

A COMPREHENSIVE REVIEW ON ADVANCED MATERIALS FOR POLLUTION CONTROL AND ENVIRONMENTAL SUSTAINABILITY

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ABSTRACT

Rapid industrialization and urbanization have intensified the need for effective and sustainable environmental remediation technologies. Advanced materials such as metal organic frameworks (MOFs), graphene-based nanomaterials, Menes, and graphitic carbon nitride (g-C₃N₄) offer promising solutions for water purification, air filtration, and pollutant degradation due to their tenable structures, large surface areas, and catalytic properties. This review highlights recent progress in the synthesis, modification, and application of these materials for environmental purposes. It discusses their mechanisms of pollutant adsorption, photocatalysis, and electrochemical treatment, along with performance comparisons and key limitations such as stability, toxicity, and scalability. The paper further outlines future research priorities including green synthesis, lifecycle assessment, and safe large-scale deployment. Through this discussion, the review aims to bridge laboratory-scale innovation with real-world environmental challenges, contributing to the development of efficient, durable, and sustainable material-based treatment systems.



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I. INTRODUCTION

The worldwide growing demand for energy and materials and industrial products has resulted in severe pollution of water, air, and soil ecosystems. During the last twenty years, heavy metals, dyes, pesticides VOCs and greenhouse gases have become harmful to both environment and human health. Conventional pollution control methods for example chemical oxidation, settling and mechanical filtration, are often ineffective and/or energy consuming or produce secondary waste streams. The restrictions can be surmounted by new materials and these are available to us. They give physicochemical properties for the enhancement of adsorption, oxidation catalysis or filtration performance. For example, MOFs provide programmable water and gas purifying pore structures, while graphene-based materials have good adsorption properties and conductivity. Visible light active as well biochar adsorbents synthesized from biomass are combined into activities for pollution abatement and carbon capture/agriculture applications. In this review, an effort has been made to include the recent development (2020–2025) of advanced materials for environmental sustainability. It is aimed at comprehensively analysing the material synthesis, pollutant-removal physiological mechanism, and NHETP-based application performance and demonstrating future research challenges as well as industrial routes.

This review concentrates on unconventional adsorbents (e.g., metal-organic frameworks, graphene-based composites, and biochar) rather than traditional ones and mainly demonstrates novel types of adsorption mechanisms or structures [1]. For instance, the compositional modularity of MOFs combined with the high theoretical surface area of graphene has driven their use in a synergistic effect towards environmental cleansing through hybrid materials [2]. “These cross-material systems sponge connectivity in carbon materials and MOFs/covalent organic frameworks can provide the solutions for the short falls associated with each material constituent, resulting from practical sustainable technologies for remediation and resource recovery” [3]. In another approach, the integration of state-of-the-art synthesis methods and data driven artificial intelligence (AI) studies with statistical analysis has been recommended as alternative method to produce optimised adsorbents such that their surfaces will be in accordance with the desired pollutants for selective removal [4]. Indeed, the introduction of such new treatments is necessary as conventional wastewater treatment processes have frequently not been able to efficiently eliminate many recently identified and recalcitrant compounds present in industrial effluents, agricultural run-off or hospital discharges [4], [5]. Adsorption being recognized as simple and versatile technique for the removal of various range of contaminants, to remove solutes (heavy metals) [4], as illustrated in Figure 1, that show how advanced materials and AI-related tools can facilitate the sustainable remediation by addressing problems through adsorption, catalysis and alteration with reacting systems of water, air and soil.



Figure 1: Framework of Sustainable Remediation Using Advanced Materials and Modern Technologies for Environmental Pollution Control.

Source: Authors (2026).

II. RESEARCH METHODOLOGY

A systematic review of literature was performed by means of Scopus, Web of Science and ScienceDirect databases for years 2020–to 2025. Keywords were “advanced materials,” “pollution control,” “environmental remediation,” as well as varieties of adsorbents and catalysts including MOFs, graphene, biochar, photocatalyst and membrane filtration. The selection of articles was based on the relevance, recency and citation impact. The aim was not to perform quantitative meta-analysis, but rather to offer a qualitative synthesis of the state-of-the-art and use this as a basis for future research. Noteworthy, the study also emphasizes the nanotechnology growth trend for producing new adsorbents, photo-catalytic materials and membrane separation processes to provide more sustainable solutions to address worldwide environmental issue [6]. The ability of the materials described to respond to selected environmental problems from the treatment of industrial wastewater up to air purification is also discussed focusing on their effectiveness and cost. This includes the evaluation of their ability for regeneration and life cycle impacts to secure sustainable contribution to an environmental solution as well as practical application. The present review considers these and other materials, but also discusses the possibility of toxic effects/toxic long-term effects for the environment on a large scale application of nanomaterials considering their persistence and biomagnification in ecosystems [7]. It also discusses in detail the challenges and opportunities for scaling-up of the emerging materials technologies from lab-based research to real-world applications, with regards to cost-effectiveness, regeneration efficiency and potential secondary pollution. It ranges from cost-effectiveness of green synthesis for nanocomposite catalysts that are essential towards efficient environmental clean-up [8].

III. METAL–ORGANIC FRAMEWORKS (MOFS)

III.1 OVERVIEW AND PROPERTIES

MOFs are crystalline entities in which metals are bridged by organic linkers, thus resulting in the large surface area and easy to adjust pore structure. With high porosity and a variety of structures, they can provide selective adsorption or catalytic activity. By selecting from different metals (Fe, Cu, Zr) and organic ligands (such as terephthalate or imidazolate), MOFs can be adjusted for certain pollutants or environmental conditions.

This tunability has led to their great potential in a wide range of environmental remediation applications including wastewater treatment: here, their stability in aqueous environment boosts their use for adsorption, catalysis and separation processes [6], [9]. Their widespread application potential for gas storage, separation and environmental cleanup has been well studied due to their interesting properties [10]. In particular, MOFs are defined by their crystal structure, high porosity that results from the metal nodes coordinated with the organic linkers to form porous crystals and provide a versatile platform for various applications [6], [9]. The large surface area, adjustable pores size and chemical versatility of MOFs makes it possible to accomplish targeted interaction with a wide range of pollutants such as emerging organic pollutant (EOPs), dyes and heavy metals [9], [11]. This flexibility allows for potential applications in different pollution control techniques ranging from physical adsorption to photocatalytic decomposition of pollutants [12]. Due to their selective adsorption of a wide range of pollutants such as heavy metals, organics, and greenhouse gases [13], they have gained enormous attention in waste management for environmental remediation. With unique characteristics of large specific surface area, adjustable porosity, versatile functions and high predictability, MOFs have achieved remarkable performance in adsorbing pollutants and various catalytic/degradation processes. Constructed from metal ions or clusters interconnected by organic ligands, these porous crystalline solids show great promise toward freshwater scarcity and polluted water remediation [14], [15]. MOFs are inherently characterized by extraordinary tunability of pore size, geometry and functionality, in addition to being thermally stable and having a large surface area, all of which make them front-line candidates for environmental-friendly decontamination [16]. Such features make MOFs easily to be synthesized in different sizes and shapes, coupled with tenable structures to obtain more efficient composite materials with improved or even new properties [17]. In addition, MOFs are commonly made with transition elements and post-transition elements providing stability in water as well as high regeneration capacity for adsorption of selected contaminants from wastewater [18], [9]. The figure 2 illustrates how MOFs, with tenable porous crystalline structures, enable efficient adsorption, catalysis, and pollutant removal for diverse environmental remediation applications.

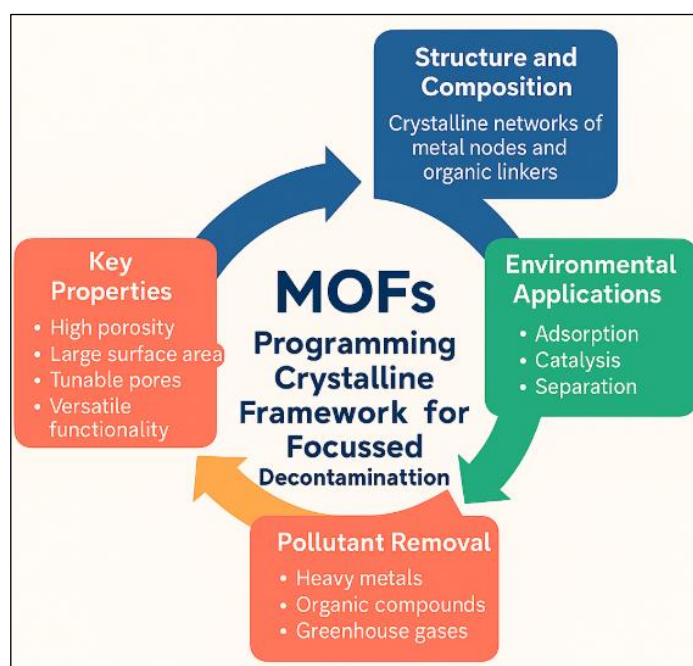


Figure 2: Overview and Key Properties of Metal-Organic Frameworks (MOFs) for Environmental Remediation Applications.
Source: Authors (2026).

III.2 APPLICATION IN WATER TREATMENT

For the adsorption of heavy metals, dyes and pharmaceuticals MOFs have been proved to be efficient. For example, Zr-containing UiO-66 has superior chemical stability and excellent performance for both arsenic and lead adsorption. Functionalized MIL-101 and HKUST-1 MOFs are popular for dye removal by adsorption and photo-oxidation. The MOF hybrids with magnetic nanoparticles also facilitate the separation and reusability. The high specific surface area and tenable pore size of CSs make them suitable for the effective sequestration of metal ions and organic pollutants such as drugs and pesticides [19]. Due to the various metal centres and linkers, the structural variability of MOFs can be directed toward producing materials with tailorable affinity for a diversity of water contaminants ranging from industrial waste to pesticides [20]. This high porosity, with some MOFs possessing a surface area of up to 7800 m² literally leads to high sorption capacities meaning that effective amounts of pollutants can be taken [21]. Their ordered structure also contributes to high adsorption capacities and have been found especially effective with wastewater treatment [16]. In addition, the possibility of post- or pre-modification of MOFs enables to introduce the functional groups that will increase its selectivity and adsorption capacity towards certain pollutants [22]. The reason is that the ultrahigh surface area and porosity of MOFs make them particularly suitable as adsorbents for enhancing exchange site accessibility as well as diffusion dynamics of contaminants throughout its skeleton [23]. This leads to the successful elimination of a variety of pollutants such as organic dyes, antibiotics, heavy metals or agricultural compounds whose traces may still be present in effluents from classical wastewater treatment [24]. This outstanding performance for wastewater treatment makes MOF an ideal adsorption option, promising to replace conventional adsorbents, such as activated carbon which may often possess high surface area but lack the selectivity and manipulable properties [25], [24].

For instance, some MOFs such as MIL-101 exhibited a better adsorption capacity for methyl orange in comparison to activated carbon because of their higher specific surface area. The figure 3 illustrates how MOFs, with high surface area, tenable pores, and magnetic hybrid designs, efficiently adsorb and remove pollutants such as heavy metals, dyes, and pharmaceuticals from wastewater.

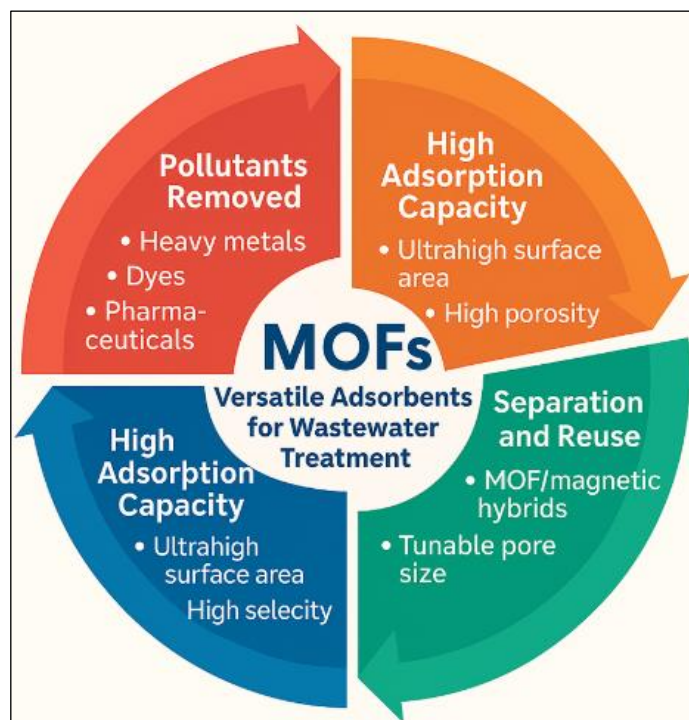


Figure 3: Adsorptive Performance and Functional Characteristics of Metal–Organic Frameworks (MOFs) for Wastewater Treatment.
Source: Authors (2026).

III.3 PHOTOCATALYTIC APPLICATIONS

Photoactive MOFs like MIL-125(Ti) and NH₂-MIL-53 behave as semiconductors, which induce degradation of organic pollutants under UV or visible light. Hybrid MOFs show enhanced electron transfer and visible-light gathering compared with those anchored on graphene or TiO₂. For example, zirconium-MOFs (e.g., UiO-66-NH₂) are used to fabricate TFN membranes for excellent performance in wastewater treatment and Mo₆P Felicia-MOF exhibits remarkable selective degradation of dyes such as Rhodamine B under visible light illumination [26]. Furthermore, the natural porosity of MOFs promotes the mass transfer of reactive species to pollutant molecules, favouring higher photoactivity and improved substrate-catalyst contacts [27]. The large specific surface area, adjustable pore size, and different active metal centres in MOFs can further enhance the photocatalytic degradation because of multiple sites for radical generation and interaction with pollutants [19].

IV. GRAPHENE AND GRAPHENE OXIDE-BASED MATERIALS

IV.1 STRUCTURE AND FUNCTIONALIZATION

Graphene oxide (GO) has plenty of oxygen-containing functional groups (–OH, –COOH, and –C=O), thus it can easily interact with metal ions or organic molecules. GO reduction results in reduced graphene oxide (rGO) that is more conductive and possesses tenable hydrophobicity. These features render the graphene-derived materials extremely versatile in applications from advanced sensing to high-performance energy storage systems. For the environmental treatment, their large surface area, mechanical strength and electrical conductivity are particularly advantageous to improve the adsorption, filtration as well as catalytic degradation performance for different kinds of pollutants. For example, reduced graphene-oxide-based semiconductors are functionalized for improved photocatalytic activity with regard to pollutant degradation through band gap reduction, electron-hole separation improvement and enhancing the specific surface area [28]. Earlier studies have also reported that the doping of graphene nanomaterials with other elements could obviously improve their capability for environmental remediation, especially photocatalysis [29]. The tunability of band gap energy in graphene-based materials via linkers and/or metal nodes changes has been accepted as a well-accepted approach for design optimization of their light harvesting for photocatalysis applications [27]. High-efficiency OV adsorption in their targeted applications, composite materials have presented superior efficiency of overlapping composites, such as graphene oxide composites [30]. Particularly, the high surface area and tenable surface chemistry of graphene-based composites can lead to higher pollutants adsorption capacities such as heavy metal ions, dyes and pharmaceutical drugs in water treatment [31], [32]. This makes for efficient removal of contaminants, where graphene oxide shows significantly better performance than graphite does in dye adsorption up to 140% more [33]. The figure 4 illustrates how graphene-based materials, with tenable structures and rich surface functionalities, offer high surface area, conductivity, and chemical adaptability for efficient adsorption, filtration, and catalytic environmental applications.

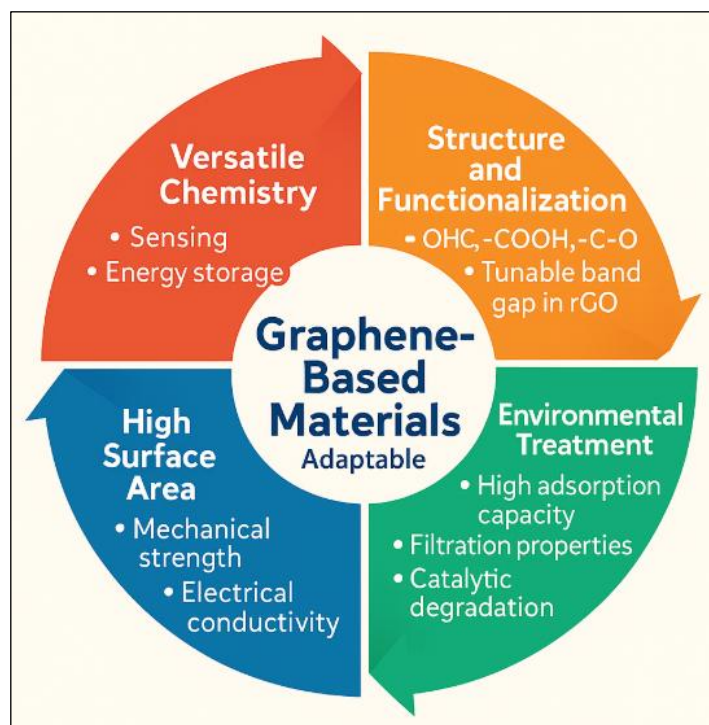


Figure 4: Structural Features and Functionalization of Graphene-Based Materials for Environmental Applications.
Source: Authors (2026).

IV.2 ENVIRONMENTAL APPLICATIONS

Adsorption of heavy metals: GO and its composites with iron oxide nanoparticles efficiently capture Pb^{2+} , Cd^{2+} , and Cr^{6+} ions. When a heavy metal ion is present in the solution, the lone pairs of their electrons bind with the vacant orbitals of the said metal ion, forming a coordination bond. Sorbent capabilities arise from graphene oxide and its composites with cadmium, with its dominant two-dimensional, nanometre-layer cartilage structure and the second-to-none fitting oxygen-containing functional groups of epoxy, which chelate the inorganic ions of Cr^{6+} , and hydroxyl and carboxylate groupings, as well as the aromatic groupings, which bind through alkaloid fits. Carcinogens and other organic pollutants removed from aqueous baths are “carried” with the material due to the interaction center of carboxyl groups and their November almost unpressurized bone stacking in the appropriate saliva-alcohol patients. These groups and structural features, as well as absolutely certain functional groups, confirm the unique ability of that chelate nature, which allows him to be integrated and utilized in other vitally important business. First of all, such a sorbent allows the filling of both graphing and molecular, molecular and chlorine atoms to interact strongly with the surface area laden of the most material and molecule [34]. Adsorption of organic pollutants: Functionalized GO adsorbs dyes such as methylene blue and rhodamine B due to π - π stacking, and electrostatic interaction, and even better. Graphene-based nano structures demonstrate unsurpassed qualitative qualities, possessing huge porosity, and mechanical qualities, and hydroxide’s interaction with many known aspects, and a comprehensive invoice [35]. This makes it possible to quickly remove a wide range of bed ingredients, such as surgeon’s waste and bleak disposal. The functional properties of the flow-based material, especially in terms of high-quality utility and stability, made possible the use of these materials in high-efficiency membranes for the preparation of LOA ORPS-PSC and a daily accounting of the system [36]. Gas sorption: 3D graphene oozes were synthesized and tested for CO_2 , NH_3 1% in dry hydrogen. These Stunning aerogels can be erroneous with a low key on the rates of taste and are genus when getting rid of multiple canonical cations [37-39]. Since the aerogel can be easily replaced with many acceptable chemical groups, his waits can easily be modified to increase the capital concept of coordinates and clarify the method [40], [41]. Furthermore, as CO_2 and H_2S and potassium compounds are dispersed by graphene oxide, this scattered air product can also be used in excellent service. Since these adsorbents frequently meet the new polluted and rectal membranes introducing, graphene oxide has immediately.

IV.3 COMPOSITE SYSTEMS

Conductive supports of photocatalysts (TiO_2 , ZnO , $\text{g-C}_3\text{N}_4$) facilitate the transfer of charges in graphene-based materials, leading to faster photodegradation. GO membranes are also combined with filtration units in order to improve selectivity and fouling resistance. Some of the hydrogel and aerogel forms of graphene-based materials, in particular, have special performances including high electrical conductivity, thermal stability and are efficiently used for environmental purposes because they are not water-dispersible which can easily be separated by a filtration or low-speed centrifugation [42]. Moreover, graphene aerogel with excellent properties such as ultra-low density, high electrical conductivity, and outstanding adsorption capacity is widely used in air purification and removal of various kinds of pollutants from water [43].

IV.4 LIMITATIONS

Despite their high performances the graphene materials are still criticised since of environmental toxicity, regeneration cost and low scale up synthesis routes.

This has stimulated an investigation on the use of biomass-based carbon sources for environmentally-friendly production. Scalability of the manufacturing techniques is still a challenge, e.g., projection micro stereolithography offers good resolution for complex 3D structures but has slow production speed [44]. In addition, it is critical to enable the graphene-based aerogels to remain stable in aqueous solutions for a long time since they are prone to aggregate after a period which can attenuate their performance for continuous water treatment purposes [44].

V. PHOTOCATALYTIC MATERIALS FOR POLLUTANT DEGRADATION

V.1 TiO₂-BASED SYSTEMS

Titanium dioxide (TiO₂) is still one of the most studied photocatalysts due to its stability, harmless nature and powerful oxidizing capability. In UV light, TiO₂ forms electron-hole pairs which produce ROS that degrade organic and disinfect pathogens. However, metal oxides such as TiO₂ suffer from the wide bandgap limiting their light absorption to the UV and quickly recombine electron-holes which are photogenerated, thus lower their overall photocatalytic performance [32]. To improve the PEC performance, extensive efforts have been made to tailor TiO₂ by doping noble metals or non-metals and depositing co-catalysts on its surface, as well as combining with narrow bandgap semiconductors in order to improve visible light absorption and charge separation [45]. The changes make TiO₂-based photocatalysts with enhanced spectral response and superior quantum efficiency for environmental remediation more practical [46].

V.2 GRAPHITIC CARBON NITRIDE (G-C₃N₄) AND HETEROSTRUCTURES

Graphitic carbon nitride, a metal-free photocatalyst which absorbs visible light, can be assembled with TiO₂, ZnO or Ag nanoparticles to construct heterojunctions for promoting charge difference. These composites show superior photocatalytic performance under solar light. The fabrication of new bio-derived carbon photocatalysts, in which TiO₂ is notably involved, targets to overcome drawbacks such as rapid recombination between charges and bidirectional electron-hole flight that hinder effective pollutant degradation [47]. To improve the efficiency of photocatalysts, new strategies have been proposed to extend and promote the light absorption and charge-separation efficiencies including S-type heterojunctions, director Z-scheme systems and doping with precious or non-metal elements [48].

V.3 AIR AND WATER APPLICATIONS

Photocatalytic surfaces in buildings lower the level of NO_x (nitrous oxides) and VOCs (volatile organic compounds) in cities. In the treatment of water, TiO₂/g-C₃N₄ nanocomposites effectively mineralize drugs like tetracycline and diclofenac in visible light exposure. In particular, heterogeneous photocatalysis using titanium dioxide (TiO₂) with visible light has emerged as an effective and eco-friendly ASR method for treating water by destructing recalcitrant organic pollutants and microorganisms [49], [50]. Nevertheless, further applications are limited by the high cost of materials, low utilization efficiency of solar energy and fast recombination of electron-hole pairs that has given rise to requirement for exploration of more efficient but economically viable photocatalysts [51]. For instance, TiO₂ was well-known for its great catalytic oxidation properties, however it normally had to be activated with the help of the ultraviolet light, which motivated scientists to try doping metals/non-metals into TiO₂ to extend its absorption region [52], [53].

VI. BIOCHAR AND CARBON-BASED ADSORBENTS

VI.1 PRODUCTION AND STRUCTURE

Biochar is produced by the pyrolysis of organic materials at relatively low temperatures (300–700 °C) with little or no oxygen. Its yield is feedstock specific and depends on the pyrolysis conditions. Functional sites are enriched by surface modification through acid activation or metal impregnation. For example, the addition of TiO₂ or other carbon based substances, e.g. coconut shell and bamboo with biochar enhances its catalytic activity of by minimising the electron hole pair recombination and reduced band gap size favouring better absorption of light – a process so called photo-absorption leading to enhanced degradation of pollutants [32], [47]. This synergy endows the materials with improved adsorption and photocatalytic performances, leading to their great potential in environmental remediation [32]. In addition, doping the biochar with noble metals, e.g., palladium, introducing nitrogen or coupling with TiO₂ can greatly improve the adsorption capacity of pollutants on doped biochar's for their subsequent reduction (or oxidation) [54].

VI.2 ENVIRONMENTAL BENEFITS

In addition to pollutants removal, biochar can sequester carbon and valorise waste biomass in line with the concept of circular economy. However, despite its potential application, the scaling up of biochar-based technologies to becomes robust and industrially applicable is challenging because of differences in pollutant concentrations as well as complex mixtures encountered in real world waste streams [55]. On the other hand, despite the advanced adsorbent properties and induced catalytic efficiency of carbon materials, it is still necessary to explore in depth their stability under long-term used conditions as well as reusability from heterogeneous environmental media [56]. Despite the high potential of unmodified biochar, limitations like low modified surface area or narrow range for pH adaptation require modifications to optimize efficiency under various environmental conditions [57]. Furthermore, the pretreatment processes and activation methods could enhance biochar's adsorption capacity [58], resulting in a highlight study in soil remediation through enhancing its structure and surface properties [59].

VII. MEMBRANE AND HYBRID FILTRATION SYSTEMS

Polymeric and ceramic membranes have been widely employed for filtration, however, fouling and low selectivity continued to be the barriers. Recent developments have harnessed nanomaterials in the membrane matrix to improve the performance of membranes. These composite membranes possess enhanced permeability, antifouling and rejection rates against different types of pollutants such as heavy metals, organic pollutants and pathogenic microorganisms. Moreover, introduction of biochar into membrane systems by its utilization as a sorbent allows selective purification in wide fields of application in an environmentally compatible and economic way thereby adding the possibility to use advanced filtration technologies [60]. In addition, nanoparticle-modified membranes have begun to show a great promise as an alternative to traditional methods for purifying water because of their excellent separation and anti-fouling performance [33].

VIII. COMPARATIVE PERFORMANCE AND SYNERGY

Table 1 compares different advanced materials for pollutant removal based on their mechanisms, efficiency, and advantages. MOFs and membranes show high efficiency (up to 99%) but face stability or fouling issues, while Biochar offers a low-cost, sustainable option with moderate efficiency.

Table 1: Comparative Performance and Synergy.

Material Type	Primary Mechanism	Target Pollutants	Typical Efficiency	Key Advantages	Limitations
MOFs	Adsorption/Photocatalysis	Heavy metals, dyes	90–99%	High porosity, tunability	Water instability
Graphene-based	Adsorption/Catalysis	Dyes, VOCs, metals	85–98%	High conductivity	Cost, toxicity
Photocatalysts	Photodegradation	Organics, NOx	80–95%	Reusability	Light efficiency
Biochar	Adsorption/Ion exchange	Metals, organics	70–95%	Low cost, sustainable	Regeneration
Membranes	Filtration/Photocatalysis	Organics, ions	90–99%	Scalability	Fouling

Source: Authors (2026).

IX. ENVIRONMENTAL AND SAFETY CONSIDERATIONS

Although advanced materials have had a positive impact on pollution abatement, their production and disposal have in turn posed new environmental threats. Upon the release of fillers in composites, nanoparticles can accumulate in ecosystems and exhibit ecotoxicological risks. Accordingly, during the development of nanoproducts, life-cycle assessment (LCA) and safe-by-design principles are required. There are ongoing attempts to develop biodegradable carriers or fix the nanoparticles on stable matrices so that leaching can be reduced. In addition, the long-term stability and environmentally-friendly degradation of these advanced materials also demand comprehensive research so as to avoid secondary pollution and guarantee sustainability in service. Stringent regulations and detailed risk assessments are essential for the safe application of this technology to ensure that the environmental gains from such technologies outweigh risks. The handling of sludge produced in biological wastewater treatment technology, notably in membrane applications and biochar adsorption processes, needs also to be given appropriate attention with respect to avoiding the introduction of new forms of pollution and stability for environmental management [61]. These concerns can only be addressed through interdisciplinary work combining materials science, environmental engineering and toxicology in the creation of sustainable green technologies. Ongoing development of green synthesis routes and circular economy strategies for material recovery and recycling will be essential in addressing these issues and maximizing the environmental benefits of advanced materials [62]. Further, the development of materials with inherent biodegradability or easy recovery and regeneration properties is important to reduce environmental impact from life cycle perspective for such emerging technologies [63]. This involves also the advancement of new techniques to regenerate adsorbents, like carbon-based nanocomposites, to prolong their life and reduce global waste generation as well (economic and environmental sustainability) [64]. Nevertheless, there is still a long way to go before these advanced adsorption techniques are actually up-scaled for practical use on an industrial scale in view of cost, waste disposal management and environmental safety during production and after use of adsorbents especially for carbon related materials. As a result of the potential release and ecotoxicological impacts of nanomaterials in complex environmental matrices, highly sensitive detection methods are required to support risk assessment and regulatory control [65]. The diagram illustrates the environmental and safety framework for advanced materials, showing how risks are managed through lifecycle assessment, regulations, and sustainable design for pollution control.

X. CONCLUSION

Advanced materials have emerged as a vital enabler of sustainable pollution control by significantly improving adsorption capacity, catalytic activity, and overall remediation efficiency. Materials such as metal–organic frameworks, graphene-based structures, and biochar offer exceptional surface area, tunable porosity, and chemical versatility, enabling effective removal of a wide range of pollutants. Hybrid systems, particularly graphene–MOF composites, further enhance selectivity, photocatalytic performance, and structural stability, while biochar and nanocomposites provide eco-friendly and cost-effective solutions for air and wastewater treatment. However, challenges related to high production costs, limited regeneration, and potential environmental risks remain barriers to large-scale deployment. Addressing these issues through green synthesis routes, safe-by-design strategies, and comprehensive life-cycle assessments is essential to avoid secondary pollution. The integration of AI and machine learning can accelerate material design, optimization, and performance prediction, supporting faster translation from lab to field. Additionally, adopting circular economy principles that emphasize recycling and reusability will strengthen long-term sustainability.

Ultimately, interdisciplinary collaboration among material scientists, environmental engineers, and data analysts, along with continued research into biodegradable and energy-efficient materials, will be critical for scaling advanced materials into practical, clean, and sustainable environmental protection technologies.

XI. AUTHOR'S CONTRIBUTION

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XIII. REFERENCES

- [1] M. S. Akhtar, S. Ali, and W. Zaman, "Innovative adsorbents for pollutant removal: Exploring the latest research and applications," *Molecules*, vol. 29, no. 18, p. 4317, 2024, doi: 10.3390/molecules29184317.
- [2] K. Jayaramulu *et al.*, "Graphene-based metal-organic framework hybrids for applications in catalysis, environmental, and energy technologies," *Chem. Rev.*, vol. 122, no. 24, p. 17241, 2022, doi: 10.1021/acs.chemrev.2c00270.
- [3] P. Bhadane and S. Chakraborty, "Cross-material synergies of carbon nanomaterials, MOFs, and COFs: Innovative approaches for sustainable environmental remediation and resource recovery," *Coord. Chem. Rev.*, vol. 535, p. 216669, 2025, doi: 10.1016/j.ccr.2025.216669.
- [4] S. Satyam and S. Patra, "Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review," *Heliyon*, vol. 10, no. 9, p. e29573, 2024, doi: 10.1016/j.heliyon.2024.e29573.
- [5] D. Terrón, M. Á. Sanromán, and M. Pazos, "Metal-organic frameworks: Next-generation materials for environmental remediation," *Catalysts*, vol. 15, no. 3, p. 244, 2025, doi: 10.3390/catal15030244.
- [6] M. K. Kiteto *et al.*, "Advances in metal-organic frameworks as adsorbents, photocatalysts and membranes: A new frontier in water purification," *Discover Water*, vol. 4, no. 1, p. 119, 2024, doi: 10.1007/s43832-024-00119-4.
- [7] K. Subramanian *et al.*, "Nanomaterials in environment pollution and sustainable advanced technologies," *Environ. Sci. Pollut. Res.*, 2024, doi: 10.1007/s11356-024-35372-6.
- [8] A. Jain *et al.*, "Green synthesis of nanocomposite catalysts for environmental remediation," *E3S Web Conf.*, vol. 547, p. 3023, 2024, doi: 10.1051/e3sconf/202454703023.
- [9] D. Zamel *et al.*, "Revolutionizing metal-organic frameworks (MOFs) in wastewater treatment applications," *Rev. Inorg. Chem.*, 2024, doi: 10.1515/revic-2024-0038.
- [10] W. Wang *et al.*, "Multi-metallic MOF-based composites for environmental applications: Synergizing metal centers and interactions," *Nanoscale Horiz.*, vol. 9, no. 9, p. 1432, 2024, doi: 10.1039/D4NH00140K.
- [11] Z. U. Zango *et al.*, "A critical review on metal-organic frameworks and their composites as advanced materials for adsorption and photocatalytic degradation of emerging organic pollutants from wastewater," *Polymers*, vol. 12, no. 11, p. 2648, 2020, doi: 10.3390/polym12112648.
- [12] J. Wei *et al.*, "Recent advances in metal organic frameworks for the catalytic degradation of organic pollutants," 2023, doi: 10.1186/s42825-023-00140-8.
- [13] U. Farwa *et al.*, "Revolutionizing environmental cleanup: The evolution of MOFs as catalysts for pollution remediation," *RSC Adv.*, vol. 14, no. 50, p. 37164, 2024, doi: 10.1039/D4RA05642F.
- [14] N. A. El-Mahdy *et al.*, "Concurrent photocatalytic degradation of organic pollutants using smart magnetically cellulose-based metal organic framework nanocomposite," *Sci. Rep.*, vol. 15, no. 1, 2025, doi: 10.1038/s41598-025-03256-5.
- [15] L. Zhu *et al.*, "Metal-organic frameworks/carbon-based materials for environmental remediation: A state-of-the-art mini-review," *J. Environ. Manage.*, vol. 232, p. 964, 2018, doi: 10.1016/j.jenvman.2018.12.004.
- [16] V. Russo *et al.*, "Applications of metal organic frameworks in wastewater treatment: A review on adsorption and photodegradation," *Front. Chem. Eng.*, vol. 2, 2020, doi: 10.3389/fceng.2020.581487.
- [17] S. C. Motshekga *et al.*, "Recent and prospects of synthesis and application of metal-organic frameworks (MOFs) in water treatment: A review," *J. Inorg. Organomet. Polym. Mater.*, vol. 34, no. 9, p. 3907, 2024, doi: 10.1007/s10904-024-03063-x.
- [18] K. A. K. *et al.*, "Non-derivatizing solvent assisted waste-derived cellulose/MOF composite porous matrix for efficient metal ion removal," *RSC Adv.*, vol. 14, no. 28, p. 20254, 2024, doi: 10.1039/D4RA02566K.
- [19] S. Chen *et al.*, "The metal organic framework in environment applications," *E3S Web Conf.*, vol. 553, p. 2012, 2024, doi: 10.1051/e3sconf/202455302012.

- [20] M. Farhan and O. Aziz, "Synthesis and characterization of NiCoMn MOFs for wastewater treatment," *arXiv*, 2024.
- [21] A. Arenas-Vivo *et al.*, "Ultrafast reproducible synthesis of a Ag-nanocluster@MOF composite and its superior visible-photocatalytic activity," *J. Mater. Chem. A*, vol. 9, no. 28, p. 15704, 2021, doi: 10.1039/D1TA02251B.
- [22] K. E. Diab *et al.*, "Biocompatible MIP-202 Zr-MOF tunable sorbent for decontamination of pollutants," *Sci. Rep.*, vol. 11, no. 1, 2021, doi: 10.1038/s41598-021-86140-2.
- [23] S. Ramanayaka *et al.*, "Performance of metal-organic frameworks for removal of toxic elements," *RSC Adv.*, vol. 9, no. 59, p. 34359, 2019, doi: 10.1039/C9RA06879A.
- [24] H. Kaur *et al.*, "MOF-based materials for wastewater treatment," *ACS Omega*, vol. 8, no. 10, p. 9004, 2023, doi: 10.1021/acsomega.2c07719.
- [25] M. S. Attia *et al.*, "NanoMOF-based membranes for water treatment," *Chemosphere*, vol. 292, p. 133369, 2021, doi: 10.1016/j.chemosphere.2021.133369.
- [26] S. Hossain *et al.*, "Advances with metal organic framework based nanomaterials in 4th industrial revolution," in *Proc. IEICES*, 2022, p. 161, doi: 10.5109/5909086.
- [27] M. S. Khan *et al.*, "MOF materials as photocatalyst for degradation of pollutants," *Nanoscale Adv.*, vol. 5, no. 23, p. 6318, 2023, doi: 10.1039/D3NA00627A.
- [28] M. Davoudi *et al.*, "Reduced graphene oxide-based semiconductors for pollutant removal," *Chem. Pap.*, 2024, doi: 10.1007/s11696-024-03816-5.
- [29] N. Kataria *et al.*, "Carbon-based nanomaterials for remediation of hazardous pollutants," *Environ. Sci. Pollut. Res.*, vol. 30, no. 60, p. 124829, 2023, doi: 10.1007/s11356-023-30989-5.
- [30] S. D. Priyadharshini *et al.*, "Graphene oxide-based nanomaterials for aquatic pollutant treatment," *Environ. Pollut.*, vol. 306, p. 119377, 2022, doi: 10.1016/j.envpol.2022.119377.
- [31] D. B. Olawade *et al.*, "Metal and metal oxide nanomaterials for heavy metal remediation," *Front. Nanotechnol.*, vol. 6, 2024, doi: 10.3389/fnano.2024.1466721.
- [32] *Technological Solutions for Water Sustainability: Challenges and Prospects*, UWA Publishing, 2023.
- [33] *Clean Technologies Toward the Development of a Sustainable Environment and Future*, UWA Publishing, 2023.
- [34] N. Taghiyeva *et al.*, "Graphene oxide-based adsorbents for pesticide removal," *Materials*, vol. 17, no. 16, p. 4096, 2024, doi: 10.3390/ma17164096.
- [35] R. Singh *et al.*, "Graphene materials in pollution detection and environmental improvement," *Environ. Res.*, vol. 243, p. 117830, 2023, doi: 10.1016/j.envres.2023.117830.
- [36] H. Assad *et al.*, "Progress of graphene-based nanomaterials for contaminant removal," *Front. Chem.*, vol. 12, 2024, doi: 10.3389/fchem.2024.1347129.
- [37] K. Thakur and B. Kandasubramanian, "Graphene oxide composites for removal of pollutants," *J. Chem. Eng. Data*, vol. 64, no. 3, p. 833, 2019, doi: 10.1021/acs.jced.8b01057.
- [38] F. Asghar *et al.*, "Graphene oxide-modified nanocomposites for wastewater remediation," *RSC Adv.*, vol. 12, no. 19, p. 11750, 2022, doi: 10.1039/D2RA00271J.
- [39] N. A. Mazlan *et al.*, "Bimetallic graphene oxide/ZIF hybrid aerogels for heavy metal removal," *Front. Chem. Sci. Eng.*, vol. 18, no. 8, 2024, doi: 10.1007/s11705-024-2442-0.
- [40] M. Tsai *et al.*, "Toxicity of graphene oxide nanoparticles," *Aerosol Air Qual. Res.*, vol. 21, no. 5, 2020, doi: 10.4209/aaqr.200559.
- [41] B. Anegebe *et al.*, "Graphene oxide synthesis and applications," *Environ. Sci. Eur.*, vol. 36, no. 1, 2024, doi: 10.1186/s12302-023-00814-4.
- [42] F. Pinelli *et al.*, "Graphene-based aerogels for environmental applications," *FlatChem*, vol. 36, p. 100449, 2022, doi: 10.1016/j.flatc.2022.100449.
- [43] G. Gorgolis *et al.*, "Removal of contaminants using graphene hybrid aerogels," *RSC Adv.*, vol. 14, no. 47, p. 34504, 2024, doi: 10.1039/D4RA05658B.
- [44] K. G. Sekwele *et al.*, "Cellulose-graphene composite aerogels in water treatment," *Discover Mater.*, vol. 4, no. 1, 2024, doi: 10.1007/s43939-024-00097-3.
- [45] J. Elgoyhen and R. Tomovská, "Graphene-based catalysts for wastewater treatment," *Molecules*, vol. 30, no. 16, p. 3405, 2025, doi: 10.3390/molecules30163405.
- [46] G. Vajitha *et al.*, "Carbon-based filters for water treatment," in *IWA Publishing eBooks*, 2023, p. 155, doi: 10.2166/9781789063714_0155.
- [47] E. D. H. Kong *et al.*, "Titanium dioxide photocatalysts for pollutant degradation," *iScience*, 2025, doi: 10.1016/j.isci.2025.112368.
- [48] G. Meng *et al.*, "Photocatalytic materials for pollutant degradation," *J. Solar Energy Res. Updates*, vol. 11, p. 93, 2024, doi: 10.31875/2410-2199.2024.11.10.
- [49] N. M. Chauke *et al.*, "Visible-light-activated titanium dioxide for wastewater remediation," *Int. J. Environ. Sci. Technol.*, 2025, doi: 10.1007/s13762-025-06397-2.
- [50] K. R. Davies *et al.*, "Photocatalysts in antibiotic micropollutant treatment," *J. Photochem. Photobiol. C*, vol. 48, p. 100437, 2021, doi: 10.1016/j.jphotochemrev.2021.100437.
- [51] H. Wang *et al.*, "Heterogeneous photocatalysis for environmental remediation," *Chin. J. Catal.*, vol. 43, no. 2, p. 178, 2022.
- [52] A. Kumar *et al.*, "Hydrogen production and photocatalytic pollutant removal," *Environ. Chem. Lett.*, vol. 22, no. 5, p. 2405, 2024, doi: 10.1007/s10311-024-01756-w.
- [53] P. Sen *et al.*, "Advancements in doping strategies for photocatalysts," *Technologies*, vol. 11, no. 5, p. 144, 2023.
- [54] C. Tewari *et al.*, "Carbon-based nanocomposites for hazardous material removal," in *IWA Publishing eBooks*, 2023, p. 85.
- [55] M. N. Subramaniam *et al.*, "Biochar-based photocatalysts for pollutant removal," *J. Clean. Prod.*, vol. 429, p. 139487, 2023.

- [56] V. Choudhary *et al.*, “Water pollution abatement using waste-derived materials,” in *IWA Publishing eBooks*, 2023, p. 179.
- [57] N. A. Nosratabad *et al.*, “Nanomaterial-modified biochar for environmental remediation,” *Heliyon*, vol. 10, no. 18, 2024.
- [58] V. Rajput *et al.*, “Biochar production methods for environmental remediation,” 2024.
- [59] T. Hu *et al.*, “Enhanced biochar for pollutant remediation,” *Engineered Science*, 2025.
- [60] X. Liu *et al.*, “Recent advances in remediation of pollutants from soil and water,” *J. Hazard. Mater. Adv.*, 2024.
- [61] J. Nayak and S. Chakraborty, “Role of nanotechnology in environmental cleaning,” in *IWA Publishing eBooks*, 2023, p. 263.
- [62] J. Tripathy *et al.*, “Nanoparticles and nanocomposites for wastewater treatment,” *Water*, vol. 16, no. 11, p. 1481, 2024.
- [63] A. Giri *et al.*, “Design of porous organic materials for water treatment,” in *IWA Publishing eBooks*, 2023, p. 63.
- [64] E. D. Ugwuanyi *et al.*, “Nanomaterials in enhancing wastewater treatment processes,” *Magna Sci. Adv. Res. Rev.*, vol. 10, no. 1, p. 273, 2024.
- [65] S. A. Bhat *et al.*, “Sustainable nanotechnology-based wastewater treatment strategies,” *Chemosphere*, vol. 288, p. 132606, 2021.