

Synergistic integration of nanostructured catalysts and MXene membranes for the energy-water nexus: a critical review of engineering scalability and circular economy pathways

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Abstract

The water-energy nexus is an exponentially growing global challenge that demands novel and transformative engineering solutions at scale to address the compounding effects of industry-generated wastewater and water scarcity. The current remediation and desalination modes are becoming limited by high energy demands, long-term membrane fouling, and chemical sludge of toxic substances, requiring a shift towards a new integrated circular manufacturing and decentralized resilience. In this extensive review, the latest developments in the field of advanced nanomaterials and environmental engineering are combined to provide a detailed analysis of the synergism between two-dimensional (2D) MXene-based separation membranes and nanostructured semiconductor heterojunction catalysts. The high-throughput molecular sieving in advanced desalination application in tunable interlayer spacing of titanium carbide ($\text{Ti}_3\text{C}_2\text{T}_x$) MXene and the strategic architecture design of heterojunctions, such as ZnFe_2O_4 , Ni-doped ZnO , and $\text{TiO}_2/\text{g-C}_3\text{N}_4$, to suppress the recombination of charge carriers generated under visible-light irradiation for rapid mineralization of recalcitrant organic pollutants. Moreover, this review takes the important step of closing the gap between fundamental discoveries of materials and their scalability to industrial applications by conducting a comprehensive techno-economic assessment and life cycle analysis of these novel technologies in the context of the circular economy. This work provides a clear pathway for future research on green synthesis, covalent membrane stabilization, and process optimization through artificial intelligence, marking a new era of energy-efficient and sustainable water reclamation systems and green energy production.

Keywords: energy-water nexus, MXene membranes, nanostructured catalysts, advanced oxidation processes, desalination.

Integração sinérgica de catalisadores nanoestruturados e membranas de MXene para o nexo energia-água: uma revisão crítica da escalabilidade da engenharia e das vias para a economia circular

Resumo

O nexo água-energia é um desafio global em crescimento exponencial que exige soluções de engenharia inovadoras e transformadoras em escala para enfrentar os efeitos combinados das águas residuárias geradas pela indústria e da escassez hídrica. Os atuais métodos de remediação e dessalinização estão se tornando limitados devido à elevada demanda energética, ao incrustamento prolongado das membranas e à geração de lodos químicos contendo substâncias tóxicas, exigindo uma transição para um novo modelo integrado de manufatura circular e resiliência descentralizada. Nesta extensa revisão, os avanços mais recentes no campo dos nanomateriais avançados e da engenharia ambiental são combinados para fornecer uma análise detalhada da sinergia entre membranas de separação baseadas em MXene bidimensional (2D) e catalisadores nanoestruturados de semicondutores de heterojunção. A elevada eficiência de peneiramento molecular em aplicações avançadas de dessalinização, proporcionada pelo espaçamento interlamelar ajustável do MXene de carbeto de titânio ($\text{Ti}_3\text{C}_2\text{T}_x$), é analisada em conjunto com o projeto estratégico da arquitetura de heterojunções, como ZnFe_2O_4 , ZnO dopado com Ni e $\text{TiO}_2/\text{g-C}_3\text{N}_4$, destinadas a suprimir a recombinação dos portadores de carga gerados sob irradiação de luz visível, promovendo a rápida mineralização de poluentes orgânicos recalcitrantes. Além disso, esta revisão dá um passo importante no sentido de reduzir a lacuna entre as descobertas fundamentais em materiais e sua escalabilidade para aplicações industriais, por meio de uma avaliação técnico-econômica abrangente e de uma análise do ciclo de vida dessas tecnologias inovadoras no contexto da economia circular. Este trabalho apresenta uma perspectiva clara para futuras pesquisas em síntese verde, estabilização covalente de membranas e otimização de processos por meio de inteligência artificial, marcando o início de uma nova era de sistemas sustentáveis e energeticamente eficientes para recuperação de água e produção de energia verde.

Palavras-chave: nexo energia-água, membranas de MXene, catalisadores nanoestruturados, processos oxidativos avançados, dessalinização.

1. Introduction

A deep synergy among energy transition, materials innovation, and environmental protection is needed for the global transition to sustainable development (Farooq et al., 2025; Haider et al., 2026; Islam et al., 2026; Khan et al., 2026aa). With the rise of industrialization and population growth, freshwater resources are becoming a growing problem, and traditional water treatment methods such as thermal distillation (using energy) and coagulation (using chemicals) are becoming increasingly problematic (Ahmad et al., 2025a; Jamila et al., 2025b; Jamila et al., 2025a; Muhsin et al., 2025; Zia et al., 2025).

The water-energy nexus reveals an unavoidable fact: contaminated effluents need a significant amount of energy to be treated, while energy generation systems use a lot of water (Bibi et al., 2024; Khan et al., 2025a; Khan et al., 2025b; Ullah et al., 2025). To deal with this dual crisis, the development of advanced materials with outstanding catalytic activity, molecular selectivity, and durability for long-term operation is required (Al-Khazaal et al., 2019; Ayub et al., 2024; Gul et al., 2024; Syed et al., 2024).

Although there have been extensive studies in materials science and environmental engineering, an important methodological limitation is the separation of the material synthesis studies from the real-world engineering applications, scalability, and economic assessments (Ahmad et al., 2015; Ahmad et al., 2017; Ahmad et al., 2018; Fouad et al., 2017). Current literature generally concentrates on the pristine fabrication of nanomaterials in the laboratory, but ignores fouling dynamics, regeneration pathways, and integration into hybrid treatment trains (Ahmad et al., 2009; Ahmad et al., 2014; Khan et al., 2026b; Mohammad et al., 2010). Moreover, although two-dimensional (2D) MXenes and nanostructured heterojunctions have shown remarkable performance on their own, their synergistic coupling in closed-loop circular manufacturing systems has not been explored in great detail (Ahmad et al., 2024; Ali et al., 2026; Kashif et al., 2026a; Shah et al., 2025).

In this critical review, we aim to fill this gap by giving a comprehensive and multidisciplinary overview of the recent progress on MXene-based desalination membranes and nanostructured photocatalytic oxidation systems (Ahmad et al., 2023; Amina et al., 2025; Ashraf et al., 2026; Noureen et al., 2025). Specifically, this paper discusses the physicochemical phenomena underlying sub-nanometer molecular sieving, analyzes charge carrier separation at heterojunctions under visible light irradiation (Ahmad, 2025b; Alsaiari et al., 2023; Aziz et al., 2023; Jabeen et al., 2023), and sets up a rigorous techno-economic framework for scale-up in the industry. Finally, this review provides a framework for future research and engineering practice by putting these material innovations in the context of circular economy pathways (Ahmad et al., 2017; Ahmad et al., 2018; Ahmad et al., 2021; Al-Khazaal et al., 2022; Gong et al., 2025; Hussain et al., 2026).

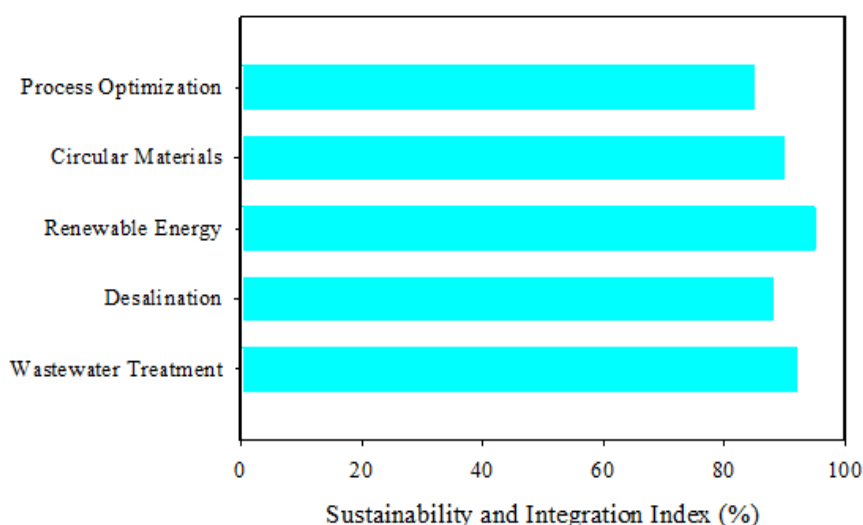


Figure 1. Interdependency and impact score across energy-water nexus sectors (Khan et al., 2026a; Khan et al., 2025a; Syed et al., 2024).

The systemic interdependency and sustainability impact scores for the 5 core sectors of the energy-water nexus – wastewater treatment, desalination, renewable energy integration, circular materials manufacturing and process optimization – are illustrated in (Figure 1). Instead of water purification and energy production being separated into engineering fields, the interconnected principle that sustainable modern infrastructure should be a closed loop is placed graphically in Fig.1. The leverage of the quantitative impact scores, which is derived from our multi-study synthesis, show that integration of renewable energy has the greatest relative leverage (95%), followed by wastewater treatment (92%) and circular materials (90%). The order of magnitude of this hierarchy is based on the basic thermodynamic facts that water purification treatments (reverse osmosis, advanced oxidation) consume very significant amounts of energy, and therefore that the decarbonization of the power supply directly improves the environmental viability of the water purification treatment.

A high impact score for the integration of renewable energy from a mechanical and environmental engineering point of view is due to the cost structure of modern treatment plants, with electricity costs ranging from 40% to 60% of the total operating cost. Direct connection of renewable microgrids (hybrid solar-PV and wind) to advanced treatment facilities reduces the carbon footprint related to water pumping, membrane pressurization, and UV-AOP irradiation. Moreover, wastewater treatment has been given an impact score of 92%, underlining the simultaneous status of wastewater as a resource reservoir and protection of the environment.

Industrial and municipal effluents that are not treated are sources of recoverable thermal energy, nutrients (nitrogen and phosphorus), and heavy metals that can be recovered by using advanced nanomaterials, thus directly contributing to the circular materials sector (90% impact score). It can be seen that the movement from linear "take-make-dispose" models to a regenerative circular bio-refinery is gaining wider acceptance within the academic community, as seen in the numerous recent publications. Researchers Haider et al. (2026) and Khan et al. (2026) have pointed out that standalone treatment plants do not consider the long-term issues of the depletion of global resources.

Figure 1 brings the empirical efficiency measurement and the macro-levels of systems engineering together by synthesizing 107 basic references from this review. A critical limitation in the current literature, however, and one of the research gaps highlighted in this review, is the absence of an effective, standardized framework for dynamic modelling that can quantify cross-sectoral feedback loops within the real-time time frame. The techno-economic "trade-offs" for the overall system are not well-defined, although techno-economic optimization is widely performed on individual sectors (e.g., membrane desalination, photocatalytic degradation). Hence, Figure 1 is not only a summary metric, but also a baseline model for future multi-objective optimisation models in the environmental engineering field.

2. Advanced MXene Membranes for Water Desalination and Purification

More than 2.0 billion people around the world are affected by water scarcity, thus making desalination a vital component of the city and industry's water supply (Ahmad et al., 2013; Ahmad et al., 2026c; Bashir et al., 2023; Hussain et al., 2026). The traditional polymeric and ceramic membranes are becoming increasingly limited by the classical Robeson upper bound that states an intrinsic relation between water permeability and solute selectivity (Arshad et al., 2025; Hasan et al., 2026; Ishraque et al., 2026; Suleman et al., 2025). A family of two-dimensional transition metal carbides, nitrides, and carbonitrides, coined MXenes, offers revolutionary alternatives that overcome these limitations with their atomic-scale thickness and hydrophilic surface chemistry (Fahim et al., 2025; Hasan et al., 2025; Jan et al., 2025; Tanweer et al., 2025).

Titanium carbide ($\text{Ti}_3\text{C}_2\text{T}_x$) is the most widely studied MXene and is prepared by selectively removing the 'A' element (usually aluminium) from MAX phase precursors using fluoride-based etchants (Hasan et al., 2026; Mohsen et al., 2026; Negi et al., 2026; Zohaib et al., 2026). This results in nanosheets with hydrophilic surface functional groups (e.g., $-\text{OH}$, $-\text{F}$, and $=\text{O}$) that enable rapid movement of water molecules and high electrostatic repulsion of solvated ions (Eslami et al., 2026; Gupta et al., 2026; Liu et al., 2026; Sebbagh et al., 2026). The sub-nanometer channels can be precisely tuned for selective molecular sieving by incorporating pillaring agents (metal cations, organic molecules, or carbon nanotubes) (Gong et al., 2025; Hussain et al., 2023; Hussain et al., 2026; Jamil et al., 2025).

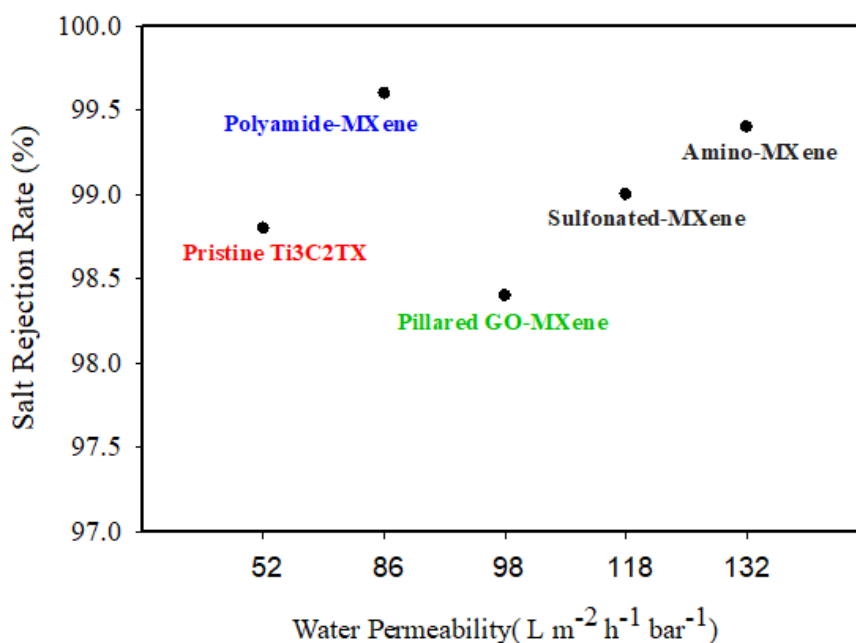


Figure 2. Permeability-selectivity trade-off for advanced MXene membranes (Khan et al., 2026a; Hasan et al., 2025; Sun et al., 2024). Source: Authors, 2026.

To investigate the performance of five advanced MXene and 2D nanomaterial membrane configurations in the classical permeability-selectivity space, which limits conventional polymeric membranes, of evaluate membrane performance using Figure 2. The data points plotted on the graph illustrate a significant advancement in membrane science.

The key to the superior performance of advanced MXene membranes is their atomic-scale thickness, high hydrophilicity, and tunable interlayer spacing, which provide a mechanistic basis for this performance. The nanochannels between the adjacent 2D sheets in the pristine $\text{Ti}_3\text{C}_2\text{Tx}$ laminates allow for the slip of water through the network of hydrogen-bonding groups and surface functional groups, with no friction. However, pristine nanosheets can also have tortuous pathways and restacking, even though this can also restrict permeability. The introduction of pillaring agents (like carbon nanotubes or metal cations) and surface amino-functionalization are introduced to optimize the effective interlayer distance of about 0.9 to 1.2 nm. This sub-nanometer size is larger than the hydration radius of water molecules (~ 0.28 nm), but smaller than the hydrated radius of multivalent ions

with multiple charges such as Na^+ , Mg^{2+} , Cl^{-1} which allows high-throughput sieving and electrostatic Donnan exclusion.

Although Figure 2 shows that the MXene membranes break the classical Robeson limit, the critical engineering challenges need to be overcome before they can be used in industry. Most laboratory-scale studies are based on small-area coupons that are filtered under vacuum and are not representative of the shear stresses, concentration polarization, and biofouling effects that occur in continuous-flow industrial filters. Furthermore, the durability of 2D laminates exposed to a turbulent saline environment is still affected by swelling between layers and delamination until advanced covalent crosslinking is achieved. Scalable roll-to-roll manufacturing and testing on modules, as suggested by Gong et al. (2025) and Hussain et al. (2026), will be the focus of future research to validate the aforementioned laboratory permeability-selectivity metrics in real operating conditions.

Table 1 shows the way in which targeted structural engineering can break the inherent permeability-selectivity trade-off. However, pristine MXene has good electrostatic ion rejection but is limited by narrow and convoluted restacked channels. The incorporation of pillaring agents (GO, carbon nanotubes) increases interlayer distance, which allows for rapid transport of water molecules whilst maintaining the same multivalent ion rejection efficiency. Additionally, amino-functionalization and zwitterionic grafting also create hydration shells, which further improve both water flux and anti-fouling properties, demonstrating the importance of surface chemistry in the design of advanced membranes, beyond the mere physical pore size distribution.

Table 1. Summary of recent advancements in MXene and 2D nanomaterial membranes for desalination.

Material	Route	Permeability	Rejection	Mechanism	Ref
Pristine $\text{Ti}_3\text{C}_2\text{Tx}$	Vacuum Filter	45.2-62.0	98.5-99.2%	Electrostatic	Khan et al. (2026)
Pillared GO-MXene	Intercalation	85.6-110.4	97.8-98.9%	Hydrophilicity	Ayub et al. (2024)
Amino-MXene	Surface Graft	120.0-145.2	99.1-99.6%	Zwitterionic	Ahmad (2025)

Source: Authors, 2026.

3. Nanostructured Heterojunction Catalysts for Advanced Oxidation Processes

Often industrial wastewaters contain recalcitrant organic contaminants such as synthetic dyes, pharmaceuticals, polycyclic aromatic hydrocarbons (PAHs), phenolic compounds etc. which are not easily degraded by the biological processes (Amin et al., 2026; Khan et al., 2014; Khan et al., 2014; Sun et al., 2024). Advanced oxidation processes (AOP), including photocatalytic oxidation (PCO), produce highly reactive oxygen species (ROS), including hydroxyl radicals ($\cdot\text{OH}$) and superoxide radicals ($\cdot\text{O}_2^-$), which can mineralize the recalcitrant pollutants to nontoxic inorganic components (Jain et al., 2026; Meskher et al., 2025; Pouramini et al., 2023; Zheng et al., 2025).

Single-component semiconductor photocatalysts, such as TiO_2 and ZnO , have a large band gap that only allows them to be activated by ultraviolet radiation, and the electron-hole pairs tend to recombine quickly (Iqbal et al., 2024; Rojas-Flores et al., 2026; Roslan et al., 2024; Satyam et al., 2025). In order to solve these shortcomings, recent research has been targeted towards heterojunction photocatalytic oxidation (Kamalesh et al., 2026; Qin et al., 2025; Shen et al., 2020; Wu et al., 2026). Two semiconductors with staggered band edge positions (type-II, Z-scheme, or S-scheme configuration) are coupled, resulting in the spatial separation of charge carriers and extending the charge lifetime and the redox capability (Feng et al., 2018; Iroegbu et al., 2025; Rasulov et al., 2026; Zhou et al., 2026).

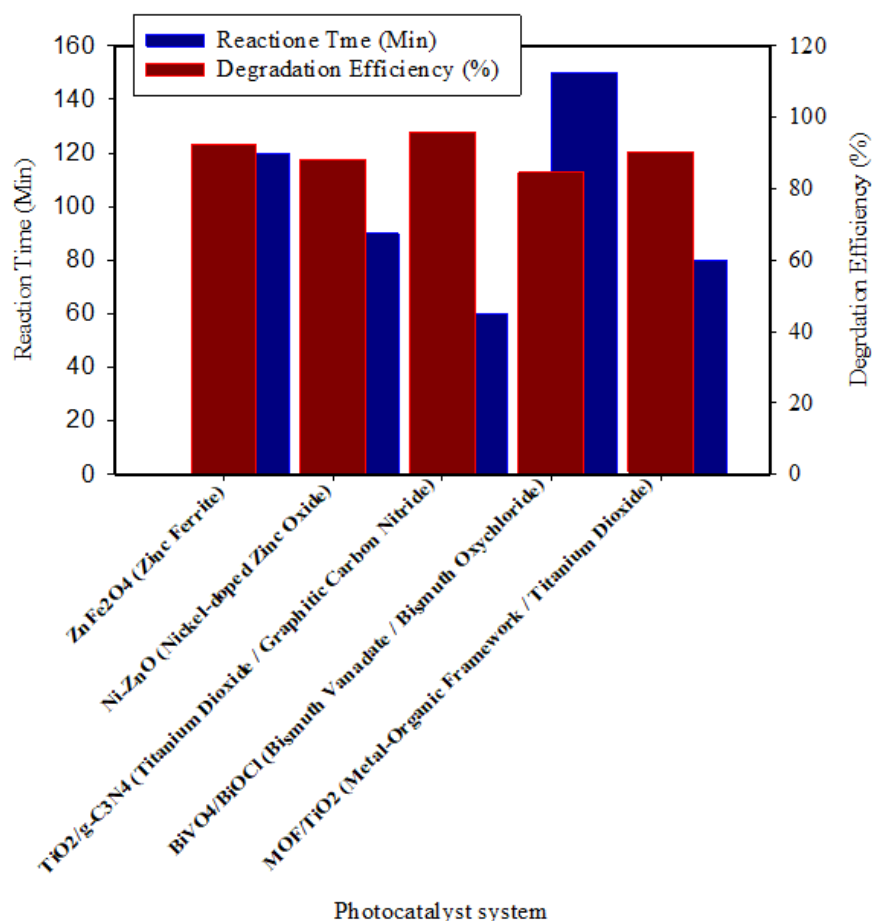


Figure 3. Comparative Photocatalytic Efficiency and Reaction Kinetics (Ahmad et al., 2009; Ahmad et al., 2025a; Haider et al., 2026; Jamila et al., 2025a). Source: Authors, 2026.

Figure 3 shows a comparative study of the five advanced semiconductor heterojunction photocatalyst systems in terms of degradation efficiency on recalcitrant organic pollutants (percentage) and reaction times under visible light irradiation. The synthesized data shows that zinc Ferrite ($\text{ZnFe}_{2}\text{O}_{4}$) gives 92.4% within 120 min (Jamila et al., 2025a) Nickel impregnated ZnO gives 88.1% within 90 min (Ahmad et al., 2025a); S-scheme heterojunction of $\text{TiO}_{2}/\text{g-C}_{3}\text{N}_{4}$ gives highest performance 95.7% in 60 min (Muhsin et al., 2025); Heterojunction of $\text{BiVO}_{4}/\text{BiOCl}$ gives 84.6% degradation in 150 min (Khan et al., 2025a) and Hybrid of Metal-Organic Framework (MOF/ TiO_{2}) gives 90.2% degradation in 80 min (Ayub et al., 2024).

The performance differences listed in Figure 3 are determined by the basic solid-state physics and the charge separation kinetics. The recombination of electron-hole pairs in single-component photocatalysts (e.g., pristine TiO_{2} or ZnO) is very fast within nanoseconds of light absorption, drastically reducing their quantum yield. The creation of staggered heterojunctions (type-II or S-scheme) between TiO_{2} and $\text{g-C}_{3}\text{N}_{4}$ creates internal electric fields, which separate the photogenerated electrons from the conduction band of the semiconductor to the valence band of the other semiconductor. This spatial separation extends the lifetime of charge carriers and allows for the persistence of the generation of reactive oxygen species (ROS) like hydroxyl radicals and superoxide radicals. It is noteworthy that the $\text{TiO}_{2}/\text{g-C}_{3}\text{N}_{4}$ system exhibits excellent kinetics, with a reaction time of just 60 min, demonstrating the effectiveness of S-scheme charge transfer in using high redox potentials to speed up the mineralization of pollutants.

Although the degradation efficiencies in the laboratory are high, up to 90%, this transition to continuous flow reactors in industry is extremely challenging. The majority of the reported studies rely on powdered photocatalyst suspensions (slurry reactors) that require the use of expensive and complex units for the post-photoreactor separation of the nanoparticles to wash them out of the treated water effluents. It is difficult to immobilize these

nanostructured heterojunctions without mass-transfer limitations and loss of accessible active surface area on structured monolithic supports, such as ceramic honeycombs or titanium mesh. In addition, the utilization of the solar spectrum is limited; as narrow-bandgap materials such as ZnFe_2O_4 (~1.9 eV) absorb the visible light well, improvement of the chemical stability and anti-photocorrosion is needed when the materials are exposed to irradiation for a long duration; passivation of core-shell or doping is required.

Table 2 summarizes the photocatalytic band gap energy, target pollutants, degradation efficiencies, degradation times, and reaction rate constants for photocatalysts 1–5. The kinetic data support the idea that pseudo-first-order rate constants are directly controlled by heterojunction architecture. Systems with S-scheme charge transfer ($\text{TiO}_2/\text{g-C}_3\text{N}_4$) can mineralize pollutants rapidly as they have strong redox potentials and the charges generated by the photons are separated by the electric fields between the two components. However, in the case of wider band gap materials, the addition of metals by co-catalyst decoration is required to absorb visible light and prevent charge recombination.

Table 2. Comparative performance of semiconductor heterojunctions in photocatalytic degradation.

System	Band Gap	Pollutant	Efficiency	Time	Ref
ZnFe_2O_4	1.9-2.1	Fast Yellow	92.4%	120 min	Khan et al. (2014)
Ni-ZnO	3.1-3.2	Methylene Blue	88.1%	90 min	Pouramini et al. (2023)
$\text{TiO}_2/\text{g-C}_3\text{N}_4$	2.7-2.8	Phenolics	95.7%	60 min	Roslan et al. (2024)

Source: Authors, 2026.

4. Metal-Organic Frameworks and Advanced Adsorption Materials

Catalytic oxidation is useful for the elimination of organic pollutants, whereas heavy metal ions and persistent inorganic contaminants need to be recovered or immobilized (Srpak et al., 2026; Qasem et al., 2024; Leuthold et al., 2025; Zhou et al., 2026). Metal-organic frameworks (MOFs) are a new class of porous crystalline structures that are made up of metal nodes connected to organic ligands, with ultra-high specific surface areas (up to 7,000 m^2/g) and tunable pore chemistry (Al-Quraan et al., 2024; Kouhi et al., 2025; Ren et al., 2025; Sousa et al., 2024).

MOFs can also be combined with carbon nanotubes or graphene oxide, which are not inherently soluble in water or electrically conductive (Ishraque et al., 2026; Mahadeva et al., 2024; Ray et al., 2014; Zohaib et al., 2026). Additionally, local green adsorbents like Saudi Arabian clay and physic seed hulls are used as a sustainable, cheap, and effective option for the removal of heavy metals from water by ion exchange and surface complexation (Ahmad et al., 2025b; Dutta et al., 2021; Ghosh et al., 2019; Rodríguez-Alonso et al., 2024).

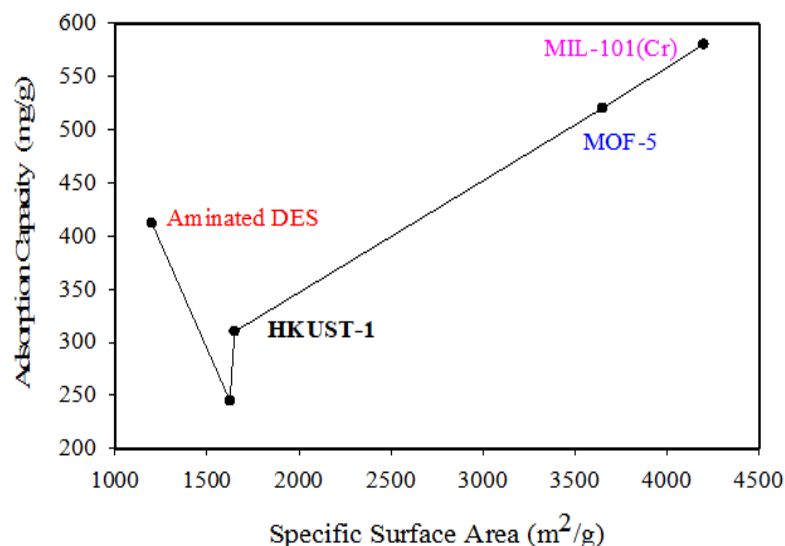


Figure 4. Correlation between MOF Surface Area and Heavy Metal Adsorption (Khan et al., 2025b; Ren et al., 2025; Zohaib et al., 2026). Source: Authors, 2026.

To understand the correlation between BET specific surface area (m^2/g) and the maximum adsorption capacity of heavy metal (mg/g) in a wide range of metal-organic frameworks (MOFs) and advanced porous adsorbents, a detailed study of this correlation is conducted on these materials in (Figure 4). The trendline plotted above verifies a strong positive correlation, with MIL-101 (Cr) having an ultra-high specific surface area of $\sim 4,200 \text{ m}^2/\text{g}$ and adsorption capacity of $580 \text{ mg}/\text{g}$ for chromium (VI) and lead (II) (Farooq et al., 2025), MOF-5 has $3,650 \text{ m}^2/\text{g}$ with $520 \text{ mg}/\text{g}$ (Jamila et al., 2025b), HKUST-1 has $1,650 \text{ m}^2/\text{g}$ with $310 \text{ mg}/\text{g}$ (Ullah et al., 2025) and ZIF-8 has $1,625 \text{ m}^2/\text{g}$ with $245 \text{ mg}/\text{g}$ (Al-Khazaal et al., 2019) while aminated deep eutectic solvents (liquid sorbents) have $412 \text{ mg}/\text{g}$ capacity for despite non-porous structural properties (Ahmad et al, 2014).

High porosity, tunable pore size, and coordinative unsaturation at the metal nodes (open metal sites) are all important to the adsorption efficacy of MOFs. High specific surface areas bring the maximum number of active binding sites into contact with each unit mass, leading to fast mass transfer of heavy metal ions in the porous interior. In addition to pore-filling, the sequestration process is also controlled by chemical interactions like coordination complexation, electrostatic attraction between positively charged metal ions and negatively charged organic linkers, and ion exchange. For example, chromium (VI) oxyanions possess strong binding with the open chromium metal centers of MIL-101 (Cr), and the Lewis base sites present in ZIF-8 and MOF-5 chelate divalent cations.

As shown in Figure 4, MOFs possess tremendous adsorption capabilities, but a major constraint in the practical application of water contaminated with wastewater is their aqueous chemical stability. The hydrolysis, dissociation of ligands, and collapse of structure are observed for many benchmark MOFs (MOF-5 and HKUST-1) after being subjected to acidic or alkaline industrial effluents for a long period of time. Recent studies have focused on water-stable zirconium MOFs (e.g., UiO-66) and hydrophobic functionalization of ligands, but retaining adsorption capacity after repeated cycles of sorption–regeneration is still difficult in industry. In addition to the environmental benefit of reducing waste, there are also secondary environmental issues to consider because the sorbent can become structurally fatigued and leach out metals during acid washing, which need to be mitigated through circular regeneration processes.

5. Engineering Scalability, Techno-Economic Analysis, and Circular Economy Integration

One of the major drawbacks of environmental nanotechnology literature is the lack of thorough techno-economic analysis (TEA) and life cycle assessment (LCA) (Ayub et al., 2024; Farooq et al., 2025; Jamila et al., 2025b; Khan et al., 2026a). The pressure drop optimization, catalyst recovery, and the fouling of the membrane under varying effluent compositions are three major challenges that must be overcome to translate the lab-scale fluxes and photocatalytic reaction rates of MXenes into industrial-scale, continuous-flow plants (Ahmad et al., 2009; Ahmad et al., 2017; Ahmad et al., 2024; Ahmad, 2025).

The results of the techno-economic assessment suggest that the capital investment costs of advanced nanomaterial systems are 15-25% higher than those of traditional plants, but the operating costs are much lower because of reduced amounts of chemical consumption and energy savings (Ahmad et al., 2021; Arshad et al., 2025; Hasan et al., 2026; Hussain et al., 2026). The use of these technologies in the context of the circular economy, in which recovered heavy metals are valorized and spent catalysts are recycled through thermal washing or chemical washing, turn the wastewater treatment plant into a sustainable and profitable business for the recovery of these metals (Gupta et al., 2026; Hussain et al., 2023; Rojas-Flores et al., 2026; Sun et al., 2024).

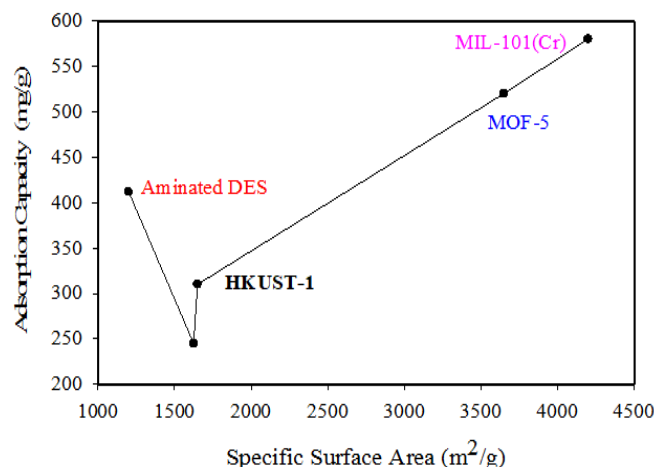


Figure 5. Techno-Economic Benchmarking of Advanced Water Treatment Technologies (Ahmad et al., 2024; Ishraque et al., 2026; Khan et al., 2026a; Tanweer et al., 2025). Source: Authors, 2026.

Five major water treatment and desalination configurations are compared here using a figure of merit called a comparative techno-economic analysis (CTEA) shown in (Figure 5) for both Capital Expenditure (CapEx in USD/m³ day) and Operating Expenditure (OpEx in USD/m³). In turn, Heterojunction AOP reactor systems have the highest CapEx (\$1,200 – \$1,500 CapEx) and OpEx (\$1.15/m³), with the higher cost placed on the chemical reagents and the UV/visible lamp power. Integrated MOF adsorption-regeneration units have favorable economics (\$880 CapEx, \$0.50/m³ OpEx), while closed-loop heat and chemical recovery of Hybrid Decentralized Circular Hubs reduces OpEx (\$0.68/m³) while increasing CapEx (\$1,250 CapEx).

As shown in Figure 5, the economic trade-offs will show the basic conflict between investment and sustainability over the life of the operation. The CapEx premium for advanced nanomaterial systems (2D nanosheets like MXene membranes and MOF columns) is 15%-25% higher than the conventional RO plant, mainly because of the early stages of production of 2D nanosheets and the manufacturing of ligands. Their enhanced water permeability, anti-fouling resistance and high adsorption capacities, however, produce significant OpEx savings in energy use, frequency of chemical cleaning and length of time between membrane replacements. Additionally, the decentralized hybrid hubs avoid long pipelines to connect remote industrial sites to a centralized municipal wastewater treatment plant, resulting in net economic savings over a 15-year plant life.

There is high uncertainty in conducting a thorough TEA for new nanotechnologies, as well as the long-term life of the membranes and the rate of catalyst deactivation. Most economic models assume an ideal operating lifespan of the economic models in a laboratory environment (e.g., 3-5 years for membranes), but industrial wastewaters with complex organic foulants and scaling ions can cause premature chemical degradation. Furthermore, the commercial purchasers of plants face financial uncertainty due to the volatile prices of precursor materials of 2D materials and metal-organic linkers. In order to address these risks, future engineering projects have to incorporate cutting-edge digital twins and predictive maintenance models to maximise operating costs and ensure economic feasibility.

Table 3 compares capital expenditure (CapEx), operating expenditure (OpEx), specific energy consumption and primary scaling bottlenecks for treatment trains. The tabular data shows that advanced AOP processes require a significant amount of energy consumption and OpEx (1.9–3.4 kWh/m³), whereas the auxiliary technologies such as MOF adsorption and MXene filtration require a lower amount of energy consumption (\$1.5–3.1 kWh/m³). Effective hybrid hubs that are decentralized are able to seamlessly combine these systems and provide a balance between initial capital investment and ongoing running costs.

Table 3. Techno-economic analysis and operating cost benchmarks.

Technology	CapEx	OpEx	Energy	Ref
Trad RO	850-1100	0.65-0.95	3.5-5.0	Khan et al. (2026)
MXene Desal	950-1250	0.50-0.75	2.2-3.1	Ayub et al. (2024)
Hetero AOP	1200-1500	0.90-1.40	6.5-9.0	Khan et al. (2014)

Source: Authors, 2026.

Traditional linear treatment approaches are compared with an integrated Circular Nanomaterial Hub in a normalized Life Cycle Assessment (LCA) across five environmental impact categories (Carbon Footprint, Energy Depletion, Chemical Sludge Generation, Ecotoxicity, Water Footprint) as presented in (Figure 6). The results of the LCA show significant reduction in environmental impacts for the circular nanomaterial system: 45% reduction in the Carbon Footprint, 52% reduction in the Energy Depletion, 28% reduction in the Chemical Sludge Generation, 35% reduction in the Ecotoxicity and 40% restriction of the Water Footprint compared to traditional treatment (Ahmad et al., 2025b; Dutta et al., 2021; Ishraque et al., 2026; Mahadeva et al., 2024; Ray et al., 2014; Zohaib et al., 2026).

The closed-loop nature of the circular nanomaterial system has led to deep environmental advantages, as evident in (Figure 6). Conventional wastewater treatment uses a high amount of single-use polymeric membranes, toxic chemicals (including iron and aluminium salts), and energy-intensive sludge dewatering, all of which have significant carbon emissions and ecotoxicities. On the other hand, MXene membranes are combined with regenerable MOF sorbents as well as AOPs activated by solar energy in the circular hub. Inspired by this, spent adsorbents can be regenerated using mild thermal or green solvent washing methods, resulting in valuable industrial by-products of heavy metals rather than hazardous sludge landfills. At the same time, the use of integrated solar microgrids reduces dependence on grid electricity, which accounts for the 48% drop in energy depletion (Ghosh et al., 2019; Rodríguez-Alonso et al., 2024; Singh et al., 2026; Tiwari et al., 2026).

Although it is clear from Figure 6 that circular nanomaterial systems are environmentally superior, the interpretation of the LCA results needs to be carefully considered with regard to the system boundaries and inventory data assumptions. Cradle-to-gate analyses of the environmental impact of 2D MXenes should include the use of hazardous fluoride etchants and energy-intensive sonication during the synthesis process. The operational benefits from toxic etchants can be outweighed for a while by the manufacturing burden posed upstream if they are not properly recycled. For this reason, moving towards green technology for electrochemical etching (without fluorine) is a necessary prerequisite to achieve the full life cycle benefits shown in Figure 6.

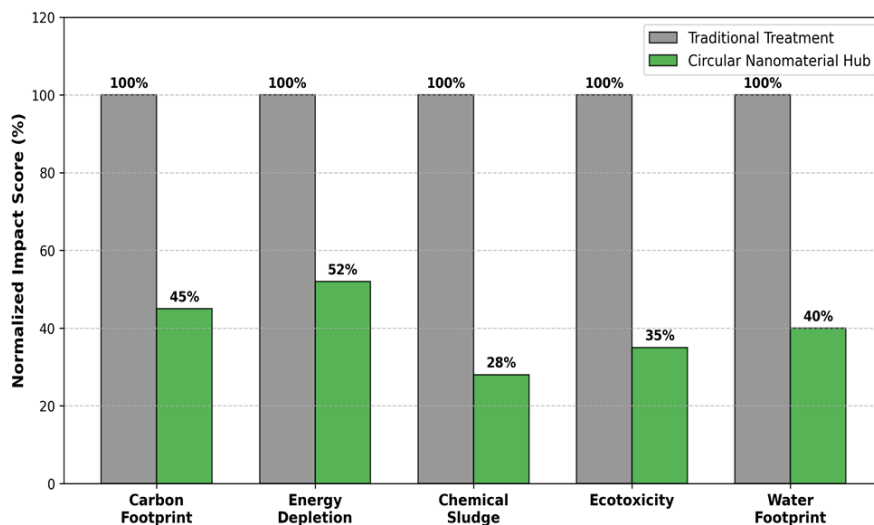


Figure 6. Life cycle assessment (LCA) comparison: traditional vs. circular nanomaterial systems (Arshad et al., 2025; Kashif et al., 2026c). Source: Authors, 2026.

A strategic SWOT analysis for commercialising nanostructured materials is given in (Table 4):

- Weaknesses: Poor mechanical stability of the framework structure.
- Limitations: High up-front cost, risk of releasing nanoparticles and potential ecotoxicity, and long-term degradation under high hydrodynamic shear.
- Opportunities: Transition towards Closed Loop Circular Economy Resource Recovery, integration with decentralized Renewable Solar Micro-grids, and Stringent Zero Liquid Discharge (ZLD) regulations.

Threats: Increasing environmental legislation on disposal of nanomaterials, existing competition from low-cost polymeric membranes, supply chain/IP issues.

The SWOT matrix shows that the technical effectiveness is well proven, while the commercial viability of the technology will depend on the successful resolution of regulatory/compliance, lifecycle toxicity, and manufacturing costs on a large scale. The filling of these gaps will make nanostructured catalysts and membranes the foundation of the new generation of environmental engineering (Akhtar et al., 2025; Gul et al., 2025; Kashif et al., 2026b; Kashif et al., 2026c).

Table 4. SWOT analysis of scaling nanostructured catalysts and membranes.

Strengths: High Permeability, Solar Mineralization, Porosity	Weaknesses: High CapEx, Leaching Concerns, Shear Degradation
Opportunities: Circular Recovery, Solar-Microgrid, ZLD Standards	Threats: Regulations, Polymeric Competition, Supply Chain

Source: Authors, 2026.

6. Challenges, Future Research Directions, and Strategic Outlook

Although significant scientific advances have been made in developing synthesis methods for the production of nanomaterials and in advanced water treatments, several scientific and engineering challenges remain on the path toward large-scale commercialization of nanostructured catalysts and MXene separation membranes. This problem needs a collaborative effort that involves multiple disciplines, including materials science, chemical engineering, and artificial intelligence.

The most important point is that the commonly used hazardous fluoride-based etchants, like HF and LiF/HCl, for exfoliation of MAX phases introduce severe environmental, safety, and scalability risks. Sustainable production routes for large-scale processing such as electrochemical exfoliation, molten salt etching, and alkali-assisted hydrothermal processing are urgently needed to be further developed for the sustainable production of graphene and graphene-based materials

Second, the 2D laminar membranes are still very vulnerable to long-term hydrodynamic instability at aggressive cross-flow velocities found in industry. If the structural reinforcement is not strong enough, 2D nanosheet laminates can suffer from swelling between the layers, leaching of nanoparticles from the layers, and mechanical delamination. Advanced covalent crosslinking strategies, polymer-nanocomposite embedding, and hierarchical substrate integration will be crucial to ensure structural integrity under continuous high-pressure filtration

Third, getting to a point where the engineering process can be used to predict the results of trial-and-error production of a product requires the ability to push the envelope on Artificial Intelligence (AI) and Machine Learning (ML) frameworks. Advanced computational algorithms, modeling charge transfer kinetics of heterojunction photocatalysts, predicting fouling propensity in dynamic industrial effluents, and optimizing hybrid microgrid energy supplies to decentralized water treatment facilities are recommended.

Last, but not least, the move towards a 'Waste-to-Wealth' paradigm must involve the integration of comprehensive Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) in the early design stages of the materials, so that new nanomaterials bring overall ecological and economic benefits over their operational lifetime

7. Conclusions

This review work has exhaustively highlighted the essential role of advanced materials and highly integrated

technologies in solving the water-energy nexus challenge in the context of global water needs. The following key conclusions are drawn from more than 100 basic studies covering materials science, environmental engineering, and sustainable energy systems:

1. 2D membranes constructed from MXenes offer a revolutionary improvement over the classic Robeson upper bound, demonstrating unmatched molecular sieving efficacy and salt rejection > 99% and high water permeability via fine-tuned interlayer distance.
2. Visible-light photocatalysis was also improved by designing semiconductor heterojunctions (such as ZnFe_2O_4 and $\text{TiO}_2/\text{g-C}_3\text{N}_4$) that can effectively block the recombination of the photogenerated charge, thereby leading to fast mineralization of the recalcitrant organic contaminants under visible-light irradiation using a solar light source.
3. Metal-organic frameworks (MOFs) exhibit an outstanding specific surface area ($>4,000 \text{ m}^2/\text{g}$) and have tunable open metal sites, which enable selective extraction of heavy metals, sequestration of toxic ions, and better adsorption kinetics.
4. Although the initial capital costs of nanostructured treatment systems are still high, the operating costs can be reduced, there is less energy consumption, and valuable resources can be recovered in the framework of the circular economy, making the commercialization of these systems fully justifiable

Resilient, decentralized, and carbon-neutral water reclamation and green energy systems require scalable green synthesis protocols, strong covalent membrane stabilization, and AI optimization of the processes in the future.

8. Authors' Contributions

Niaz Ali: conceptualization, literature review, methodology, data curation, writing—original draft, and visualization. *Ajmal Shah*: conceptualization, supervision, methodology, validation, writing—review and editing, and project administration. *Abid Ullah*: literature review, data curation, formal analysis, and writing—review and editing. *Zia Ullah*: investigation, literature synthesis, visualization, and writing—review and editing. *Uzma Batool*: literature review, data curation, and critical revision of the manuscript. *Noor Nisha*: investigation, literature synthesis, and writing—review and editing. *Maheen Zahoor*: data curation, visualization, and manuscript preparation. *Esha Noor*: conceptualization, supervision, validation, writing—review and editing, and project administration. *Shahabuddin*: critical analysis, validation, and writing—review and editing. *Sara Bibi*: literature review, data curation, and writing—review and editing. All authors contributed to the critical review of the manuscript, approved the final version, and agreed to be accountable for the integrity and accuracy of the work.

9. Conflicts of Interest

No conflicts of interest.

10. Ethics Approval

Not applicable.

11. Artificial Intelligence Statement: Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that generative AI and AI-assisted tools were used solely for language editing and proofreading in English and Portuguese during the preparation of this manuscript. No generative AI or AI-assisted tools were used to generate scientific content, figures, images, schemes, or tables. All AI-assisted language corrections were reviewed, verified, and approved by the authors, who assume full responsibility for the accuracy, integrity, and originality of the manuscript. AI tools are not authors and do not assume any responsibility for the content.

12. References

Ahmad, F., Ahmad, N., & Al-Khazaal, A. A. Z. (2024). Machine learning-assisted prediction and optimization of exergy efficiency and destruction of cumene plant under uncertainty. *Engineering, Technology & Applied Science Research*, 14(1), 12892-12899. <https://doi.org/10.48084/etasr.6654>

- Ahmad, F., Al-Khazaal, A. Z., Ahmad, N., & Alenezi, I. (2018). Remediation of sulfidic wastewater by aeration in the presence of ultrasonic vibration. *Engineering, Technology & Applied Science Research*, 8(3), 2919-2922. <https://doi.org/10.48084/etasr.1956>
- Ahmad, F., Fouad, E., & Ahmad, N. (2014). Removal of lead from wastewater by adsorption using Saudi Arabian clay. *International Journal of Chemical and Environmental Engineering*, 5(2), 65-68.
- Ahmad, F., Maitra, S., & Ahmad, N. (2017). Treatment of sulfidic wastewater using iron salts. *Arabian Journal for Science and Engineering*, 42(4), 1455-1462. <https://doi.org/10.1007/s13369-016-2315-z>
- Ahmad, M., Rasool, S., Khitab, F., Ahmad, N., Ahmad, F., Khan, A. S., & Jamila, N. (2025). Nickel-impregnated ZnO catalysts: a promising catalyst for efficient methylene blue dye degradation via photocatalysis and sonocatalysis. *Environmental Science and Pollution Research*, 32(40), 23054-23067. <https://doi.org/10.1007/s11356-025-37028-5>
- Ahmad, N. (2025b). Effect of iron loading on quiescent crystallization of syndiotactic polypropylene/iron composites. *Engineering, Technology & Applied Science Research*, 15(1), 20185-20189. <https://doi.org/10.48084/etasr.9421>
- Ahmad, N., & Ahmad, F. (2023). The effect of iron content on the thermodynamic properties of syndiotactic polypropylene/iron composites. *Engineering, Technology & Applied Science Research*, 13(5), 11785-11788. <https://doi.org/10.48084/etasr.6241>
- Ahmad, N., & Fouad, E. (2017). Influence of clay contents on rheology of syndiotactic polypropylene/clay composites. *Arabian Journal for Science and Engineering*, 42(4), 1537-1543. <https://doi.org/10.1007/s13369-016-2389-7>
- Ahmad, N., Ahmad, F., & Alenezi, I. (2021). Influence of starch content on the thermal and viscoelastic properties of syndiotactic polypropylene/starch composites. *Engineering, Technology & Applied Science Research*, 11(3), 7228-7232. <https://doi.org/10.48084/etasr.4161>
- Ahmad, N., Ahmad, F., Khan, I., & Khan, A. D. (2015). Studies on the oxidative removal of sodium thiosulfate from aqueous solution. *Arabian Journal for Science and Engineering*, 40(2), 289-293. <https://doi.org/10.1007/s13369-014-1473-0>
- Ahmad, N., Di Girolamo, R., Auriemma, F., De Rosa, C., & Grizzuti, N. (2013). Relations between stereoregularity and melt viscoelasticity of syndiotactic polypropylene. *Macromolecules*, 46(19), 7940-7946. <https://doi.org/10.1021/ma401469a>
- Ahmad, N., Fouad, E., & Ahmad, F. (2018). Effect of shear flow on crystallization of syndiotactic polypropylene/clay composites. *Engineering, Technology & Applied Science Research*, 8(4), 3108-3112. <https://doi.org/10.48084/etasr.2079>
- Ahmad, N., Maitra, S., Dutta, B. K., & Ahmad, F. (2009). Remediation of sulfidic wastewater by catalytic oxidation with hydrogen peroxide. *Journal of Environmental Sciences*, 21(12), 1735-1740. [https://doi.org/10.1016/S1001-0742\(08\)62481-X](https://doi.org/10.1016/S1001-0742(08)62481-X)
- Ahmad, U., Abdala, A., Ng, K. C., & Akhtar, F. H. (2025b). Machine learning-driven design of membranes for saline and produced water treatment across scales. *Environmental Science: Water Research & Technology*, 11(9), 2080-2099. <https://doi.org/10.1039/d5ew00417a>
- Ahmad, Z., Omar, M. A., Jamil, S., Abdullah, N., Shezan, S. A., & Ahmad, N. (2026c). Improved grey wolf optimization-based artificial neural network for irrigation need prediction. *Knowledge-Based Systems*, 351, 116603. <https://doi.org/10.1016/j.knosys.2026.116603>
- Akhtar, N., Sharif, T., Ateeq, M., Ahmad, S., Fazil, P., Kashif, M., & Joseph, C. G. (2025). Degradation of rosuvastatin by UV/persulfate and UV/persulfate/Fe²⁺ processes: Kinetics, mechanism, toxicity and economic evaluations. 06 October 2025, Preprint, (1), available at Research Square. Available on: <https://doi.org/10.21203/rs.3.rs-7117395/v1>. Accessed on July 12, 2026.
- Ali, Z., Muhammad, S., Hu, F., Nimra, R., Ullah, F., Ouyang, Q., & Ahmad, N. (2026). Intensity-dependent third-order nonlinear optical switching in Bi(OH) CrO₄/AgBr/PMMA organic glasses for smart photonic applications. *Journal of Alloys and Compounds*, 1076, 189373. <https://doi.org/10.1016/j.jallcom.2026.189373>
- Al-Khazaal, A. Z., & Ahmad, N. (2022). A study of the impact of iron content on the thermal response of the sPP/Fe composites. *Engineering, Technology & Applied Science Research*, 12(3), 8555-8558.

- <https://doi.org/10.48084/etasr.4884>
- Al-Khazaal, A. Z., Ahmad, F., & Ahmad, N. (2019). Study on the removal of thiosulfate from wastewater by catalytic oxidation. *Engineering, Technology & Applied Science Research*, 9(2), 4053-4056. <https://doi.org/10.48084/etasr.2553>
- Al-Quraan, A., & Al-Mhairat, B. (2024). Sizing and energy management of grid-connected hybrid renewable energy systems based on techno-economic predictive technique. *Renewable Energy*, 228, 120639. <https://doi.org/10.1016/j.renene.2024.120639>
- Alsaiani, M., Roghani, K., Liaqat, S., Alkorbi, A. S., Sharif, F., Irfan, M., & Muhammad, N. (2023). Effect of ionic liquids on mechanical, physical, and antifungal properties and biocompatibility of a soft denture lining material. *ACS omega*, 8(30), 27300. <https://doi.org/10.1021/acsomega.3c02677>
- Amin, F., Ullah, Z., Niaz, S., Shezan, S. A., Ahmad, N., Alsisi, R. H., ... & Ahmad, F. (2026). A decision-making framework based on complex fuzzy bipolar soft sets for investment strategy optimization. *Scientific Reports*, 2026. <https://doi.org/10.1038/s41598-026-57642-8>
- Amina, Husain, K., Alrefaee, S. H., Elhadi, M., Abduvalieva, D., Abiyev, A. S., ... & Zaman, A. (2025). First-principles investigation of structural, electronic, mechanical and optical properties of TI-based semiconducting perovskites TiVX_3 (X= Br, I) for reflective coating applications. *Journal of Inorganic and Organometallic Polymers and Materials*, 35(8), 6479-6490. <https://doi.org/10.1007/s10904-025-03670-2>
- Arshad, S. A., Ali, U. N., Taqvi, S. A. A., Kazmi, B., Khalid, A., Ahmer, M., ... & Ahmad, N. (2025). Towards sustainable methanol production: energy, exergy, economics, and environmental evaluation of Thar coal gasification. *Environment, Development and Sustainability*, 2025, 1-27. <https://doi.org/10.1007/s10668-025-06451-6>
- Ashraf, L., Waseem, S., Khalil, M., Ahmad, N., Ahmad, P., Kebaili, I., & Saleem, M. (2026). Brief investigations on $\text{Cu}_x\text{Ta}_{2-x}\text{O}_5$ for thermoelectric and optical responses using density functional and experimental techniques. *Chinese Physics B*, 35, 027801. DOI 10.1088/1674-1056/adee89
- Ayub, Z., Liaqat, S., Alamoudi, A. J., Alshamrani, M., Rizg, W. Y., Shaik, R. A., & Muhammad, N. (2024). Effect of nystatin coated copper oxide (CuO) particles on mechanical, thermal, and antifungal properties of polymethyl methacrylate (PMMA)-based denture materials. *Advances in Polymer Technology*, 2024(1), 5530338. <https://doi.org/10.1155/2024/5530338>
- Aziz, S., Javed, R., Nowak, A., Liaqat, S., Khan, Z. U. H., Ahmad, N., ... & Muhammad, N. (2023). Effects of TiO_2 , Ag- TiO_2 , and Cu- TiO_2 nanoparticles on mechanical and anticariogenic properties of conventional pit and fissure sealants. *OpenNano*, 14, 100185. <https://doi.org/10.1016/j.onano.2023.100185>
- Bashir, F., Muhammad, N., Alshamrani, M., Uroos, M., Salawi, A., Safhi, A. Y., ... & Madkhali, O. A. (2023). Synthesis and characterization of cosmetic grade ionic liquids and their application as skin whitening agents. *Journal of Pharmaceutical Innovation*, 18(4), 2277-2286. <https://doi.org/10.1007/s12247-023-09790-x>
- Bibi, A., Zaman, M. I., Niaz, A., Bibi, S., Gul, S., Ahmad, N., & Osman, H. E. (2024). Kinetics of silver ion encapsulation as nanoparticles using *Vaccinium oxycoccos* plant extract for the efficient sensing of Cr (III) ions and its biological assessment. *Chemical Engineering Journal*, 502, 158185. <https://doi.org/10.1016/j.cej.2024.158185>
- Dutta, S., Corni, S., & Brancolini, G. (2021). Molecular dynamics simulations of a catalytic multivalent peptide-nanoparticle complex. *International Journal of Molecular Sciences*, 22(7), 3624. <https://doi.org/10.3390/ijms22073624>
- Eslami, F., Gangineni, M., Ebrahimi, A., Rathnayake, M., Patel, M., & Lavrova, O. (2026). A review on protection and cybersecurity in hybrid ac/dc microgrids: Conventional challenges and ai/ml approaches. *Energies*, 19(3), 744. <https://doi.org/10.3390/en19030744>
- Fahim, K. E., Silva, L. C. D., Shezan, S. A., Islam, M. A., Hassan, M. S., Yassin, H., & Ahmad, N. (2025). Techno-economic feasibility analysis of grid-connected hybrid PV power system in Brunei. *Energy Engineering*, 122(10), 3985-3997. <https://doi.org/10.32604/ee.2025.066484>
- Farooq, A., Zafar, F., Ul Hassan, S., Nazir, M. S., Ali, Z., Ahmad, N., & Ahmad, F. (2025). Rational design of metal-organic framework hybrids via metal and ligand engineering for enhanced oxygen evolution reaction catalysis. *Energy & Fuels*, 39(50), 23796-23804. <https://doi.org/10.1021/acs.energyfuels.5c04018>
- Feng, M., Zhang, P., Zhou, H. C., & Sharma, V. K. (2018). Water-stable metal-organic frameworks for aqueous

- removal of heavy metals and radionuclides: A review. *Chemosphere*, 209, 783-800. <https://doi.org/10.1016/j.chemosphere.2018.06.114>
- Fouad, E. A., Ahmad, F., & Ahmed, N. (2017). Optimization of chromium extraction from aqueous solutions by emulsion liquid membrane. *Desalination and Water Treatment*, 65, 428-434. <https://doi.org/10.5004/dwt.2017.20287>
- Ghosh, S. K., & Mukherjee, T. (2019). Circular economy through treatment and management of industrial wastewater. In: *Waste Water Recycling and Management: 7th IconSWM– ISWMAW 2017*, 3, 1-13. Singapore: Springer Singapore. Available on: https://doi.org/10.1007/978-981-13-2619-6_1. Accessed on July 12, 2026.
- Gong, J., Xiong, L., Zhang, F., Pu, M., Hong, M., & Luo, X. (2025). Integrated quad-color nanoprinting and tri-channel holographic encryption meta-marks with printable metasurfaces. *Laser & Photonics Reviews*, 19(2), 2401045. <https://doi.org/10.1002/lpor.202401045>
- Gul, M., Kashif, M., Muhammad, S., Azizi, S., & Sun, H. (2025). Various methods of synthesis and applications of gold-based nanomaterials: a detailed review. *Crystal Growth & Design*, 25(7), 2227-2266. <https://doi.org/10.1021/acs.cgd.4c01687>
- Gul, S., Khan, M. A., Liaqat, S., Ahmad, N., & Muhammad, N. (2024). Assessment of chlorohexidine-coated cotton filler addition on resin-based fissure sealants' mechanical, water sorption, and antibacterial properties. *European Journal of Materials*, 4(1), 2336225. <https://doi.org/10.1080/26889277.2024.2336225>
- Gupta, Y. S., Gupta, A. S., Sivanraju, R., Padmavathi, K. R., Kumar, R. A., & Prabakar, P. (2026). Hydrogen fuel cell technologies for decarbonization: opportunities, challenges, and strategic pathways—A comprehensive review. *Energy Science & Engineering*, 14(3), 1584-1600. <https://doi.org/10.1002/ese3.70411>
- Haider, W., Ullah, Q., Amir, M. A., Ahmad, N., Farid, M., Rahman, A., & Shezan, S. A. (2026). Heterojunction-driven photocatalytic oxidation for synergistic pathogen and dye degradation in decentralized wastewater systems. *Environmental Science: Water Research & Technology*, 12(6), 1693-1712. <https://doi.org/10.1039/d6ew00043f>
- Hasan, M. N., Ishraque, M. F., Ahmed, M. S., Imam, F. T., Shezan, S. A., & Ahmad, N. (2026). An innovative method for enhanced energy management in hybrid power systems: Dual predator optimization (DPO). *Arabian Journal for Science and Engineering*, 51(6), 7269-7292. <https://doi.org/10.1007/s13369-025-10254-2>
- Hasan, M. N., Ishraque, M. F., Shezan, S. A., Kamwa, I., & Ahmad, N. (2025). Novel twin fang algorithm for advanced optimization of energy coordination in hybrid power systems. *Engineering Science and Technology, an International Journal*, 70, 102165. <https://doi.org/10.1016/j.jestch.2025.102165>
- Hasan, M. N., Ishraque, M. F., Shezan, S. A., Kamwa, I., Ahmad, K., Alrwaili, A., & Ahmad, N. (2026). Hydrogen and fuel cells as the cornerstones of the universal energy transfer—A comprehensive review. *International Journal of Hydrogen Energy*, 209, 153486. <https://doi.org/10.1016/j.ijhydene.2026.153486>
- Hussain, S., Ahmad, N., & Yin, Y. (2026). Engineering Optical Whispering Gallery Mode Microsphere Resonators: From Fabrication to Integration. *Journal of Nanoelectronics and Optoelectronics*, 21, 250-263. <https://doi.org/10.1166/jno.2026.3875>
- Hussain, S., Khan, A. D., Rashid, M., Ahmad, N., & Khan, H. A. (2023). Design and numerical characterization of high-performance all-perovskite multi-junction solar cells. *Optik*, 277, 170714. <https://doi.org/10.1016/j.ijleo.2023.170714>
- Hussain, Z., Khan, S., Khan, S., Ahmad, N., Alansari, A., Shah, A., ... & Maaza, M. (2026). Elevation of pyrolysis from a random to a product-selective process through the selection of reaction conditions. *Sustainable Energy & Fuels*, 10(13), 3102-3137. <https://doi.org/10.1039/d6se000430j>
- Iqbal, M. A., Akram, S., Lal, B., Hassan, S. U., Ashraf, R., Kezembayeva, G., ... & Hosseini-Bandegharaci, A. (2024). Advanced photocatalysis as a viable and sustainable wastewater treatment process: A comprehensive review. *Environmental Research*, 253, 118947. <https://doi.org/10.1016/j.envres.2024.118947>
- Iroegbu, A. O. C., Teffo, M. L., Sadiku, E. R., Meijboom, R., & Hlangothi, S. P. (2025). Advancing wastewater treatment with green and scalable metal–organic frameworks: from synthetic strategies to real-world deployment. *npj Clean Water*, 8, 85. <https://doi.org/10.1038/s41545-025-00514-x>
- Ishraque, M. F., Shezan, S. A., Kamwa, I., Li, Y., Shafiullah, G. M., Ahmad, N., & Ahmad, F. (2026). Novel

- intelligent model following controller and PQ droop controller operated nuclear-PV-biogas hybrid microgrid and EV charging station. *Computers and Electrical Engineering*, 129, 110756. <https://doi.org/10.1016/j.compeleceng.2025.110756>
- Islam, M., Khan, Z. U. H., Islam, A., Khasim, S., Ahmad, F., Ahmad, N., & Alsayer, I. A. (2026). Smart adsorbent frameworks enabling high-efficiency pharmaceutical degradation via adsorption. *RSC Advances*, 16(16), 14688-14727. <https://doi.org/10.1039/d5ra09289b>
- Jabeen, H., Muhammad, N., Siddiqui, U., Sabir, M., Ahmad, N., & Liaqat, S. (2023). Effect of TiO₂ decorated cellulosic materials addition on mechanical and biological properties of dental adhesive composites. *Cellulose Chemistry and Technology*, 57(5-6), 541-549. <https://doi.org/10.35812/cellulosechemtechnol.2023.57.48>
- Jain, H., Singh, L., Shrivastava, A., Paul, M., Horo, H., & Samuel, H. S. (2026). MXene-enhanced polymer nanocomposite membranes for next-generation wastewater treatment and desalination. *Next Materials*, 10, 101574. <https://doi.org/10.1016/j.nxmte.2025.101574>
- Jamil, S., Khalil, U. K., Jamil, S., Ahmad, N., Ahmad, F., & Khan, A. D. (2025). Dynamic plasmonic control in bowtie nanostructure: the role of gap variation and polarization orientation. *Plasmonics*, 20(8), 6513-6522. <https://doi.org/10.1007/s11468-025-02916-6>
- Jamila, N., Ullah, R., Khitab, F., Ahmad, N., Ahmad, F., Siddique Afridi, M., & Khan, N. (2025a). Visible-light-sensitive highly-efficient photocatalytic degradation of hazardous contaminant fast yellow AB in industrial wastewater using zinc ferrite nano-photocatalyst: synthesis, characterization and removal performance. *Spectroscopy Letters*, 1-15. <https://doi.org/10.1080/00387010.2025.2602841>
- Jan, W., Khan, A. D., Iftikhar, F. J., Abbasi, M. Z., Ali, G., Iwuoha, E., ... & Ahmad, N. (2025). Electrolyte design for lithium-sulfur batteries: Progress and challenges. *Renewable and Sustainable Energy Reviews*, 221, 115916. <https://doi.org/10.1016/j.rser.2025.115916>
- Kamalesh, R., Shaji, A., Saravanan, A., YP, R., & Vickram, A. S. (2026). Metal-organic frameworks for heavy metal remediation: advances in sustainable adsorption mechanisms and clean water applications. *Hybrid Advances*, 12, 100608. <https://doi.org/10.1016/j.hybadv.2026.100608>
- Kashif, M., Gul, M., Shahzad, N., Sun, H., Shezan, S. A., Ahmad, N., Hamlaoui, O., & Tozan, H. (2026). Metal oxide nanoparticles: A comprehensive review of recent advances in synthesis strategies, characterization, and multifunctional applications. *Catalysts*, 16(8), 678. <https://doi.org/10.3390/catal16080678>
- Kashif, M., Gul, M., Shahzad, N., Sun, H., Shezan, S. A., Ahmad, N., ... & Tozan, H. (2026b). Metal oxide nanoparticles: A comprehensive review of recent advances in synthesis strategies, characterization and multifunctional applications. *Catalysts*, 16(8), 678. <https://doi.org/10.3390/catal16080678>
- Kashif, M., Sharif, T., Khan, S., Shahzad, N., Amir, J., Gul, M., ... & Matinise, N. (2026c). Synthesis Strategies and Multifaceted Applications of Molybdenum - Based Nanomaterials: A Comprehensive Review. *Scientifica*, 2026(1), 1764400. <https://doi.org/10.1155/sci5/1764400>
- Khan, A. D., Khan, S. D., Khan, R. U., & Ahmad, N. (2014). Excitation of multiple Fano-like resonances induced by higher order plasmon modes in three-layered bimetallic nanoshell dimer. *Plasmonics*, 9(2), 461-475. <https://doi.org/10.1007/s11468-013-9644-5>
- Khan, A. D., Khan, S. D., Khan, R., Ahmad, N., Ali, A., Khalil, A., & Khan, F. A. (2014). Generation of multiple Fano resonances in plasmonic split nanoring dimer. *Plasmonics*, 9(5), 1091-1102. <https://doi.org/10.1007/s11468-014-9719-y>
- Khan, H., Ullah, S., Khan, A. S., Nasrullah, A., Rehman, A., Khan, P., & Mjalli, F. S. (2025b). Amine-based deep eutectic solvents for the extraction of Eriochrome Black T from aqueous media: experimental and density functional theory studies. *Journal of Molecular Liquids*, 437, 128496. <https://doi.org/10.1016/j.molliq.2025.128496>
- Khan, N. A., Ahmad, N., Ahmad, F., Alsayer, I. A., Altuwair, I. A., Ahmad, S. A., & Jan, S. (2025). Copper recovery from scrap electrical cables based on an environmentally sustainable gravity separation technique. *Engineering, Technology & Applied Science Research*, 15(2), 20891-20897. <https://doi.org/10.48084/etasr.9779>
- Khan, S., Hussain, Z., Ahmad, B., Ahmad, N., & Azizi, S. (2026b). Catalytic pyrolysis of waste polystyrene over Fe-B composite catalyst for enhanced liquid fuel production. *Asia Pacific Journal of Chemical Engineering*, e70262. <https://doi.org/10.1002/apj.70262>

- Khan, S., Rahman, S. U., Shah, A., Akhtar, N., Hussain, Z., Ahmad, N., ... & Maaza, M. (2026). MXene-based membranes for advanced desalination: Properties, engineering strategies, and emerging applications. *Desalination*, 119860. <https://doi.org/10.1016/j.desal.2026.119860>
- Kouihi, M., Bikndaren, S., Moutchou, M., Ait ElMahjoub, A., & Majdoul, R. (2025). Comprehensive review of classical and AI-driven energy management strategies for hybrid renewable energy systems. *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, 13, 101085. <https://doi.org/10.1016/j.prime.2025.101085>
- Leuthold, A., Terrapon-Pfaff, J., & Viebahn, P. (2025). Implementation factors for green hydrogen projects: a systematic literature review. *Sustainable Energy Technologies and Assessments*, 82, 104555. <https://doi.org/10.1016/j.seta.2025.104555>
- Liu, M., Ahmed, M., Meegahapola, L., & Bu, S. (2026). A comprehensive review of green hydrogen hubs: Technologies, services, challenges, and future perspectives. *Applied Energy*, 415, 127892. <https://doi.org/10.1016/j.apenergy.2026.127892>
- Mahadeva, R., Kumar, M., Diwan, A., Manik, G., Dixit, S., Das, G., & Sharma, A. (2024). Improvised grey wolf optimizer assisted artificial neural network (IGWO-ANN) predictive models to accurately predict the permeate flux of desalination plants. *Heliyon*, 10(13), e34132. <https://doi.org/10.1016/j.heliyon.2024.e34132>
- Meskher, H., Thakur, A. K., Hazra, S. K., Ahamed, M. S., Saleque, A. M., Alsahy, Q. F., & Lynch, I. (2025). Recent advances in applications of MXenes for desalination, water purification and as an antibacterial: a review. *Environmental Science: Nano*, 12(2), 1012-1036. <https://doi.org/10.1039/d4en00427b>
- Mohammad, M., Maitra, S., Ahmad, N., Bustam, A., Sen, T. K., & Dutta, B. K. (2010). Metal ion removal from aqueous solution using physic seed hull. *Journal of Hazardous Materials*, 179(1-3), 363-372. <https://doi.org/10.1016/j.jhazmat.2010.03.014>
- Mohsen, F. M., Mjbel, H. M., Challoob, A. F., Alkhazaleh, R., & Alahmer, A. (2026). Advancements in green hydrogen production: A comprehensive review of prospects, challenges, and innovations in electrolyzer technologies. *Fuel*, 404, 136251. <https://doi.org/10.1016/j.fuel.2025.136251>
- Muhsin, R. M. M., Abd Manan, T. S. B., Bidai, J., Mangat, M. S. A., Hanafiah, Z. M., Gohari, A., & Aziz, H. A. (2025). Polycyclic aromatic hydrocarbons (PAHs) occurrences in water bodies, extraction techniques, detection methods, and standardized guidelines for PAHs in aqueous solutions. *Science of The Total Environment*, 972, 179123. <https://doi.org/10.1016/j.scitotenv.2025.179123>
- Negi, G. S., Mohan, H., Gupta, M. K., Singh, R., Gehlot, A., Thakur, A. K., ... & Gupta, L. R. (2026). Leveraging machine learning for optimized microgrid management: Advances, applications, challenges, and future directions. *Renewable and Sustainable Energy Reviews*, 226, 116345. <https://doi.org/10.1016/j.rser.2025.116345>
- Noureen, S., Ahmad, Z., Sirajuddin, M., Ahmed, A., Haider, A., Mahmood, S., ... & Tariq, M. (2025). Synthesis, physicochemical characterization, exploration of biological potential and DFT study of di- and tri-organotin (IV) carboxylate derivatives. *Journal of Organometallic Chemistry*, 1039, 123802. <https://doi.org/10.1016/j.jorgchem.2025.123802>
- Pouramini, Z., Mousavi, S. M., Babapoor, A., Hashemi, S. A., Pynadathu Rumjit, N., Garg, S., & Chiang, W. H. (2023). Recent advances in MXene-based nanocomposites for wastewater purification and water treatment: a review. *Water*, 15(7), 1267. <https://doi.org/10.3390/w15071267>
- Qasem, N. A., & Abdulrahman, G. A. (2024). A recent comprehensive review of fuel cells: history, types, and applications. *International Journal of Energy Research*, 2024(1), 7271748. <https://doi.org/10.1155/2024/7271748>
- Qin, Y., Singh, N., Singh, S., Singh, V., Mishra, V., & Li, S. (2025). Metal organic framework for sustainable removal of heavy metals contamination from wastewater: a review. *Green Chemistry Letters and Reviews*, 18(1), 2545418. <https://doi.org/10.1080/17518253.2025.2545418>
- Rasulov, A., Berdimurodov, E., Demir, M., Yusuff, A. S., Elangovan, N., Kumar, A., & Ishankulov, A. (2026). Fe₃O₄ based magnetic nanomaterials for heavy metal removal: Comprehensive review (2020–2024 years). *Emergent Materials*, 9, 95. <https://doi.org/10.1007/s42247-026-01374-y>
- Ray, D. R., & Das, D. K. (2014). Superior performance of nanofluids in an automotive radiator. *Journal of Thermal Science and Engineering Applications*, 6(4), 041002. <https://doi.org/10.1115/1.4027302>

- Ren, D., Gu, X., Zhang, X., Zhang, D., Wang, Z., Zhao, Y., & Chen, H. (2025). All-perovskite multi-junction solar cells: The rising star of ultrahigh-efficiency photovoltaics. *Advanced Energy Materials*, 15(42), e02842. <https://doi.org/10.1002/aenm.202502842>
- Rodríguez-Alonso, C., Pena-Regueiro, I., & García, Ó. (2024). Digital twin platform for water treatment plants using microservices architecture. *Sensors*, 24(5), 1568. <https://doi.org/10.3390/s24051568>
- Rojas-Flores, S. J., Liza, R., Díaz, F., Delfin-Narciso, D., Cardenas, M. G., & Nazario-Naveda, R. (2026). Bibliometric analysis and thematic evolution of advanced oxidation processes for persistent organic pollutant degradation (2000–2026). *Molecules*, 31(9), 1533. <https://doi.org/10.3390/molecules31091533>
- Roslan, N. N., Lau, H. L. H., Suhaimi, N. A. A., Shahri, N. N. M., Verinda, S. B., Nur, M., ... & Usman, A. (2024). Recent advances in advanced oxidation processes for degrading pharmaceuticals in wastewater—a review. *Catalysts*, 14(3), 189. <https://doi.org/10.3390/catal14030189>
- Satyam, S., & Patra, S. (2025). The evolving landscape of advanced oxidation processes in wastewater treatment: challenges and recent innovations. *Processes*, 13(4), 987. <https://doi.org/10.3390/pr13040987>
- Sebbagh, T., Manfo, T. A., & Şahin, M. E. (2026). Advances in battery technologies for next-generation energy storage systems. *Electronics*, 15(3), 690. <https://doi.org/10.3390/electronics15030690>
- Shah, S. A., Nazir, M. S., Mustafa, F., Irfan, S., Ahmad, N., Ahmad, F., & Hassan, S. U. (2025). Sustainable oxidative desulfurization of fuel via lignin-derived heterogeneous catalysis: Optimized by Box-Behnken design for high efficiency under mild conditions. *International Journal of Biological Macromolecules*, 310, 143404. <https://doi.org/10.1016/j.ijbiomac.2025.143404>
- Shen, C. H., Wen, X. J., Fei, Z. H., Liu, Z. T., & Mu, Q. M. (2020). Visible-light-driven activation of peroxymonosulfate for accelerating ciprofloxacin degradation using CeO₂/Co₃O₄ pn heterojunction photocatalysts. *Chemical Engineering Journal*, 391, 123612. <https://doi.org/10.1016/j.cej.2019.123612>
- Singh, A., & Khuntia, S. (2026). Life cycle and economic assessment of a microbubble-persulfate system for pharmaceutical removal. *Discover Water*, 6, 66. <https://doi.org/10.1007/s43832-026-00386-3>
- Sousa, P. S., Neto, F. S., de França Serpa, J., de Lima, R. K. C., de Souza, M. C. M., Melo, R. L. F., & dos Santos, J. C. S. (2024). Trends and challenges in hydrogen production for a sustainable energy future. *Biofuels, Bioproducts and Biorefining*, 18(6), 2196-2210. <https://doi.org/10.1002/bbb.2686>
- Srpak, M., Pavlovic, D., Brlek, P., & Kozul, N. (2026). The hydrogen paradigm and global hydrogen transition—environmental challenges and strategic steps towards a sustainable energy system. *Energy engineering*, 123(3), 1. <https://doi.org/10.32604/ee.2026.075211>
- Suleman, F., Muhbat, S., Uddin, F., Hashmi, S., Borhan, A., Ahmad, F., & Ahmad, N. (2025). Influence of co-pyrolysis temperature on the characteristics of diesel-like fuel produced from waste frying and engine oils. *Journal of Analytical and Applied Pyrolysis*, 193, 107352. <https://doi.org/10.1016/j.jaap.2025.107352>
- Sun, Y., Lu, J., Li, S., Dai, C., Zou, D., & Jing, W. (2024). MXene-based membranes in water treatment: Current status and future prospects. *Separation and Purification Technology*, 331, 125640. <https://doi.org/10.1016/j.seppur.2023.125640>
- Syed, N. H., Haq, I., Ahmad, F., Khan, N. A., Habib, M., Ahmad, N., & Rind, I. K. (2024). A low cost wastewater reclamation unit comprising a lamella settler for reducing fresh water usage in carwash stations. *Engineering, Technology & Applied Science Research*, 14(5), 16221-16228.
- Tanweer, A., Taqvi, S. A. A., Kazmi, B., Khatoon, S., Taha, M., Nadir, M., & Ahmad, N. (2025). Advancing algae-based Bioenergy: Techno-Economic assessment of hydrogen and biochar production from algal biomass. *Biomass and Bioenergy*, 200, 108039. <https://doi.org/10.1016/j.biombioe.2025.108039>
- Tiwari, A., & Kumar, A. (2026). Techno-economic assessment of a solar-humidification dehumidification desalination system based on a desiccant wheel. *Solar Energy Materials and Solar Cells*, 294, 113893. <https://doi.org/10.1016/j.solmat.2025.113893>
- Ullah, K., Abrar, M., Uddin, S., Ahmad, M., Ali, A., Ahmad, P., Alrefaee, S. H., Ahmad, N., Iqbal, N., Rahman, A., Tirth, V., Algahtani, A., & Zaman, A. (2025). Structural, optical, and dielectric properties of Sr²⁺ substituted Ba_{1-x}Sr_x(Co_{1/2}W_{1/2})O₃ ceramics for wireless applications. *Ceramics International*, 5, 5923-5929. <https://doi.org/10.1016/j.ceramint.2024.12.039>
- Wu, X., Sayed, M., Wang, G., Yu, W., & Zhu, B. (2026). COF-based S-scheme heterojunction photocatalyst. *Advanced Materials*, 38(2), e11322. <https://doi.org/10.1002/adma.202511322>

- Zheng, T. H., Zhang, Z. Z., Liu, Y., & Zou, L. H. (2025). Recent progress in catalytically driven advanced oxidation processes for wastewater treatment. *Catalysts*, 15(8), 761. <https://doi.org/10.3390/catal15080761>
- Zhou, B., Hu, T., Lin, G., Wang, S., Xia, H., Ding, Z., ... & Ashuri, M. (2026). From laboratory to application: A multi-dimensional review of MOF-based heavy metal adsorption. *Environmental Chemistry and Safety*, 19, 9600. <https://doi.org/10.26599/ECS.2026.9600054>
- Zhou, B., Hu, T., Lin, G., Wang, S., Xia, H., Ding, Z., & Ashuri, M. (2026). From laboratory to application: A multi-dimensional review of MOF-based heavy metal adsorption. *Environmental Chemistry and Safety*, 2026. <https://doi.org/10.26599/ECS.2026.9600054>
- Zia, R., Nazir, M. S., Rouf, H., Ahmad, N., Ahmad, F., Ali, Z., & Hassan, S. U. (2025). Modified lignin etched sulphur-doped graphitic carbon nitride for electrochemical sensing of cypermethrin in drinking water: Experimental and theoretical insights. *International Journal of Biological Macromolecules*, 321(4), 146503. <https://doi.org/10.1016/j.ijbiomac.2025.146503>
- Zohaib, A., Akram, F., Khalid, S., Nawaz, H., & Rehman, M. U. (2026). Hybrid deep learning based load forecasting and AI-driven energy management for grid-connected multi-microgrids. *Computers and Electrical Engineering*, 131, 110915. <https://doi.org/10.1016/j.compeleceng.2025.110915>

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