, face shields, and protective suits are the direct process for the protection against SARS-CoV-2. The surgical masks made of different layers protect against the entry of viruses. Numerous materials such as polymeric film with nanopores, carbon-based materials, and 2D materials were used to synthesize protective coating. However, due to safety and cost concerns, these nanomaterials have not been used to protect viruses, especially SARS-CoV-2. Researchers continue to focus on the toxicity aspects of nanomaterials, including 2D-materials, which suggest that most nanomaterials, mainly carbon-based nanomaterials have insignificant toxicity, which is safer to be used as protective agents.

Detection of SARS-CoV-2: Usually, rapid identification or detection of SARS-CoV-2 infected patients helps to control the viral infection. The immunoassay and Polymerase Chain Reaction (PCR) are extensively used to detect SARS-CoV-2 infection through protein and nucleic acid. The sensitivity and selectivity of the immunoassay mainly depend on the materials and instruments. Numerous 2D materials, such as graphene, have been used to detect SARS-CoV-2 or its variant COVID-19 [59-61]. For example, Fathi-Hafshejani, et al. [62] fabricated the WSe2 based Fet-based COVID biosensor. The data suggested that the SARS-CoV-2 antibody was immobilized onto the WSe2 through 11-mercaptoundecanoic acid-activated N-hydroxysuccinimide and carbodiimide hydrochloride, thereby efficiently detect SARS-CoV-2 infection. Seo, et al. [63] fabricated graphene (as a sensing material) based FET sensor to detect SARS-CoV-2 infection. The data suggested that the graphene conjugated with the spike protein via 1- pyrene butyric acid N-hydroxysuccinimide ester. The prepared biosensor is highly sensitive and detects SARS-CoV-2 in the clinical sample. Muratore, et al. [64] fabricated the MoS2 based biosensor for the detection of SARS-CoV-2 and influenza virus. The data suggested that the sulfur vacancy of MoS2 aided advantages to bind ACE-2 enzymes with the SARS-CoV-2 samples. The angiostatin converts ACE-2 enzyme for the spike protein of SARS-CoV-2 that modified protein acted as recognizing element for the detection of SARS-CoV-2.

In general, functionalized 2D-material-based biosensors offer simple, cost-effective, sensitive, and highly responsive for detecting SARS-CoV-2. The pandemic of COVID-19 required newer technologies that efficiently combat the

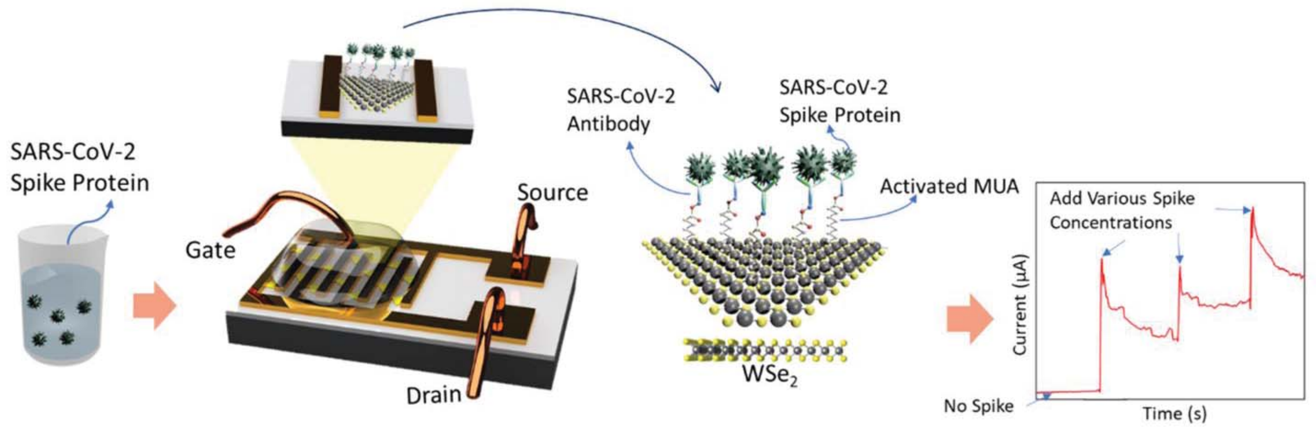

Figure 4 A schematic illustration of the WSe2 based FET sensor for the detection of SARS-CoV-2. The image was taken with permission [62].

life threatens viruses. The exceptional characteristics such as high electrical, mechanical and functional ability of the 2D-materials like graphene and its derivative make a suitable candidate for making a novel and innovative sensing device [65-69]. Figure 4 shows the schematic illustration of the WSe2 based FET sensor for the detection of SARS-CoV-2. The 2D-materials-based novel sensing device might be efficiently tackled COVID-19. Moreover, 2D materials provide a technological platform for the protection, detection, and treatment of life-threatening viral diseases.

CONCLUSION

In summary, 2D materials are a promising candidate for advanced environments, energy devices, and biomedical applications. The technological advancement eventually depends on structural modifications of 2D materials. Several strategies such as band gap tunning, deformation control, and surface chemistry modifications are essential to enhance performance. Environmental application of 2D materials needs specific bonding toward analyte to remove the analyte from solution. However, energy application requires high surface area, active sites, mechanical stability, and flexibility. 2D materials need more understanding as they may have both positive and negative responses towards biomedical application in terms of toxicity and impact over the cell. Hence, future demand of 2D materials concluded that specific modification promotes the applicability of 2D material in several end applications, including energy, environment, and biomedical.

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References

1. Geng D, Yang HY. Recent Advances in Growth of Novel 2D Materials: Beyond Graphene and Transition Metal Dichalcogenides. Adv Mater. 2018 Nov;30(45):e1800865. doi: 10.1002/adma.201800865. Epub 2018 Jul 31. PMID: 30063268.
2. Niu T, Zhang J, Chen W. Surface Engineering of Two-Dimensional Materials. ChemNanoMat. 2019;5:6-23. doi: 10.1002/cnma.201800181.
3. Ng SW, Noor N, Zheng Z. Graphene-based two-dimensional Janus materials. NPG Asia Materials. 2018;10:217-237. https://go.nature.com/3vMZJos
4. Peng X, Peng L, Wu C, Xie Y. Two dimensional nanomaterials for flexible supercapacitors. Chem Soc Rev. 2014 May 21;43(10):3303-23. doi: 10.1039/c3cs60407a. Epub 2014 Mar 11. PMID: 24614864.
5. Zhang P , Wang F , Yu M , Zhuang X , Feng X . Two-dimensional materials for miniaturized energy storage devices: from individual devices to smart integrated systems. Chem Soc Rev. 2018 Oct 1;47(19):7426-7451. doi: 10.1039/c8cs00561c. PMID: 30206606.
6. Li X, Ran F, Yang F, Long J, Shao L. Advances in MXene Films: Synthesis, Assembly, and Applications. Transactions of Tianjin University. 2021;27:217-247. https://bit.ly/312ITYO
7. Bhat A, Anwer S, Bhat KS, Mohideen MIH, Liao K, Qurashi A. Prospects challenges and stability of 2D MXenes for clean energy conversion and storage applications. 2D Materials and Applications. 2021;5:61. https://go.nature.com/3nyCL0Z
8. Yildiz G, Bolton-Warberg M, Awaja F. Graphene and graphene oxide for bio-sensing: General properties and the effects of graphene ripples. Acta Biomater. 2021 Sep 1;131:62-79. doi: 10.1016/j.actbio.2021.06.047. Epub 2021 Jul 5. PMID: 34237423.
9. Wang Y, Wang L, Zhang X, Liang X, Y. Feng, W. Feng, Two-dimensional nanomaterials with engineered bandgap: Synthesis, properties, applications. Nano Today. 2021;37:101059. doi: 0.1016/j.nantod.2020.101059.
10. Mathkar, Tozier D, Cox P, Ong P, Galande C, Balakrishnan K, Leela Mohana Reddy A, Ajayan PM. Controlled, Stepwise Reduction and Band Gap Manipulation of Graphene Oxide. The Journal of Physical Chemistry Letters. 2012;3:986-991.
11. Ikram R, Jan BM, Ahmad W. Advances in synthesis of graphene derivatives using industrial wastes precursors; prospects and challenges. Journal of Materials Research and Technology. 2020;9:15924-15951. doi: 10.1016/j.jmrt.2020.11.043.
12. Saha JK, Dutta A. A Review of Graphene: Material Synthesis from Biomass Sources. Waste Biomass Valorization. 2021 Sep 17:1-45. doi: 10.1007/s12649-021-01577-w. Epub ahead of print. PMID: 34548888; PMCID: PMC8446731.
13. Jeevanandam J, Barhoum A, Chan YS, Dufresne A, Danquah MK. Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations. Beilstein J Nanotechnol. 2018 Apr 3;9:1050-1074. doi: 10.3762/bjnano.9.98. PMID: 29719757; PMCID: PMC5905289.
14. Ariga K, Watanabe S, Mori T, Takeya J. Soft 2D nanoarchitectonics. NPG Asia Materials. 2018;10:90-106. https://go.nature.com/3pGbSdT
15. Schneemann A, Dong R, Schwotzer F, Zhong H, Senkovska I, Feng X, Kaskel S. 2D framework materials for energy applications. Chemical Science. 2021;12:1600-1619. doi: 10.1039/D0SC05889K.
16. Liu H, Hsu CH, Lin Z, Shan W, Wang J, Jiang J, Huang M, Lotz B, Yu X, Zhang WB, Yue K, Cheng SZD. Two-Dimensional Nanocrystals of Molecular Janus Particles. Journal of the American Chemical Society. 2014;136:10691-10699. doi: 10.1021/ja504497h.
17. Pan Z, Li J, Zhou K. Wrinkle-free atomically thin CdS nanosheets for photocatalytic hydrogen evolution. Nanotechnology. 2018 May 25;29(21):215402. doi: 10.1088/1361-6528/aab4d5. Epub 2018 Mar 7. PMID: 29513263.

18. Ju L, Shang J, Tang X, Kou L. Tunable Photocatalytic Water Splitting by the Ferroelectric Switch in a 2D AgBiP2Se6 Monolayer. Journal of the American Chemical Society. 2020;142:1492-1500. doi: 10.1021/jacs.9b11614.

19. Yan X, Zhao H, Li T, Zhang W, Liu Q, Yuan Y, Huang L, Yao L, Yao J, Su H, Su Y, Gu J, Zhang D. In situ synthesis of BiOCl nanosheets on three-dimensional hierarchical structures for efficient photocatalysis under visible light. Nanoscale. 2019;11:10203-10208. https://rsc.li/3jH6e7x.

20. Yousaf Z, Sajjad S, Ahmed Khan Leghari S, Mehboob M, Kanwal A, Uzair B. Interfacial charge transfer via 2D-NiO and 2D-graphene nanosheets combination for significant visible photocatalysis. Journal of Solid State Chemistry. 2020;291:121606. doi: 10.1016/j.jssc.2020.121606.

21. Jiang R, Lu G, Yan Z, Wu D, Liu J, Zhang X. Enhanced photocatalytic activity of a hydrogen bond-assisted 2D/2D Z-scheme SnNb2O6/Bi2WO6 system: Highly efficient separation of photoinduced carriers. Journal of Colloid and Interface Science. 2019;552:678-688. doi: 10.1016/j.jcis.2019.05.104.

22. Chauhan D, Talreja N, Ashfaq M, Chapter 13 - Nanoadsorbents for wastewater remediation. In: Abd-Elsalam KA, Zahid M (Eds.) Aquananotechnology. Elsevier; 2021. p. 273-290. https://bit.ly/3CoV26Y

23. Ashfaq M, Talreja N, Chauhan D, Rodríguez A, Mera AC, Mangalaraja RV. A novel bimetallic (Fe/Bi)-povidone-iodine micro-flowers composite for photocatalytic and antibacterial applications. Journal of Photochemistry and Photobiology B: Biology. 2021;219:112204. doi: 10.1016/j.jphotobiol.2021.112204.

24. Sasidharan V, Sachan D, Chauhan D, Talreja N, Ashfaq M. Three-dimensional (3D) polymer-metal-carbon framework for efficient removal of chemical and biological contaminants. Scientific Reports. 2021;11:7708. https://go.nature.com/3vLVLMU

25. Afreen S, Omar RA, Talreja N, Chauhan D, Ashfaq M. Carbon-Based Nanostructured Materials for Energy and Environmental Remediation Applications. In: Prasad R, Aranda E (Eds.) Approaches in Bioremediation: The New Era of Environmental Microbiology and Nanobiotechnology. Springer International Publishing; Cham: 2018. p. 369-392. https://bit.ly/3GjH8W2

26. Ashfaq M, Talreja N, Chuahan D, Srituravanich W. Carbon Nanostructure-Based Materials: A Novel Tool for Detection of Alzheimer's Disease. In: Ashraf GM, Alexiou A (Eds.) Biological, Diagnostic and Therapeutic Advances in Alzheimer's Disease: Non-Pharmacological Therapies for Alzheimer's Disease. Singapore: Springer Singapore; 2019. p. 71-89. https://bit.ly/3ElJhPf

27. Irsad, Talreja N, Chauhan D, Rodríguez CA, Mera AC, Ashfaq M. Nanocarriers: An Emerging Tool for Micronutrient Delivery in Plants. In: Aftab T, Hakeem KR (Eds.) Plant Micronutrients: Deficiency and Toxicity Management, Springer International Publishing; Cham: 2020. p. 373-387. https://bit.ly/3blGadv

28. Afreen A, Talreja N, Chauhan D, Ashfaq M, Chapter 15 - Polymer/metal/carbon-based hybrid materials for the detection of heavy metal ions. In: Abd-Elsalam KA (Ed.) Multifunctional Hybrid Nanomaterials for Sustainable Agri-Food and Ecosystems. Elsevier; 2020. p. 335-353.

29. Tyagi D, Wang H, Huang W, Hu L, Tang Y, Guo Z, Ouyang Z, Zhang H. Recent advances in two-dimensional-material-based sensing technology toward health and environmental monitoring applications. Nanoscale. 2020 Feb 14;12(6):3535-3559. doi: 10.1039/c9nr10178k. Epub 2020 Jan 31. PMID: 32003390.

30. Hu R, Liao G, Huang Z, Qiao H, Liu H, Shu Y, Wang B, Qi X. Recent advances of monoelemental 2D materials for photocatalytic applications. J Hazard Mater. 2021 Mar 5;405:124179. doi: 10.1016/j.jhazmat.2020.124179. Epub 2020 Oct 23. PMID: 33261976.

31. Zhang K, Feng Y, Wang F, Yang Z, Wang J. Two dimensional hexagonal boron nitride (2D-hBN): synthesis, properties and applications. Journal of Materials Chemistry C. 2017;5:11992-12022. https://rsc.li/2ZsBBf3

32. Kanahashi K, Pu J, Takenobu T. 2D Materials for Large-Area Flexible Thermoelectric Devices. Advanced Energy Materials. 2020;10:1902842. doi: 10.1002/aenm.201902842.

33. Sun Z, Talreja N, Tao H, Texter J, Muhler M, Strunk J, Chen J. Catalysis of Carbon Dioxide Photoreduction on Nanosheets: Fundamentals and Challenges. Angew Chem Int Ed Engl. 2018 Jun 25;57(26):7610-7627. doi: 10.1002/anie.201710509. Epub 2018 May 16. PMID: 29219235.

34. Tao H, Gao Y, Talreja N, Guo F, Texter J, Yan C, Sun Z. Two-dimensional nanosheets for electrocatalysis in energy generation and conversion. Journal of Materials Chemistry A. 2017;5:7257-7284. https://rsc.li/3nqCPzu

35. Chauhan D, Afreen S, Talreja N, Ashfaq M. Chapter 8 - Multifunctional copper polymer-based nanocomposite for environmental and agricultural applications. In: Abd-Elsalam KA (Ed.) Multifunctional Hybrid Nanomaterials for Sustainable Agri-Food and Ecosystems. Elsevier; 2020. p. 189-211.

36. Ikram M, Khan MI, Raza A, Imran M, Ul-Hamid A, Ali S. Outstanding performance of silver-decorated MoS2 nanopetals used as nanocatalyst for synthetic dye degradation. Physica E: Low-dimensional Systems and Nanostructures. 2020;124:114246. doi: 10.1016/j.physe.2020.114246.

37. Iqbal MA, Ali SI, Amin F, Tariq A, Iqbal MZ, Rizwan S. La- and Mn-Codoped Bismuth Ferrite/Ti_3C_2 MXene Composites for Efficient Photocatalytic Degradation of Congo Red Dye. ACS Omega. 2019 May 17;4(5):8661-8668. doi: 10.1021/acsomega.9b00493. PMID: 31459955; PMCID: PMC6648404.

38. Zhu SR, Wu MK, Zhao WN, Liu PF, Yi FY, Li GC, Tao K, Han L. In Situ Growth of Metal–Organic Framework on BiOBr 2D Material with Excellent Photocatalytic Activity for Dye Degradation. Crystal Growth & Design. 2017;17:2309-2313. doi: 10.1021/acs.cgd.6b01811.

39. Liu J, Hu ZY, Peng Y, Huang HW, Li Y, Wu M, Ke XX, Tendeloo GV, Su BL. 2D ZnO mesoporous single-crystal nanosheets with exposed {0001} polar facets for the depollution of cationic dye molecules by highly selective adsorption and photocatalytic decomposition. Applied Catalysis B: Environmental. 2016;181:138-145. doi: 10.1016/j.apcatb.2015.07.054.

40. Monga D, Basu S. Single-crystalline 2D BiOCl nanorods decorated with 2D MoS2 nanosheets for visible light-driven photocatalytic detoxification of organic and inorganic pollutants. FlatChem. 2021;28:100267. doi: 10.1016/j.flatc.2021.100267.

41. Rodwihok C, Wongratanaphisan D, Thi Ngo YL, Khandelwal M, Hur SH, Chung JS. Effect of GO Additive in ZnO/rGO Nanocomposites with Enhanced Photosensitivity and Photocatalytic Activity. Nanomaterials (Basel). 2019 Oct 11;9(10):1441. doi: 10.3390/nano9101441. PMID: 31614525; PMCID: PMC6835891.

42. Talreja N, Jung S, Yen LTH, Kim T. Phenol-formaldehyde-resin-based activated carbons with controlled pore size distribution for high-performance supercapacitors. Chemical Engineering Journal. 2020;379:122332.

43. Forouzandeh P, Pillai SC. Two-dimensional (2D) electrode materials for supercapacitors. Materials Today: Proceedings. 2021;41:498-505. doi: 10.1016/j.matpr.2020.05.233.

44. Pomerantseva E, Gogotsi Y. Two-dimensional heterostructures for energy storage. Nature Energy. 2017;2: 17089. https://go.nature.com/3BdnqHS

45. Khan K , Tareen AK , Aslam M , Zhang Y , Wang R , Ouyang Z , Gou Z , Zhang H . Recent advances in two-dimensional materials and their nanocomposites in sustainable energy conversion applications. Nanoscale. 2019 Nov 21;11(45):21622-21678. doi: 10.1039/c9nr05919a. PMID: 31702753.

46. Rajapakse M, Karki B, Abu UO, Pishgar S, Musa MRK, Riyadh SMS, Yu M, Sumanasekera G, Jasinski JB. Intercalation as a versatile tool for fabrication, property tuning, and phase transitions in 2D materials. npj 2D Materials and Applications. 2021;5:30. https://go.nature.com/2XOKuPz

47. Wang Z, Li R, Su C, Loh KP. Intercalated phases of transition metal dichalcogenides. SmartMat. 2020;1:e1013. doi: 10.1002/smm2.1013.

48. Feng C, Ma J, Li H, Zeng R, Guo Z, Liu H. Synthesis of molybdenum disulfide (MoS2) for lithium ion battery applications. Materials Research Bulletin. 2009;44:1811-1815. doi: 10.1016/j.materresbull.2009.05.018.

49. Teng Y, Zhao H, Zhang Z, Li Z, Xia Q, Zhang Y, Zhao L, Du X, Du Z, Lv P, Świerczek K. MoS2 Nanosheets Vertically Grown on Graphene Sheets for Lithium-Ion Battery Anodes. ACS Nano. 2016 Sep 27;10(9):8526-35. doi: 10.1021/acsnano.6b03683. Epub 2016 Aug 26. PMID: 27556425.

50. Liu F, Liu Y, Zhao X, Liu K, Yin H, Fan LZ. Prelithiated V_2 C MXene: A High-Performance Electrode for Hybrid Magnesium/Lithium-Ion Batteries by Ion Cointercalation. Small. 2020 Feb;16(8):e1906076. doi: 10.1002/smll.201906076. Epub 2020 Jan 27. PMID: 31984674.

51. Wen Y, Rufford TE, Chen X, Li N, Lyu M, Dai L, Wang L. Nitrogen-doped Ti3C2Tx MXene electrodes for high-performance supercapacitors. Nano Energy. 2017;38:368-376. doi: 10.1016/j.nanoen.2017.06.009.

52. Zhang M, Chen X, Sui J, Abraha BS, Li Y, Peng W, Zhang G, Zhang F, Fan X. Improving the performance of a titanium carbide MXene in supercapacitors by partial oxidation treatment. Inorganic Chemistry Frontiers. 2020;7:1205-1211. https://rsc.li/3jIOrNl

53. Jiang Q, Kurra N, Alhabeb M, Gogotsi Y, Alshareef HN. All Pseudocapacitive MXene-RuO2 Asymmetric Supercapacitors. Advanced Energy Materials. 2018;8:1703043. doi: 10.1002/aenm.201703043.

54. Yan J, Ren CE, Maleski K, Hatter CB, Anasori B, Urbankowski P, Sarycheva A, Gogotsi Y. Flexible MXene/Graphene Films for Ultrafast Supercapacitors with Outstanding Volumetric Capacitance. Advanced Functional Materials. 2017;27:1701264. doi: 10.1002/adfm.201701264.

55. Yang W, Yang J, Byun JJ, Moissinac FP, Xu J, Haigh SJ, Domingos M, Bissett MA, Dryfe RAW, Barg S. 3D Printing of Freestanding MXene Architectures for Current-Collector-Free Supercapacitors. Adv Mater. 2019 Sep;31(37):e1902725. doi: 10.1002/adma.201902725. Epub 2019 Jul 25. PMID: 31343084.

56. Lin TW, Sadhasivam T, Wang AY, Chen TY, Lin JY, Shao LD. Ternary Composite

Nanosheets with MoS2/WS2/Graphene Heterostructures as High-Performance Cathode Materials for Supercapacitors. ChemElectroChem. 2018;5:1024-1031. doi: 10.1002/celc.201800043.

57. Chauhan G, Madou MJ, Kalra S, Chopra V, Ghosh D, Martinez-Chapa SO. Nanotechnology for COVID-19: Therapeutics and Vaccine Research. ACS Nano. 2020 Jul 28;14(7):7760-7782. doi: 10.1021/acsnano.0c04006. Epub 2020 Jun 29. PMID: 32571007; PMCID: PMC7325519.

58. Varongchayakul N , Song J , Meller A , Grinstaff MW . Single-molecule protein sensing in a nanopore: a tutorial. Chem Soc Rev. 2018 Nov 26;47(23):8512-8524. doi: 10.1039/c8cs00106e. PMID: 30328860; PMCID: PMC6309966.

59. Mohseni AH, Taghinezhad-S S, Xu Z, Fu X. Body fluids may contribute to human-to-human transmission of severe acute respiratory syndrome coronavirus 2: evidence and practical experience. Chin Med. 2020 Jun 5;15:58. doi: 10.1186/s13020-020-00337-7. PMID: 32514291; PMCID: PMC7273816.

60. Navarra A, Albani E, Castellano S, Arruzzolo L, Levi-Setti PE. Coronavirus Disease-19 Infection: Implications on Male Fertility and Reproduction. Front Physiol. 2020 Nov 17;11:574761. doi: 10.3389/fphys.2020.574761. PMID: 33312128; PMCID: PMC7704452.

61. Morelli F, Meirelles LEF, de Souza MVF, Mari NL, Mesquita CSS, Dartibale CB, Damke GMZF, Damke E, da Silva VRS, Souza RP, Consolaro MEL. COVID-19 Infection in the Human Reproductive Tract of Men and Nonpregnant Women. Am J Trop Med Hyg. 2021 Jan 18;104(3):814–25. doi: 10.4269/ajtmh.20-1098. Epub ahead of print. PMID: 33534765; PMCID: PMC7941816.

62. Fathi-Hafshejani P, Azam N, Wang L, Kuroda MA, Hamilton MC, Hasim S, Mahjouri-Samani M. Two-Dimensional-Material-Based Field-Effect Transistor Biosensor for Detecting COVID-19 Virus (SARS-CoV-2). ACS Nano. 2021 Jun 28:acsnano.1c01188. doi: 10.1021/acsnano.1c01188. Epub ahead of print. PMID: 34181385; PMCID: PMC8265534.

63. Seo G, Lee G, Kim MJ, Baek SH, Choi M, Ku KB, Lee CS, Jun S, Park D, Kim HG, Kim SJ, Lee JO, Kim BT, Park EC, Kim SI. Rapid Detection of COVID-19 Causative Virus (SARS-CoV-2) in Human Nasopharyngeal Swab Specimens Using Field-Effect Transistor-Based Biosensor. ACS Nano. 2020 Apr 28;14(4):5135-5142. doi: 10.1021/acsnano.0c02823. Epub 2020 Apr 20. Erratum in: ACS Nano. 2020 Sep 22;14(9):12257-12258. PMID: 32293168; PMCID: PMC7172500.

64. Muratore C, Muratore MK, Austin DR, Look P, Benton AK, Beagle LK, Motala MJ, Moore DC, Brothers MC, Kim SS, Krupa K, Back TA, Grant JT, Glavin NR. Biofunctionalized Two-dimensional MoS_2Receptors for Rapid Response Modular Electronic SARS-CoV-2 and Influenza A Antigen Sensors. medRxiv. 2020. doi: 10.1101/2020.11.17.20233569.

65. Afroj S, Britnell L, Hasan T, Andreeva DV, Novoselov KS, Karim N. Graphene-Based Technologies for Tackling COVID-19 and Future Pandemics. Advanced Functional Materials. 2021;2107407. doi: 10.1002/adfm.202107407.

66. Kevadiya BD, Machhi J, Herskovitz J, Oleynikov MD, Blomberg WR, Bajwa N, Soni D, Das S, Hasan M, Patel M, Senan AM, Gorantla S, McMillan J, Edagwa B, Eisenberg R, Gurumurthy CB, Reid SPM, Punyadeera C, Chang L, Gendelman HE. Diagnostics for SARS-CoV-2 infections. Nat Mater. 2021 May;20(5):593-605. doi: 10.1038/s41563-020-00906-z. Epub 2021 Feb 15. PMID: 33589798; PMCID: PMC8264308.

67. Lam CY, Zhang Q, Yin B, Huang Y, Wang H, Yang M, Wong SH. Recent Advances in Two-Dimensional Transition Metal Dichalcogenide Nanocomposites Biosensors for Virus Detection before and during COVID-19 Outbreak. Journal of Composites Science. 2021;5. doi: 10.3390/jcs5070190.

68. Zhang B, Sun JY, Ruan MY, Gao PX. Tailoring two-dimensional nanomaterials by structural engineering for chemical and biological sensing. Sensors and Actuators Reports. 2020;2:100024. doi: 10.1016/j.snr.2020.100024.

69. Khedri M, Maleki R, Dahri M, Sadeghi MM, Rezvantalab S, Santos HA, Shahbazi MA. Engineering of 2D nanomaterials to trap and kill SARS-CoV-2: a new insight from multi-microsecond atomistic simulations. Drug Deliv Transl Res. 2021 Sep 3:1–15. doi: 10.1007/s13346-021-01054-w. Epub ahead of print. PMID: 34476766; PMCID: PMC8413075.

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