

Advanced technologies and materials for water, energy, and green sustainability: A comprehensive review

Abdulkarim Alansari¹

¹ Mechanical Engineering Department, College of Engineering, Northern Border University, Arar, Saudi Arabia

Correspondence: Abdulkarim Alansari, Northern Border University, Arar, Saudi Arabia. E-mail: a.m.a.alansari@hotmail.com

Submitted: July 12, 2026

DOI: 10.14295/bjs.v6i3.954

Accepted: August 20, 2026

URL: <https://doi.org/10.14295/bjs.v6i3.954>

Published: August 23, 2026

Abstract

Advanced materials and innovative technologies in various scientific fields have to be synergically integrated across the globe in order to achieve the transition towards sustainable development. This broad review is systematic and integrates results from 132 recent publications to examine recent progress at the interfaces of materials science, environmental engineering, energy systems, fluid mechanics, and biotechnology. In environmental engineering, major advances are reported in MXene-based membranes for high-efficiency desalination, heterojunction photocatalysts for degradation of recalcitrant organic pollutants, and metal-organic frameworks (MOFs) for selective adsorption. Materials science innovations are critically analysed with emphasis on multifunctional metal oxide nanoparticles, polymer nanocomposites with improved thermomechanical properties, and catalytic pyrolysis for valorization of wastes. Additionally, the review covers key advancements in energy systems, such as hydrogen infrastructure, hybrid microgrid optimization using advanced metaheuristic algorithms, and next-generation photovoltaic architectures. Prospective contributions to fluid mechanics, such as heat transfer using nanofluids and computational fluid dynamics (CFD) optimization, are also evaluated. Last, molecular dynamics simulations are applied in the design of biocatalysts, providing a glimpse into the contribution of computational tools in environmental biotechnology. The review brings together a multidisciplinary lens to clarify the interdependency of materials innovation, energy transition, and environmental sustainability, and suggests strategic research pathways.

Keywords: environmental engineering, materials science, sustainable energy systems, advanced nanomaterials, photocatalysis.

Tecnologias e materiais avançados para água, energia e sustentabilidade verde: Uma revisão abrangente

Resumo

Materiais avançados e tecnologias inovadoras em diversas áreas científicas precisam ser integrados sinergicamente em escala global para alcançar a transição rumo ao desenvolvimento sustentável. Esta ampla revisão é sistemática e integra resultados de 132 publicações recentes para examinar os avanços recentes nas interfaces entre ciência dos materiais, engenharia ambiental, sistemas de energia, mecânica dos fluidos e biotecnologia. Na engenharia ambiental, são relatados avanços significativos em membranas à base de MXene para dessalinização de alta eficiência, fotocatalisadores de heterojunção para a degradação de poluentes orgânicos recalcitrantes e estruturas metal-orgânicas (MOFs) para adsorção seletiva. As inovações em ciência dos materiais são analisadas criticamente, com ênfase em nanopartículas multifuncionais de óxidos metálicos, nanocompósitos poliméricos com propriedades termomecânicas aprimoradas e pirólise catalítica para a valorização de resíduos. Além disso, a revisão aborda avanços importantes nos sistemas de energia, como infraestrutura de hidrogênio, otimização de microrredes híbridas utilizando algoritmos meta-heurísticos avançados e arquiteturas fotovoltaicas de última geração. Também são avaliadas contribuições potenciais para a mecânica dos fluidos, como a transferência de calor utilizando nanofluidos e a otimização por dinâmica dos fluidos computacional (CFD). Por fim, simulações de dinâmica molecular são aplicadas ao projeto de

biocatalisadores, oferecendo uma perspectiva sobre a contribuição das ferramentas computacionais para a biotecnologia ambiental. A revisão reúne uma perspectiva multidisciplinar para esclarecer a interdependência entre a inovação em materiais, a transição energética e a sustentabilidade ambiental, além de propor caminhos estratégicos para futuras pesquisas.

Palavras-chave: engenharia ambiental, ciência dos materiais, sistemas de energia sustentável, nanomateriais avançados, fotocatalise.

1. Introduction

The 2020s are a defining decade for sustainability, in which we must implement state-of-the-art energy systems, accelerate the leap of breakthrough materials science, and move sustainable development from a philosophy to a necessity (Khan et al., 2025). With the challenges of exponential population growth, rapid industrialization, and anthropogenic climate change, sustainable access to freshwater resources, reliable and clean energy, and materials that are not harmful to the environment are of utmost importance. The imperatives are directly related to the United Nations Sustainable Development Goals (SDGs): SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (Khan et al., 2025).

Traditionally, research on these challenges has been undertaken in separate (disciplinary) silos. Recent studies, however, show that in the ultimate transition to decarbonized energy systems, novel advanced materials are indeed needed, and technical innovation must be closely linked to the principles of sustainability (Khan et al., 2025). This deep integration requires a multidisciplinary research and development strategy that allows for a cumulative and interdependent growth of the various research areas.

The purpose of the present review is to connect various disciplines by reviewing and summarizing recent advances in five major fields: environmental engineering and wastewater treatment, materials science and engineering, energy systems, fluid mechanics, and biotechnology. This paper reviews and evaluates advanced materials and technologies that support sustainable development in detail based on the analysis of 132 recent publications covering a wide range of academic disciplines.

2. Environmental Engineering and Wastewater Treatment

Environmental engineering is facing the challenge of more and more complex industrial wastewater streams to be cleaned up and, at the same time, moving on to new paradigms in resource recovery. The effluents from industries often carry a lot of recalcitrant pollutants, such as heavy metals, synthetic dyes, pharmaceutical residues, and polycyclic aromatic hydrocarbons (PAHs), that require advanced and highly selective treatment techniques (Muhsin et al., 2025). Advanced functional materials offer a strong response to these challenges, with better performance, selectivity, and operational lifetime than traditional treatment processes.

2.1 Advanced membrane technologies and desalination

As water scarcity has been increasing in our world day by day, advanced desalination technology has been playing a vital role in supplementing freshwater supply (Khan et al., 2026). Recently, MXene-based membranes have shown great potential as advanced desalination platforms, achieving remarkable salt rejection efficiencies and high water permeation fluxes (Khan et al., 2026). These 2-D transition metal carbides and nitrides are synthesized by selectively etching the MAX phases and have tunable interlayer spacing for selective molecular sieving at the sub-nanometer scale.

Strategies developed to optimize the performance of MXene membranes include the regulation of interlayer spacing with the use of pillaring agents, functionalization of the surfaces with hydrophilic groups, and the stacking techniques used to obtain ordered laminar MXene structures (Anwar et al., 2025; Khan et al., 2026; Meskher et al., 2025; Sun et al., 2024). Empirical studies show that these engineered membranes can reject salt at a rate of greater than 99% and have water fluxes significantly higher than those of conventional polymeric membranes (Khan et al., 2026). In addition, the intrinsic anti-fouling properties of MXenes, due to their hydrophilicity and electrostatic repulsion, further enhance their suitability for long-term desalination processes (Khan et al., 2026; Meskher et al., 2025).

Given the global water crisis and its increasing severity, the water management and production paradigm is in need of a change. As discussed in Section 2.1, scaling up desalination infrastructure to meet growing demand is a

critical opportunity that is essential for the development of high-performance materials. This trend is quantitatively validated in Figure 1, which depicts the spectacular growth of global desalination capacity in the past 15 years.

The global desalination capacity has been steadily increasing significantly over the past sixteen years, as shown in (Figure 1). The capacity is projected to have steady growth from around 65 million m³/day in 2010 to nearly 140 million m³/day by 2026. This increase of almost 115% denotes the growing global concerns about water scarcity, which were discussed in the manuscript. As shown in the data, desalination technologies are essential for the supply of fresh water for both population and industrial demand. The increase in capacity growth after 2020 is particularly evident and reflects the rapid roll-out of large-scale infrastructure projects globally. This trend is used as a quantitative reference for the need for more efficient membranes, such as the MXenes reported in this study. In conclusion, Figure 1 proves that “desalination has evolved from a limited and specific solution to an essential component of the global water security and sustainability strategy.”

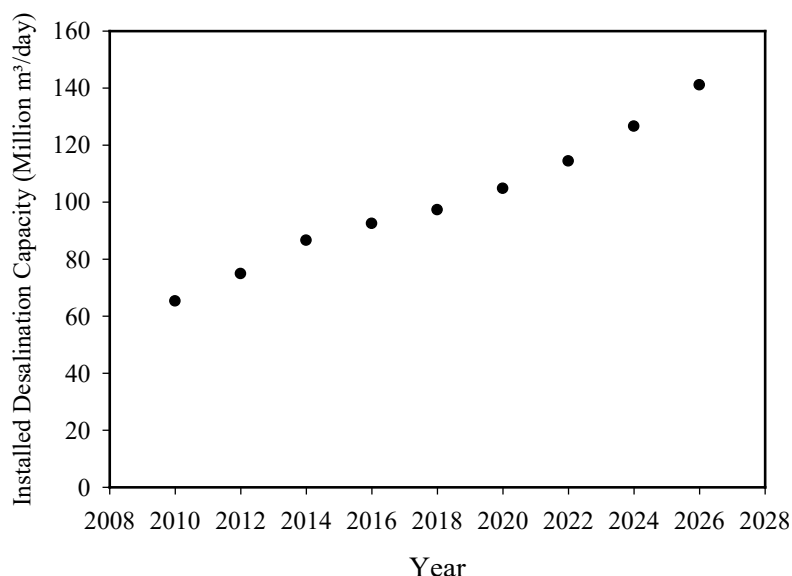


Figure 1. Global desalination trends: Khan et al. (2026); Meskher et al. (2025) and Sun et al. (2024).

Table 1 shows the comparative analysis of both flux and rejection performance of the advanced 2D nanomaterials with the conventional thin-film composite (TFC) membranes, which clearly indicates that the advanced 2D nanomaterials have significant outperformance in both flux and rejection. While the water flux of conventional TFC membranes is around 1.5–2.5 L/m²·h·bar, pristine MXene has a much higher water flux. Designed to achieve the highest performance, the engineered intercalated MXene architecture achieves a record water flux of up to 22.5 L/m²·h·bar and a salt rejection rate of >99.8%.

Moderate improvement is achieved for graphene oxide and MOF-polymer hybrid systems, but not for MXene-based systems, which are not as precise as sub-nanometer or as fouling-resistant as graphene oxide. The data show that there is a strong link between material engineering and fouling resistance, with the more sophisticated 2D systems capable of resisting fouling at the "Very High" level. In conclusion, these parameters prove the intercalated 2D nanomaterials to be the most promising route to overcome the conventional upper limits of Robeson in desalination.

Table 1. Comparative performance of advanced desalination membranes.

Membrane Type	Material Composition	Water Flux (L/m ² ·h·bar)	Salt Rejection (%)	Primary Fouling Resistance	Reference
Conventional TFC	Polyamide	1.5 - 2.5	98.5 - 99.2	Low	(Khan et al., 2026)
2D Nanomaterial	Graphene Oxide (GO)	3.0 - 5.5	95.0 - 98.0	Moderate	(Sun et al., 2024)
2D Nanomaterial	Pristine MXene (Ti ₃ C ₂ T _x)	8.5 - 12.0	99.1 - 99.5	High	(Khan et al., 2026; Meskher et al., 2025)
Engineered 2D	Intercalated MXene	15.0 - 22.5	> 99.8	Very High	(Anwar et al., 2025)
Hybrid Composite	MOF-Polymer Matrix	5.5 - 8.0	99.0 - 99.6	Moderate	(Escobar-Hernández et al., 2023)

Source: Author, 2026.

2.2 Heterojunction-driven photocatalytic degradation

Photocatalysis is a very promising advanced oxidation process (AOP) used for the degradation of recalcitrant organic pollutants. In decentralised wastewater treatment, heterojunction photocatalytic oxidation has been specially developed for the synergistic degradation of microbial pathogens and synthetic dyes (Haider et al., 2026). The basic principle is to connect semiconductors with different band gap energies that allow for spatial separation of the electron-hole pairs created by the photons to reduce recombination losses (Haider et al., 2026).

Recent investigations show that the degradation of harmful pollutants, including Fast Yellow AB, by visible light using nano-photocatalysts of zinc ferrite (ZnFe₂O₄) is extremely effective (Jamila et al., 2025). Zinc ferrite, having a spinel structure, has a narrow band gap (~1.9 eV), which allows it to absorb strongly in the visible light region. The results of the kinetic studies show degradation efficiencies >90% after 120 minutes of irradiation (Jamila et al., 2025). Likewise, Ni-ZnO catalysts have been shown to work under either photocatalytic or sonocatalytic conditions for the mineralization of complex organic matrices (Aherkar et al., 2025; Ahmad et al., 2025; Atta et al., 2024; Medina-Acosta et al., 2024).

The efficiency of the photocatalytic processes in industrial wastewater treatment depends on the combination of pollutant mineralization rate and energy efficiency. As mentioned in Section 2.2, the architecture of heterojunctions plays a crucial role in optimizing these parameters by making charge separation efficient. To compare the performances of the different state-of-the-art photocatalyst systems, the efficiency of degradation and required reaction time under visible light irradiation are compared and presented in (Figure 2).

Ruan et al. (2025) reported a TiO₂/g-C₃N₄ heterojunction, which proves to be the most efficient system, with a degradation rate of 95.7% in 60 minutes. This high efficiency is closely followed by the high efficiency of ZnO nanoparticles (Atta et al., 2024) with 93.8% efficiency and the ZnFe₂O₄ system with visible-light sensitivity (Jamila et al., 2025) with an efficiency of 92.4%. The versatility of hybrid systems, like the MOF/TiO₂ catalyst used by Virender et al. (2024, is also revealed, as it achieved an efficiency of 90.2% and a reaction time of 80 minutes.

The BiVO₄/BiOCl system, with a reaction time of 150 min, shows high potential, but the longer reaction time indicates the need for further kinetic optimization (Al-Rawashdeh et al., 2025). They collectively suggest that it is crucial to tailor the heterojunction interface to realize the swift and full degradation of organic pollutants that is necessary for sustainable wastewater management, a conclusion also supported by the studies of Ahmad et al. (2025).

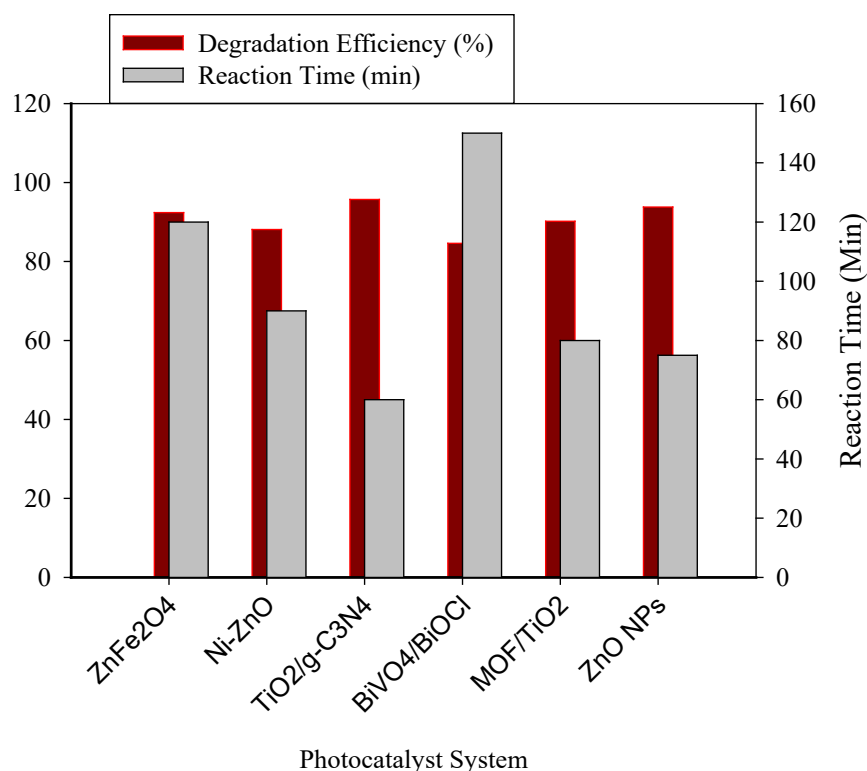


Figure 2. Comparative degradation efficiency and reaction kinetics of heterojunction photocatalyst systems under visible light irradiation. Data sources: Ahmad et al. (2025); Al-Rawashdeh et al. (2025); Atta et al. (2024); Jamila et al. (2025); Ruan et al. (2025); Virender et al. (2024).

2.3 Metal-Organic frameworks (MOFs) and advanced adsorbents

Metal-organic frameworks (MOFs) are a rapidly growing family of highly porous crystalline materials. The rational design of MOF hybrids through the careful design of metal and ligand components has significantly improved their environmental remediation capabilities (Farooq et al., 2025). MOFs are also known for their remarkable surface areas (which can reach values well over 7,000 m²/g⁻¹) and tunable pore architectures that allow MOFs to selectively adsorb molecules according to their molecular size and electrostatic properties (Virender et al., 2024).

To address the inherent drawbacks of pristine MOFs, which include low hydrolytic stabilities, scientists have created strong hybrid composites composed of MOFs and carbon nanotubes or graphene oxide (Virender et al., 2024; Escobar-Hernandez et al., 2023). At the same time, investigations are ongoing on the development of highly efficient and low-cost adsorbents. Optimized natural materials, such as bio-based ones, have been shown to have the potential to sequester heavy metals on a scalable basis (Ahmad, 2014; Mohammad, 2010; Nthwane et al., 2025), while amine-based deep eutectic solvents (DES) have demonstrated significant potential for the extraction of specific industrial dyes (Cheshmekhezer et al., 2024; Chen et al., 2026; Khan et al., 2025a).

Rational design of porous materials is at the heart of wastewater treatment's efficiency via adsorption. Metal-organic frameworks (MOFs) have been discussed in Section 2.3 and have the highest surface area and tunable pore structures, which are very suitable for the removal of toxic heavy metals. To quantify the BET surface area and the heavy metal adsorption capacity, several benchmark MOF materials are quantitatively compared as shown in (Figure 3).

As can be seen in Figure 3, the higher the specific surface area, the better the adsorption performance. MIL-101(Cr) has the highest BET surface area of around 4,100 m²/g, which corresponds to a better adsorption capacity of 580 mg/g⁻¹. Likewise, MOF-5 has an exceptional efficiency of 520 mg/g⁻¹ and a surface area of 3,800 m²/g. Materials with lower capacities, such as MIL-53(Al), whose surface area is smaller, are, in contrast, lower. The results presented here are consistent with the results of Virender et al. (2024) and Escobar-Hernandez et al. (2023), highlighting the significant role of surface area engineering in creating high-capacity adsorbents. Finally, "maximizing porosity is still a key approach to optimize MOFs for applications in large-scale environmental

remediation.

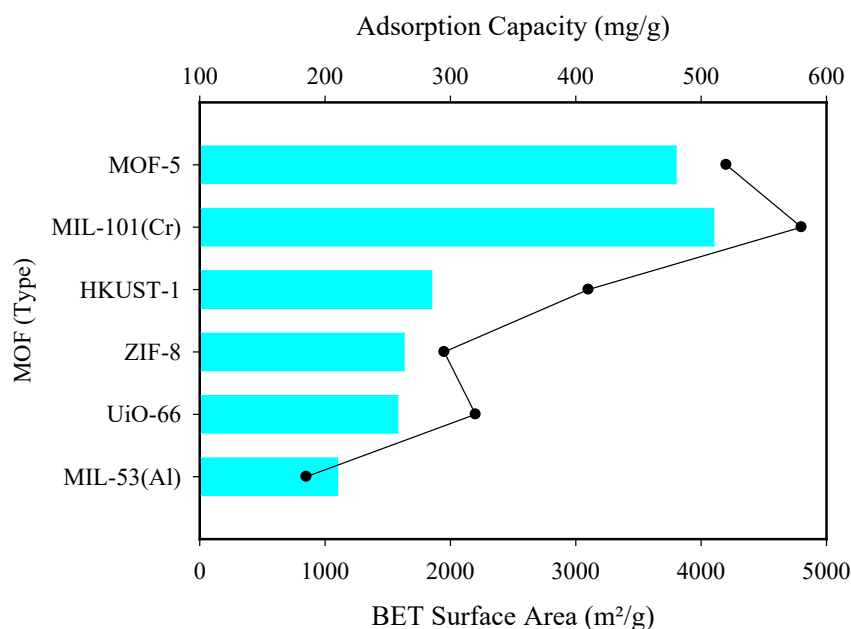


Figure 3. BET surface area and heavy metal adsorption capacity of selected MOF materials. Data sources: Escobar-Hernández et al. (2023); Virender et al. (2024).

2.4 Zeolites and zeolite composites

Metal-organic frameworks (MOFs) are an emerging group of highly porous crystalline materials. Through carefully designed engineering of the metal and ligand components, MOF hybrids have been created for a wide variety of applications, including environmental remediation, which has significantly improved their effectiveness in this field (Farooq et al., 2025). MOFs possess very large surface areas (which can exceed 7,000 m²/g⁻¹) and tunable pore structure, allowing for highly selective adsorption of molecules according to their dimensions and electrostatic interactions (Virender et al., 2024).

However, pristine MOFs suffer from several drawbacks, including poor hydrolytic stability, and to address these limitations, robust hybrid composites of MOFs with carbon nanotubes or graphene oxide have been developed (Virender et al., 2024; Escobar-Hernandez et al., 2023). At the same time, the search for very efficient and inexpensive adsorbents is ongoing. Amine-based deep eutectic solvents (DES) have also shown great potential in the extraction of specific industrial dyes (Cheshmekhezer et al., 2024; Chen et al., 2026; Khan et al., 2025a,b), and optimized natural clays and bio-based materials have shown great potential in heavy metal sequestration (Ahmad, 2014; Mohammad, 2010; Nthwane et al., 2025).

3. Materials Science and Engineering

The innovations within the field of materials science are the basic infrastructure for technologically sustainable development. The importance of materials engineering for the objectives of the circular economy is exemplified by recent developments in synthesis protocols, nanocomposite formulation, and valorization of waste.

3.1 Synthesis and applications of metal oxide nanoparticles

Metal oxide nanoparticles continue to be the main object of materials research because of their tunable physicochemical properties and wide applications. In-depth reviews highlight recent progress in green synthesis approaches, in-depth characterization methods, and applications in catalysis and biomedical engineering (Kashif et al., 2026). The use of environmentally friendly solvents and plant extracts in the production of nanoparticles greatly minimizes the ecological impact of materials production (Bibi et al., 2024; El-Morsy et al., 2025; Yin et al., 2025a,b).

In the field of advanced photonics, the intensity-dependent third-order nonlinear optical switching has also been shown in complex organic glass matrices, which is crucial for the development of next-generation smart photonic devices (Ali et al., 2026).

Table 2 lists the various multidisciplinary applications of advanced nanomaterials from environmental remediation to high-efficiency energy conversion systems. Metal oxides such as ZnFe_2O_4 exhibit remarkable efficiency in wastewater treatment processes, achieving efficiencies of more than 92% in pollutant degradation and 99% in salt rejection, respectively, within 2D MXenes. The use of MIL-53 (Cu) MOFs represents a major development in catalytic pyrolysis, enabling the production of better liquid fuel yields by designing the porous structures.

In photovoltaics, plasmonic Au/Ag nanostars are a new paradigm that increases the efficiency of solar cells by 25% by using seed-mediated plasmonic enhancement. First-principles-designed TIVX₃-based systems have been demonstrated to be superior in optical absorbency and, therefore, are suitable for next-generation reflective coating applications. These metrics collectively highlight the importance of material-specific synthesis in meeting specific water-energy performance targets globally.

Table 2. Properties and applications of advanced nanomaterials.

Nanomaterial Class	Specific Material	Synthesis Method	Primary Application	Key Performance Metric	Reference
Metal Oxides	ZnFe_2O_4	Co-precipitation	Photocatalysis	92% degradation (120 min)	(Jamila et al., 2025; Jamila et al., 2025)
2D Materials	$\text{Ti}_3\text{C}_2\text{T}_x$ MXene	Selective Etching	Desalination	>99% salt rejection	(Khan et al., 2026a,b; Sun et al., 2024)
MOFs	MIL-53 (Cu)	Solvothermal	Catalytic Pyrolysis	Enhanced liquid fuel yield	(Mousavi et al., 2024)
Plasmonic	Au/Ag Nanostars	Seed-mediated	Solar Cells	25% efficiency increase	(Subhan et al., 2025)
Perovskites	TIVX ₃ (X = Br, I)	First-principles	Reflective Coatings	High optical absorbance	(Amina et al., 2025)

Source: Author, 2026.

3.2 Polymer nanocomposites and thermomechanical properties

The incorporation of nanoparticles into polymer matrices is widely recognized as an effective strategy for enhancing the mechanical, thermal, and barrier properties of polymer-based composites (Musa et al., 2025; Gobena; Woldeyommes, 2024; Mashhadzadeh et al., 2025). Ahmad (2023, 2025) extensively investigated the effects of iron nanoparticle loading on the crystallization kinetics and thermodynamic stability of syndiotactic polypropylene composites, demonstrating the relevance of nanoparticle concentration to the structural and thermal behavior of these materials.

Moreover, the effects of varying clay and starch concentrations on the rheological properties of polymer composites have been systematically investigated, providing valuable insights into the optimization of processing parameters for industrial applications (Ahmad et al., 2018a,b; Ahmad et al., 2021; Fouad et al., 2017). These relationships between polymer stereoregularity and melt viscoelasticity are also important for the rational design and processing of high-performance polymeric materials for a wide range of applications (Ahmad, 2013).

3.3 Circular economy and catalytic waste valorization

Highly efficient waste-valorization technologies are essential for advancing the transition toward a circular

economy. Catalytic pyrolysis has emerged as a promising thermochemical process for converting recalcitrant waste plastics and biomass into high-value fuels and chemical feedstocks (Bassyouni et al., 2025; Saxena, 2025). Recent studies have demonstrated that the catalytic pyrolysis of waste polystyrene (PS) using iron–boron composite catalysts can significantly enhance liquid-fuel yields, highlighting the potential of tailored catalysts for improving product recovery and process efficiency (Khan et al., 2026a,b; Mousavi et al., 2024).

Similarly, the co-pyrolysis of waste oils has been optimized to produce fuels with diesel-range characteristics suitable for combustion applications (Suleman et al., 2025). In addition, sustainable oxidative desulfurization (ODS) has demonstrated considerable potential for reducing sulfur content in fuels. In particular, lignin-based heterogeneous catalysts optimized using advanced statistical approaches have achieved high desulfurization efficiencies under relatively mild operating conditions (Shah et al., 2025). Collectively, these approaches demonstrate the potential of catalytic conversion and upgrading technologies to simultaneously address waste management, resource recovery, and the production of cleaner energy carriers.

4. Sustainable Energy Systems

The world has a need to decarbonize, and the high efficiency of energy conversion, storage, and management technologies must be developed and deployed as quickly as possible.

4.1 Hybrid microgrid architecture and metaheuristic optimization

This section introduces the hybrid microgrid architecture and metaheuristic optimization. The hybrid microgrid architecture and metaheuristic optimization are introduced in this chapter. Hybrid microgrids, which combine different types of renewable energy sources, are extremely challenging to manage dynamically. Nuclear power, photovoltaics, and biogas generation for complex microgrids have been successfully implemented with novel intelligent control architectures such as advanced model-following control and PQ droop control of electric vehicle infrastructure (Ishraque et al., 2026).

Maximizing energy coordination (Esparza et al., 2025; Paul et al., 2025) is crucial and will be achieved using advanced metaheuristic optimization algorithms. Recently, several innovations in the field of microgrid energy management have emerged, such as the Dual Predator Optimization (DPO) and Twin Fang Algorithms, which showed better performance in terms of convergence rate and identification of the global optimum compared to the classical optimization frameworks (Hasan et al., 2025a,b,c).

The smart management of hybrid microgrids plays a vital role in the shift toward resilient energy systems, which must address renewable energy in relation to demand. As per Section 4, minimizing operational cost using system stability is an important part of implementing a metaheuristic optimization algorithm. To compare the convergence behavior of five significant algorithms over 500 iterations, see (Figure 4). The 'Twin Fang' and 'Dual Predator Optimization' (DPO) algorithms (Hasan et al., 2025) outperformed conventional optimization techniques, such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), as shown.

In particular, Twin Fang is the fastest to converge, and it has the lowest cost value, well ahead of the old benchmarks. The findings align with those from Ahmad et al. (2026) and Paul et al. (2025) and highlight the significance of developing sophisticated algorithms for optimizing the economic viability of green energy hubs. Finally, the new techniques are converging with greater accuracy, which is critical for real-time energy management and efficient operation of decentralized renewable microgrids.

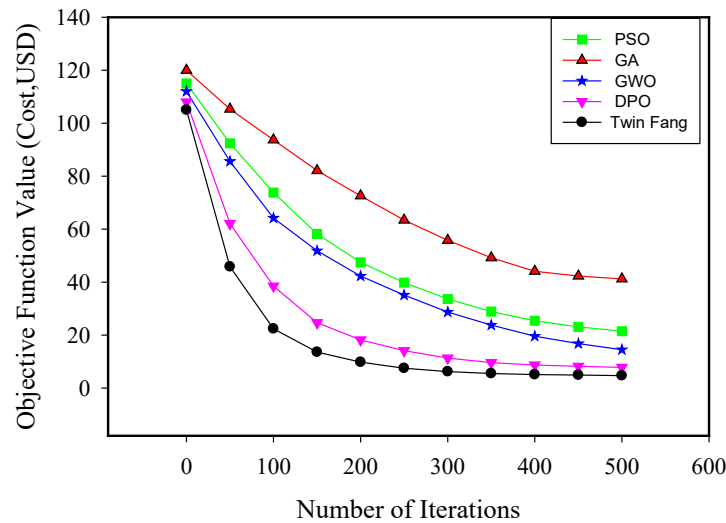


Figure 4. Convergence characteristics of metaheuristic optimization algorithms for hybrid microgrid energy management. Data sources: Ahmad et al. (2026); Esparza et al. (2025); Hasan et al. (2025); Paul et al. (2025).

Table 3 offers a comparative benchmark of the metaheuristic algorithms showing the progression of the optimization techniques from the basic ones to the latest real-time dispatch algorithms. The traditional algorithms such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) have low to moderate complexity, but have moderate global search and convergence. However, the Grey Wolf Optimizer (GWO) shows much faster convergence, which is appropriate for predictive modelling for irrigation and load management.

The most significant improvement in this direction is the Dual Predator Optimization (DPO), which is a dual predator algorithm that guarantees "Very Fast" convergence and high capability of search, essential for dynamic dispatch in a real-time environment in hybrid microgrids. In addition, the Twin Fang Algorithm offers "Very High" global search, which ensures the best performance in multi-source and complex grid structures. The overall picture indicates a preference for developing high-performance algorithms, such as DPO and Twin Fang, to meet the growing complexity and real-time requirements of decentralized energy systems.

Table 3. Comparison of metaheuristic algorithms for microgrid optimization.

Optimization Algorithm	Convergence Speed	Global Search Capability	Computational Complexity	Primary Application	Reference
Particle Swarm (PSO)	Moderate	Moderate	Low	Baseline energy dispatch	(Paul et al., 2025)
Genetic Algorithm (GA)	Slow	High	High	Long-term capacity planning	(Esparza et al., 2025)
Grey Wolf (GWO)	Fast	Moderate	Moderate	Irrigation/Load prediction	(Ahmad et al., 2026)
Dual Predator (DPO)	Very Fast	High	Moderate	Real-time dynamic dispatch	(Hasan et al., 2025a,b,c)
Twin Fang Algorithm	Fast	Very High	High	Complex multi-source grids	(Hasan et al., 2025a,b,c)

Source: Author, 2026.

4.2 Green hydrogen and bioenergy technologies

The role of hydrogen technologies as a key enabler for the universal transfer of clean energy is ever more important. A comprehensive analysis of the fast development of green hydrogen production hubs and the

necessary strategic pathways towards global industrial decarbonization is presented by Hasan et al. (2026), Hasan et al. (2026), Liu et al. (2026), Mohsen et al. (2026), Gupta et al. (2026), Mansilha et al. (2026), and Abudureyimu et al. (2025).

At the same time, bioenergy produced from algal biomass provides a very sustainable way of fuel production. The techno-economic study of simultaneous hydrogen and biochar production from particular algal strains shows that it is feasible, which indicates great potential for carbon-negative energy systems (Bahiri et al., 2025; Ihsanullah et al., 2015; Tanweer et al., 2025; Varkolu et al., 2025).

The widespread rollout of the green hydrogen hubs is a critical element in achieving a decarbonized global economy. As mentioned in Section 4, although hydrogen is a promising energy carrier, major economic differences in production pathways still exist and limit its widespread use. A comparative study of the levelized cost of hydrogen (LCOH) for different technologies is shown in (Figure 5), demonstrating the difference between conventional and sustainable hydrogen, highlighting the potential cost competitiveness of hydrogen in the future. Figure 5 shows a comparative analysis of the levelized cost of hydrogen (LCOH) for different technologies, which illustrates the difference between conventional and sustainable hydrogen and the potential cost competitiveness of hydrogen in the future.

But, as shown in Figure 5, fossil fuel-derived 'Grey' and 'Brown' hydrogen are still the only technologies that can match the industry \$2/kg goal. Biomass gasification is a more competitive green hydrogen production alternative, costing about \$4/kg, but is still twice the target price, while the cost of 'Green' hydrogen from PEM and Alkaline electrolysis is much higher, ranging from \$5.4 to \$6.2/kg. The economic barriers outlined here and in Hasan et al. (2026) and Gupta et al. (2026) underscore the importance of the materials innovations mentioned throughout this review. These developments have the potential to enhance the efficiency and lifespan of electrolyzers and renewable energy systems, which will help to lower the LCOH closer to the \$2/kg benchmark, thereby supporting the sustainability of a hydrogen economy.

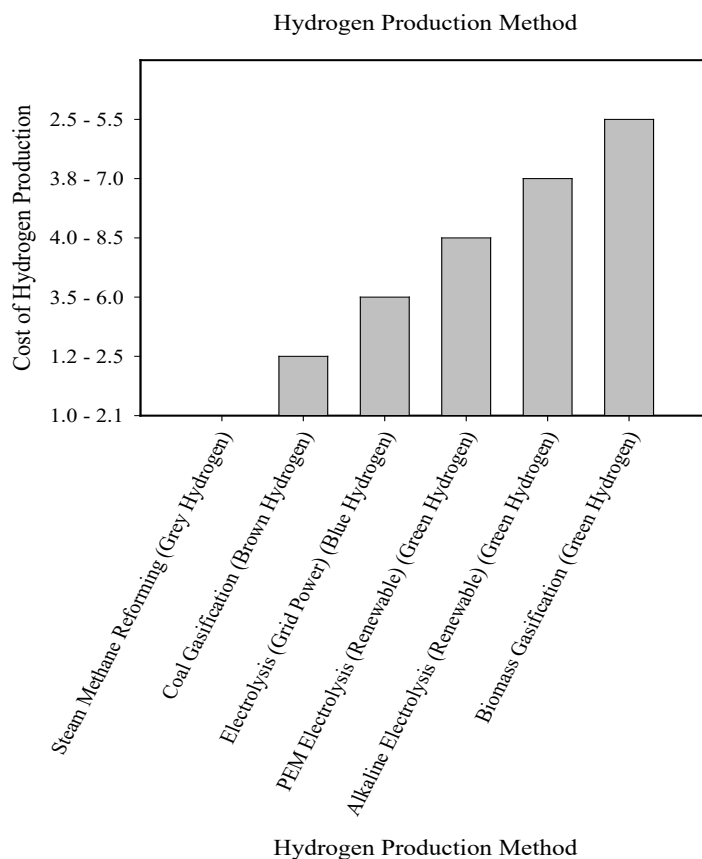


Figure 5. Cost comparison of hydrogen production technologies. Data sources: Hasan et al. (2026); Abudureyimu et al. (2025); Gupta et al. (2026).

4.3 Next-generation energy conversion and storage

The advancements of energy storage are of crucial importance to tackle the intermittency of renewable energy generation. Significant strides have been made in achieving the rational design of electrolytes for lithium-sulfur batteries that effectively suppress the polysulfide shuttle, and the cyclic stability has been drastically improved (Jan et al., 2025; Sebbagh et al., 2026).

The computational design and numerical characterization of all-perovskite multi-junction solar cells have also been performed, showing that it is possible to exceed the theoretical efficiency limits of the traditional silicon architecture in PV research (Fatima et al., 2025; Hussain et al., 2023; Wang et al., 2025). In addition, incorporation of dynamic plasmonic nanostructures offers new strategies to boost light absorption and thermal dissipation in sophisticated solar cells (Jamil et al., 2025; Khan et al., 2014; Subhan et al., 2025).

The worldwide shift to renewables is absolutely reliant on breakthroughs in PV technologies that are efficient and cheap to produce. Innovative material engineering and architectural design have made perovskite solar cells (PSCs) the most rapidly advancing solar technology in history, as discussed in Section 4. Data in Figure 6 show the outstanding improvement of the efficiency records of PSCs over the past four years and how the various cell configurations have developed.

Single-junction PSCs have achieved a respectable efficiency of $\sim 27.6\%$ as illustrated in (Figure 6), but are fundamentally limited by the Shockley-Queisser limit ($\sim 33.7\%$). To resolve this challenge, two architectures have been developed: 'Perovskite/Si Tandem' and 'All-Perovskite Multi-Junction' that have already overcome the Shockley-Queisser limit, with efficiencies of 34.6% and 37.2% , respectively, expected to be achieved by 2026. Their advancements are backed by the findings of Fatima et al. (2025), Hussain et al. (2023), and Wang et al. (2025), highlighting the essential role multi-junction designs play in maximizing solar energy harvesting. In conclusion, the swift advancements portrayed in Figure 6 highlight the important role of PSCs in advancing the future of high-performance energy systems and provide a promising avenue for realizing global energy sustainability and decarbonization objectives.

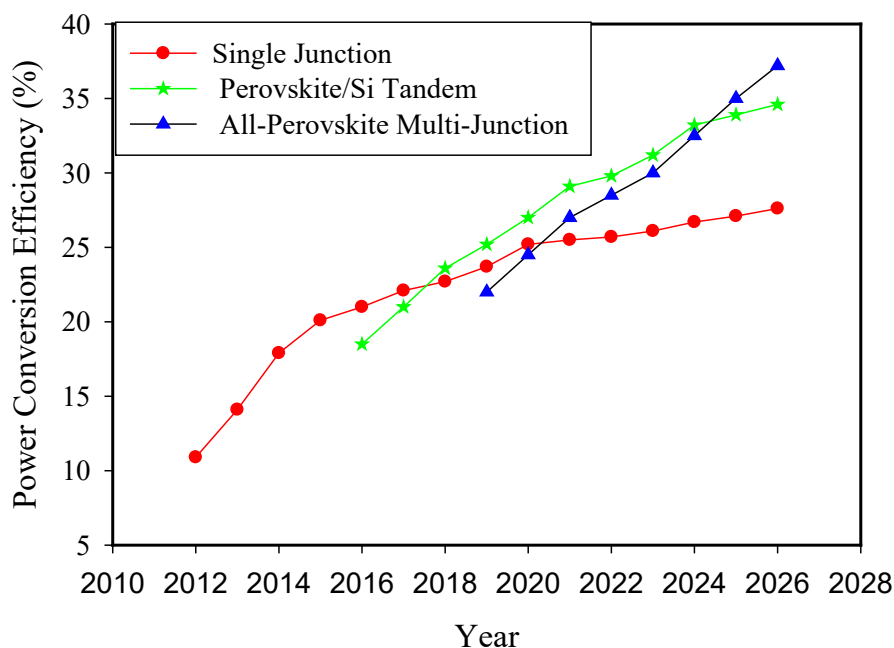


Figure 6. Evolution of perovskite solar cell efficiency records (2012-2026). Data sources: Fatima et al. (2025); Hussain et al. (2023), and Wang et al. (2025).

5. Fluid Mechanics and Thermal Management

The optimization of fluid flow and heat transfer is essential for improving the thermodynamic performance,

energy efficiency, and operational stability of energy systems and industrial chemical reactors. Effective thermal management and fluid-flow control are particularly important for minimizing energy losses, enhancing heat-transfer efficiency, and ensuring reliable operation across a wide range of industrial applications.

5.1 Nanofluid dynamics and heat transfer enhancement

Nanofluids are a key development in thermal management technologies (Atofarati et al., 2024; Kalsi et al., 2025; Aksoy, 2025; Atofarati et al., 2024), defined as engineered colloidal suspensions of nanoparticles in base fluids. The effective thermal conductivity and convective heat transfer coefficient of the fluid are significantly enhanced with the dispersion of highly conductive nanoparticles (Atofarati et al., 2024). Recently, advanced theoretical models have studied entropy-optimized radiative Maxwell ternary nanofluid flows with complex magnetohydrodynamic (MHD) and internal heat generation effects (Abbas et al., 2026). These are strict mathematical models that will give the needed information on the coupled physical phenomena of heat transfer and entropy generation in highly efficient thermal systems.

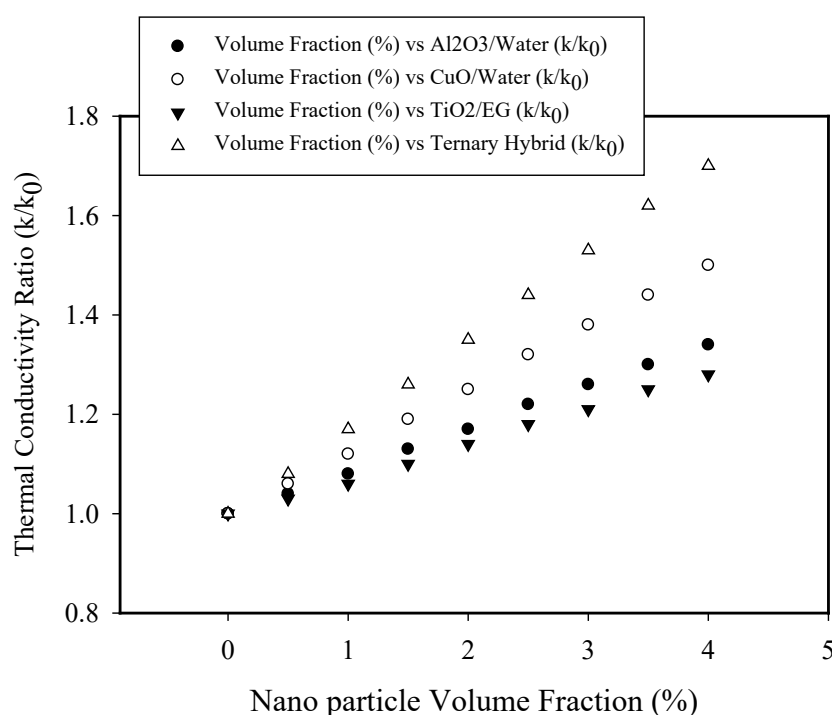


Figure 7. Thermal conductivity enhancement ratio as a function of nanoparticle volume fraction for various nanofluid systems. Data sources: Abbas et al. (2026); Aksoy et al. (2025); Atofarati et al. (2024); Kalsi et al. (2025).

The optimization of thermal management systems in industrial processes is increasingly reliant on the development of advanced heat transfer fluids. As discussed, nanofluids have emerged as a superior alternative to traditional coolants due to their enhanced thermophysical properties. Figure 7 provides a quantitative assessment of the thermal conductivity enhancement ratio (k/k_0) for various nanofluid systems as a function of nanoparticle volume fraction.

As illustrated in Figure 7, all investigated systems exhibit a linear increase in thermal conductivity with rising nanoparticle concentration. The 'Ternary Hybrid' nanofluid, reported by Abbas et al. (2026), demonstrates the most significant performance gain, achieving a 70% enhancement ($k/k_0 = 1.7$) at a 4% volume fraction. This is followed by the CuO/Water system (Aksoy, 2025) and the Al₂O₃/Water system (Kalsi et al., 2025), which reach enhancement ratios of 1.5 and 1.34, respectively. In contrast, the TiO₂/Ethylene Glycol (EG) system (Atofarati et al., 2024) shows a comparatively lower enhancement. These results underscore the synergistic effect of hybridizing different nanoparticles to maximize thermal performance. Ultimately, the data confirms that tailoring

the nanoparticle composition and concentration is a critical strategy for optimizing the efficiency of next-generation thermal systems.

Table 4 compares the thermophysical performance of various types of nanofluid systems with that of base fluids, which showed an improvement in thermophysical performance compared to the traditional base fluids. It is observed from the above data that the enhancement of thermal conductivity due to the incorporation of nanoparticles like Al_2O_3 , CuO , and TiO_2 is 12.5% to 18.2% even at low volume fractions (0.5%–2.0%). Multi-walled carbon nanotubes (MWCNT) have shown a high aspect ratio benefit with an efficiency of 22.0% at 0.5% volume fraction.

The highest performance level is the ternary hybrid system ($\text{Cu-Al}_2\text{O}_3\text{-TiO}_2$) with a 28.5% increase in thermal conductivity and a Nusselt number ratio of 1.45. The relationship between the improvement of thermal conductivity and the Nusselt number is clearly positive, in which it is seen that the improvement in fluid properties leads to the improvement in convective heat transfer. Finally, the obtained results stress the strategic value of using a ternary hybrid nanofluid to achieve maximum efficiency in industrial thermal management systems and energy-integrated systems.

Table 4. Comparative analysis of thermophysical properties and heat transfer enhancement in mono and hybrid nanofluid systems.

Base Fluid	Nanoparticle Type	Volume Fraction (%)	Thermal Conductivity Enhancement (%)	Nusselt Number Ratio (Nu/Nu_0)	Reference
Water	Al_2O_3	1.0	12.5	1.15	(Atofarati et al., 2024)
Water	CuO	2.0	18.2	1.28	(Kalsi et al., 2025)
Ethylene Glycol	TiO_2	1.5	15.4	1.22	(Aksoy, 2025)
Water/EG (50:50)	MWCNT	0.5	22.0	1.35	(Atofarati et al., 2024)
Ternary Hybrid	$\text{Cu-Al}_2\text{O}_3\text{-TiO}_2$	1.0	28.5	1.45	(Abbas et al., 2026)

Source: Author, 2026.

5.2 Computational fluid dynamics (CFD) applications

Computational fluid dynamics (CFD) has become an essential tool for the design, analysis, and optimization of thermal systems, enabling detailed assessment of fluid flow, temperature distribution, pressure drop, and heat transfer characteristics. In heat exchanger applications, CFD simulations provide valuable insights into the influence of complex internal geometries and flow-disturbing devices on thermal-hydraulic performance. Recent studies have investigated the effects of internal structures in concentric-tube heat exchangers, demonstrating that the strategic incorporation of inserts, such as twisted tapes, can substantially enhance heat transfer performance (Benmbarek; Moujaes, 2025; Syed et al., 2024a,b).

The improved performance is primarily associated with the generation of secondary flows, enhanced fluid mixing, increased turbulence, and repeated disruption of the thermal boundary layer. These mechanisms promote more effective interaction between the fluid and heat-transfer surfaces, thereby increasing the overall heat transfer coefficient. At the same time, CFD enables the evaluation of the associated pressure-drop penalty, allowing thermal enhancement techniques to be assessed from an integrated thermal-hydraulic perspective. Consequently, CFD represents a powerful computational framework for identifying optimal geometries and operating conditions while reducing the need for extensive experimental trials.

6. Computational Biotechnology and Molecular Dynamics

The integration of advanced computational approaches with biotechnology and molecular modeling is providing unprecedented insights into biological systems at the molecular and atomistic levels. Computational biotechnology encompasses a broad range of methods, including molecular dynamics (MD) simulations, molecular docking, quantum chemical calculations, bioinformatics, and machine-learning-based approaches, which can be used to elucidate molecular interactions, predict structural behavior, and guide the development of functional biomaterials and biocatalysts.

Molecular dynamics simulations, in particular, enable the investigation of the structural, conformational, and dynamic properties of proteins, enzymes, nucleic acids, and biomolecular complexes under different environmental conditions. By revealing molecular interactions and conformational changes that are difficult to capture experimentally, these approaches support the rational design and optimization of enzymes, bio-inspired materials, drug-delivery systems, and other biotechnology-based applications. The integration of molecular simulations with experimental biotechnology further strengthens predictive capabilities, facilitating the development of more efficient, selective, and sustainable biocatalytic and biomolecular systems.

6.1 Molecular dynamics of enzyme functionality

Single nucleotide polymorphisms (SNPs) have been studied using rigorous molecular dynamics (MD) simulations to explain how these mutations affect the function of a protein, specifically on the phosphorylation and binding kinetics of the substrates, especially for critical detoxification enzymes such as GSTP1 (Bickel; Vranken, 2024; Shahwar et al., 2026).

These simulations provide a high-resolution view of the catalytic efficiency of the enzyme in the presence and absence of specific genetic variants, which in turn can predict how changes in structure and dynamics of the protein affect its abilities to detoxify environmental contaminants (Shahwar et al., 2026). The molecular-level understanding combined with environmental engineering concepts provides a solid basis for the rational, computational design of advanced biocatalysts for use in the degradation of highly persistent organic pollutants (Qu et al., 2026; Yin et al., 2025).

Table 5 shows the critical need for multi-scale computational approaches to speed up sustainable industrial system development and optimization. The fundamental electronic and conformational properties of biocatalysts and solar cells are essential to be understood by atomistic simulations such as Molecular Dynamics (MD) or Density Functional Theory (DFT). Thermo-hydraulic performance of a heat exchanger can be optimized with a high degree of accuracy using Computational Fluid Dynamics (CFD), and by analysing the exchange in a spatially resolved way, energy losses are minimized.

Machine Learning (ANN/SVM) has transformed the management of microgrids with its ability to deliver high-accuracy forecasting and non-linear pattern recognition in complex energy systems. Life Cycle Assessment (LCA) is the "holy grail" of sustainability as it measures and represents the life-time environmental impact of the production of nanomaterials from cradle to grave, including toxicity. They are combined to achieve an integration of fundamental materials science and large-scale industrial implementation, which guarantees technical efficiency and environmental compliance.

Table 5. Multi-scale computational frameworks and modeling methodologies for the design and optimization of sustainable technologies.

Computational Method	Primary Application Area	Target Parameters Analyzed	Key Advantage	Reference
Molecular Dynamics (MD)	Biocatalyst Design	Conformational dynamics, binding free energy	Atomistic resolution of protein-ligand interactions	(Shahwar et al., 2026; Bickel; Vranken, 2024)
Density Functional Theory	Perovskite Solar Cells	Band gap, electronic structure, optical absorption	Precise quantum mechanical property prediction	(Amina et al., 2025; Ashraf et al., 2026)
Computational Fluid Dynamics	Heat Exchanger Optimization	Velocity profiles, pressure drop, Nusselt number	Spatially resolved thermo-hydraulic analysis	(Syed et al., 2024a,b; Benmbarek; Moujaes, 2025)
Machine Learning (ANN/SVM)	Microgrid Load Forecasting	Power demand, solar irradiance, system efficiency	High accuracy in non-linear pattern recognition	(Ahmad et al., 2026; Negi et al., 2026)
Life Cycle Assessment (LCA)	Nanomaterial Production	Carbon footprint, toxicity, energy consumption	Comprehensive environmental impact quantification	(Escobar-Hernández et al., 2023; Saavedra; Osma, 2024)

Source: Authors, 2026.

7. Discussion and Future Perspectives

The synthesis of materials science with the field of environmental and energy engineering is of utmost importance as advanced materials serve as the key enabler for next-generation sustainable technologies (Jamwal; Kiani, 2022; Tarlochan et al., 2025). AI and ML integration in process optimization is a paradigm shift and is evolving into highly data-driven and adaptive systems that can react autonomously to the changing operational parameters (Ahmad, 2024; Ahmad et al., 2026; Eslami et al., 2026; Negi et al., 2026; Zohaib et al., 2026).

Scale-up from lab validation to industrial production scale for new technologies is a major challenge in all fields studied in this review (Hachchach et al., 2025; Saavedra; Osma, 2024). Making a product from the bench to commercialization requires careful planning of continuous manufacturing approaches, quality control (QC) systems, and comprehensive life-cycle assessment (LCA) systems to ensure positive environmental results.

Finally, the most radical improvements in sustainability around the world will be the result of sustained inter-disciplinary innovation. For example, the combination of MXene membrane filtration, heterojunction photocatalysis and MOF-based adsorption would provide highly advanced, closed-loop wastewater treatment plants that would simultaneously generate potable water, recover critical metals, and produce green hydrogen.

5. Conclusions

This thorough and valuable overview focuses on the significance of advanced materials and new technologies in global sustainability and the move towards a low-carbon future. Based on the examination of recent studies, a large number of advancements have been achieved in the fields of environmental engineering, materials science, energy science, fluid mechanics, and biotechnology, highlighting the need for interdisciplinary and multidisciplinary approaches to research and technological solutions.

The emergence of advanced materials like MXene-based membranes, heterojunction photocatalysts, metal-organic framework (MOF) hybrids, and smart sensors has greatly enhanced wastewater treatment, pollutant degradation, and resource recovery in environmental engineering. The development of materials

science has made it possible to fabricate high-performance materials with improved physicochemical, mechanical, and functional properties in materials science through the development of metal oxide nanoparticles, polymer nanocomposites, and computational materials design.

In the realm of energy science, advancements in hydrogen technologies, hybrid microgrids, optimization algorithms, bioenergy systems, and innovative solar cell designs are enhancing the shift towards cleaner, more efficient, and sustainable energy solutions. The development of new techniques in fluid mechanics, such as nanofluid heat transfer and computational fluid dynamics (CFD), has enhanced heat transfer, energy efficiency, and performance of engineering systems.

In the field of biotechnology, molecular dynamics simulations have assisted in generating a molecular understanding of protein behavior and enzyme functions, as well as the design of biocatalysts to create advanced biomedical and industrial applications. The impact of advanced materials is seen in a wide range of engineering disciplines with the introduction of new technologies such as next-generation battery technologies, self-starting vertical axis wind turbines (VAWTs), and gallium oxide protective coatings.

Future work should focus on the scalable and cost-effective manufacturing of advanced materials, increasing their commercial viability, optimizing the integration of the system, and minimizing the environmental impact with a comprehensive lifecycle assessment. Ongoing cooperation between researchers, engineers, industry, and policymakers will be crucial to help close this fundamental research-to-use divide and to speed up the progress of innovative technologies that help achieve sustainable development, energy security, environmental protection, and global resilience.

6. Authors' Contributions

Abdulkarim Alansari: investigation, writing – original draft, writing – review & editing, project administration, and publication.

7. Conflicts of Interest

No conflicts of interest.

8. Ethics Approval

Not applicable.

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

While conducting this research, the author(s) utilized Manus AI to format the manuscript following the journal's requirements. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

10. References

- Abbas, A., Rahman, A., Farman, M., Hafez, M. A., & Hincal, E. (2026). Entropy-optimized radiative Maxwell ternary nanofluid flow with magnetohydrodynamics and heat generation effects. *International Journal of Optimization and Control: Theories & Applications*, 16(4), 1319-1352. <https://doi.org/10.11121/ijocta.2026.1319>
- Abudureyimu, A., TuluHong, A., Chang, Q., Wang, F., & Luo, B. (2025). A comprehensive review of green hydrogen technology: Electrolysis methods, topologies and control strategies, applications. *Materials*, 18(21), 12609. <https://doi.org/10.3390/ma18214826>
- Aherkar, V. V., Mohammed, A. A., Al-Shimary, A. A., Kshirsagar, V., Shendage, R., Ubale, P. A., Bhairungi, S. B., & Ovhal, R. M. (2025). Photocatalytic dye degradation efficacy and antimicrobial potency of zinc oxide nanoparticles synthesized via sol-gel method. *Next Materials*, 9, 100972. <https://doi.org/10.1016/j.nxmte.2025.100972>
- Ahmad, F., Fouad, E. F., & Ahmad, N. (2014). Removal of lead from wastewater by adsorption using Saudi

- Arabian clay. *International Journal of Chemical and Environmental Engineering*, 5, 65-68.
- Ahmad, F., Ahmad, N., Al-Khazaal, A. Z., & Alenezi, I. (2018a). Remediation of sulfidic wastewater by aeration in the presence of ultrasonic vibration. *Engineering, Technology & Applied Science Research*, 8(4), 2919-2922.
- 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., Maitra, S., & Ahmad, N. (2017). Treatment of sulfidic wastewater using iron salts. *Arabian Journal of Science and Engineering*, 42, 1455-1462. <https://doi.org/10.1007/s13369-016-2315-z>
- Ahmad, N., & Fouad, E. (2017). Influence of clay contents on rheology of syndiotactic polypropylene/clay composites. *Arabian Journal for Science and Engineering*, 42, 1537-1543. <https://doi.org/10.1007/s13369-016-2389-7>
- Ahmad, Z., Omar, M. A., Jamil, S., Abdullah, N., Shezan, S. A., & Ahmad, N. (2026). Improved grey wolf optimization-based artificial neural network for irrigation need prediction. *Knowledge-Based Systems*, 351(part A), 116603. <https://doi.org/10.1016/j.knosys.2026.116603>
- 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, 23054-23067. <https://doi.org/10.1007/s11356-025-37028-5>
- Ahmad, N. (2025). 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., 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., 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, 289-293. <https://doi.org/10.1007/s13369-014-1473-0>
- Ahmad, N., Fouad, E., & Ahmad, F. (2018b). Effect of shear flow on crystallization of syndiotactic polypropylene/clay composites. *Engineering, Technology & Applied Science Research*, 8(3), 3108-3112.
- Ahmad, N., Ahmad, F., & Alenezi, I. (2021). Influence of starch content on thermal and rheological properties of syndiotactic polypropylene/starch composites. *Engineering Technology & Applied Science Research*, 11(3), 7228-7232. <https://doi.org/10.48084/etasr.4161>
- Ahmad, N., Maitra, S., Dutta, B., & Ahmad, F. (2009). Remediation of sulfidic wastewater by catalytic oxidation using 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)
- Aksoy, Y. T. (2025). Nanofluids for sustainable heat transfer enhancement: Beyond thermal conductivity. *Sustainability*, 17(17), 8006. <https://doi.org/10.3390/su17178006>
- Alsaiani, M., Roghani, K., Liaqat, S., Alkorbi, A. S., Sharif, F., Irfan, M., Rizk, M. A., Uroos, M., Ahmad, N., & Muhammad, N. (2023). Effect of ionic liquids on mechanical, physical, and antifungal properties and biocompatibility of a soft denture lining material. *Journal of ACS Omega*, 8(30), 27300-27300. <https://doi.org/10.1021/acsomega.3c02677>
- 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.
- Al-Khazaal, A. Z., Ahmad, F., & Ahmad, N. (2019). Laboratory scale studies on removal of thiosulfate from wastewater by catalytic oxidation. *Engineering, Technology & Applied Science Research*, 9(2), 4053-4056.
- Al-Rawashdeh, N. A. F. (2025). Advances in photocatalytic methods for organic pollutant removal. *Catalysis*

Research, 5(3). <http://dx.doi.org/10.21926/cr.2503007>

- Ali, Z., Sohail, M., Razzaq, N., Ullah, F., Ouyang, Q., Khan, S., & 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>
- Amin, F., Ullah, Z., Niaz, S., Shezan, S. A., Ahmad, N., Alsisi, R. H., Amin, N., & Ahmad, F. (2026). A decision-making framework based on complex fuzzy bipolar soft sets for investment strategy optimization. *Scientific Reports*. <https://doi.org/10.1038/s41598-026-57642-8>
- Amina, Husain, K., Alrefae, S. H., Elhadi, M., Abduvalieva, D., Abiyev, A. S., Akter, N., Ahmad, N., Tirth, V., Algahtani, A., & Zaman, A. (2025). First-principles investigation of structural, electronic, mechanical and optical properties of TI Based Semiconducting Perovskites TlVX₃ (X = Br, I) for reflective coating applications. *Journal of Inorganic and Organometallic Polymers and Materials*, 35, 6479-6490. <https://doi.org/10.1007/s10904-025-03670-2>
- Anwar, F. A., Rahmah, W., & Kadja, G. T. M. (2025). Recent advances in two-dimensional MXene membranes for emerging nanofiltration applications: A review. *Nano Trends*, 12, 100154. <https://doi.org/10.1016/j.nwnano.2025.100154>
- Ashraf, L., Waseem, S., Khalil, M., Ahmad, N., Ahmad, P., Kebaili, I., & Saleem, M. (2026). Brief investigations on Cu_xTa_{2-x}O₅ for thermoelectric and optical response using density functional and experimental techniques. *Chinese Physics B*, 35, 027801. DOI 10.1088/1674-1056/adee89
- Atta, D., Wahab, H. A., Ibrahim, M. A., & Battisha, I. K. (2024). Photocatalytic degradation of methylene blue dye by ZnO nanoparticles. *Scientific Reports*, 14, 26961. <https://doi.org/10.1038/s41598-024-76938-1>
- Atofarati, E. O., Sharifpur, M., & Huan, Z. (2024). Nanofluids for heat transfer enhancement: a holistic analysis of research advances, technological progress and regulations for health and safety. *Cogent Engineering*, 11(1), 2434623. <https://doi.org/10.1080/23311916.2024.2434623>
- Arshad, S. A., Ali, U. N., Taqvi, S. A. A., Kazmi, B., Khalid, A., Ahmer, M., Ahmad, F., & Ahmad, N. (2025). Towards sustainable methanol production: energy, exergy, economics, and environmental evaluation of Thar coal gasification. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-025-06451-6>
- Aziz, S., Javed, R., Nowak, A., Liaqat, S., Khan, Z. U. H., Ahmad, N., Dulski, M., Matus, K., Ahmad, P., & Muhammad, N. (2023). Effects of TiO₂, Ag-TiO₂, and Cu-TiO₂ nanoparticles on mechanical and anticariogenic properties of conventional pit and fissure sealants. *Open Nano*, 14, 100185. <https://doi.org/10.1016/j.onano.2023.100185>
- Ayub, Z., Liaqat, S., Alamoudi, A. J., Alshamrani, M., Rizg, W. Y., Shaik, R. A., Ahmad, N., Feroz, S., & 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*. <https://doi.org/10.1155/2024/5530338>
- Bahiri, I., Ibrahim, M. M., Gautam, & Zaabout, A. (2025). Mapping techno-economic prospects of biochar production through biomass waste pyrolysis pathway. *Energy Conversion and Management*, 327, 119526. <https://doi.org/10.1016/j.enconman.2025.119526>
- Bashir, F., Muhammad, N., Alshamrani, M., Uroos, M., Salawu, A., Safhi, A. Y., Ahmed, N., Sabei, F. 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>
- Bassyouni, M., Nasser, R., El-Bagoury, M., Shaker, I., Attia, A. M., Elherawy, Y., & Aboelela, D. (2025). Integrating medical plastic waste pyrolysis and circular economy for environmental sustainability. *Renewable and Sustainable Energy Reviews*, 209, 115062. <https://doi.org/10.1016/j.rser.2024.115062>
- Benmbarek, M. M., & Moujaes, S. F. (2025). CFD Analysis of heat transfer enhancement for twisted tape inserted in spirally corrugated tubes and proposal of a new vane-inserted geometry. *Fluids*, 10(3), 73. <https://doi.org/10.3390/fluids10030073>
- 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>
- Bickel, D., & Vranken, W. (2024). Effects of phosphorylation on protein backbone dynamics and conformation. *Journal of Molecular Biology*, 20(12), 4998-5011. <https://doi.org/10.1021/acs.jctc.4c00206>
- Chen, J., Bae, B., & Lee, J. (2026). Emerging deep eutectic solvents for organic contaminant analysis in food and environmental matrices: A review. *TrAC Trends in Analytical Chemistry*, 195, 118547. <https://doi.org/10.1016/j.trac.2025.118547>
- Cheng, J., Cheng, B., Xu, J., Yu, J., & Cao, S. (2025). Organic-inorganic S-scheme heterojunction photocatalysts: Design, synthesis, applications, and challenges. *eScience*, 5(3), 100354. <https://doi.org/10.1016/j.esci.2024.100354>
- Cheshmekhezer, S., Rothee, S. R., Nazaripour, M., Rahman, A., Heidari, H., Masrura, S. U., & Khan, E. (2024). Exploring ionic liquids and deep eutectic solvents for pollutant removal from water and wastewater. *Nature, npj Materials Sustainability*, 2, 38. <https://doi.org/10.1038/s44296-024-00042-8>
- El-Morsy, M. T., Khafaga, D. S. R., Diab, A. H., Faried, H., Shehab, S., Elhady, R. H., & Ali, G. A. M. (2025). Recent advancements in multifunctional nanomaterials for dental applications. *RSC Advances*, 15(57), 49009-49029. <https://doi.org/10.1039/d5ra07176c>
- Escobar-Hernandez, H. U., Quan, Y., Papadaki, M. I., & Wang, Q. (2023). Life cycle assessment of metal-organic frameworks: Sustainability study of zeolitic imidazolate framework-67. *ACS Sustainable Chemistry & Engineering*, 11(10), 4219-4225. <https://doi.org/10.1021/acssuschemeng.2c07276>
- 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>
- Esparza, A., Blondin, M., & Trovão, J. P. F. (2025). A review of optimization strategies for energy management in microgrids. *Energies*, 18(13), 3245. <https://doi.org/10.3390/en18133245>
- Fahim, K. E., de Silva, L. C., 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. <http://dx.doi.org/10.32604/ee.2025.066484>
- Farooq, A., Zafar, F., Hassan, S. U., 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 and Fuels*, 39(50), 23796-23804. <https://doi.org/10.1021/acs.energyfuels.5c04018>
- Fatima, S. K., Alzard, R. H., Amna, R., Alzard, M. H., Zheng, K., & Abdellah, M. (2025). Lead-free perovskites for next-generation applications: a comprehensive computational and data-driven review. *Materials Advances*, 6(21), 7634-7661. <https://doi.org/10.1039/d5ma00681c>
- 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>
- Ghasemi, S., Parastesh, A., Padervand, M., Ren, H., Li, X., Labidi, A., Signoretto, M., Dawi, E. A., Hamzehlouyan, T., Lichtfouse, E., & Wang, C. (2025). Recent progress on Z- and S-scheme photocatalysis: mechanistic understanding toward green applications. *Current Opinion in Chemical Engineering*, 47, 101059. <https://doi.org/10.1016/j.coche.2024.101059>
- Gobena, S. T., & Woldeyannes, A. D. (2024). A review of synthesis methods, and characterization techniques of polymer nanocomposites for diverse applications. *Discover Materials*, 4, 52. <https://doi.org/10.1007/s43939-024-00119-0>
- 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, 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>
- Ibrahim, H., Abdullatef, Y., & Zaidi, A. A. (2026). Self-starting enhancement of small-scale H-Darrieus VAWTs for urban low-wind conditions: A taxonomy of strategies, biomimetic flow control, and design guidelines.

- Journal of Energy, Materials & Sustainability*, 2(1), 123-154. <https://doi.org/10.66173/jenmas.2026.123>
- Ihsanullah, Shah, S., Ayaz, M., Ahmed, I., Ali, M., Ahmad, N., & Ahmad, I. (2015). Production of biodiesel from algae. *Journal of Pure and Applied Microbiology*, 9(1), 79-85.
- Irfan, I., Mushtaq, K., Agrawal, R., & Pato-Doldán, B. (2026). CVD-synthesized gallium-oxide thin films as protective coating for energy storage applications. *Journal of Energy, Materials & Sustainability*, 2(1), 39-54. <https://doi.org/10.66173/jenmas.2026.39>
- 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(part A), 110756. <https://doi.org/10.1016/j.compeleceng.2025.110756>
- Habib, M. I. (2026). Quantifying solar irradiation and photovoltaic energy yield at optimal tilt angles: A case study of Gojra, Punjab, Pakistan. *Journal of Energy, Materials & Sustainability*, 2(1), 18-38. <https://doi.org/10.66173/jenmas.2026.18>
- Hachhach, M., Bayou, S., Kasmi, A. E., Saidi, M. Z., Akram, H., Hanafi, M., Achak, O., Moujahid, C. E., & Chafik, T. (2025). Towards sustainable scaling-up of nanomaterials fabrication: Current situation, challenges, and future perspectives. *Eng*, 6(7), 149. <https://doi.org/10.3390/eng6070149>
- 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., Rahman, M. A., Ishraque, M. F., Ahmad, K., Shezan, S. A., Ahmed, M. S., Ahmad, N., & Ahmad, F. (2025a). An improved energy management strategy for hybrid power systems using dual predator optimization. *Journal of Sustainable Development of Energy, Water and Environment Systems*, 13(3), 1130586. <https://doi.org/10.13044/j.sdewes.d13.0586>
- Hasan, M. N., Ishraque, M. F., Ahmed, M. S., Imam, F. T., Shezan, S. A., & Ahmad, N. (2025b). An innovative method for enhanced energy management in hybrid power systems: dual predator optimization (DPO). *Arabian Journal for Science and Engineering*, 51, 7269-7292. <https://doi.org/10.1007/s13369-025-10254-2>
- Hasan, M. N., Ishraque, M. F., Shezan, S. A., Kamwa, I., & Ahmad, N. (2025c). 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.jestech.2025.102165>
- Hasan, M. N., Ishraque, M. F., Shezan, S. A., Kamwa, I., Ahmad, K., Alrwaili, A., Alruwaili, M., Amin, N., & 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, Z., Khan, S., Khan, S., Ahmad, N., Alansari, A., Shah, A., Azizi, S., & 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/d6se00430j>
- 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. *Optiks*, 277, 170714. <https://doi.org/10.1016/j.ijleo.2023.170714>
- Hussain, T., Farhan, M., Kamaran, P., I-L., Ahmad, N., Alshammari, H. O., Jamel, L., & Mahariq, I. (2025). Exact solutions of Einstein's field equations via homothetic symmetries of non-static plane symmetric spacetime. *Open Physics*, 23(1), 20250238.
- 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. *Journal of Cellulose Chemistry and Technology*, 57(5-6), 541–549.
- 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, 6513-6522. <https://doi.org/10.1007/s11468-025-02916-6>
- Jamila, N., Ullah, R., Khitab, F., Ahmad, N., Ahmad, F., Afridi, M. S., Kanwal, F., & Khan, N. (2025). 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*. <https://doi.org/10.1080/00387010.2025.2602841>
- Jamwal, N. S., & Kiani, A. (2022). Gallium oxide nanostructures: A review of synthesis, properties and applications. *Nanomaterials*, 12(12), 2061. <https://doi.org/10.3390/nano12122061>
- Jan, W., Khan, A. D., Iftikhar, F. J., Abbasi, M. S., Ali, G., Iwuoha, E., Shahzad, S., Ahmad, F., & 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>
- Kalsi, S., Kumar, S., Kumar, A., Alam, T., Sharma, A., & Yadav, A. S. (2025). A review on hybrid nanofluids for heat transfer: advancements, synthesis, challenges and applications. *Discover Applied Sciences*, 7(7), 698. <https://doi.org/10.1007/s42452-025-07141-8>
- 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>
- Khader, E. H., Muslim, S. A., Cata Saady, N. M., Ali, N. S., Salih, I. K., Albayati, T. M., & Zendehboudi, S. (2024). Recent advances in photocatalytic advanced oxidation processes for organic compound degradation: A review. *Desalination and Water Treatment*, 318, 100384. <https://doi.org/10.1016/j.dwt.2024.100384>
- Khan, A. D., Khan, S. D., Khan, R. U., & Ahmad, N. (2014a). Excitation of multiple Fano-like resonances induced by higher order plasmon modes in three-layered bimetallic nanoshell dimer. *Plasmonics*, 9, 461-475. <https://doi.org/10.1007/s11468-013-9644-5>
- Khan, A. D., Khan, S. D., Khan, R. U., Ahmad, N., Ali, A., Khalil, A., & Khan, F. A. (2014b). Generation of multiple fano resonances in plasmonic split nanoring dimer. *Plasmonics*, 9, 1091-1102. <https://doi.org/10.1007/s11468-014-9719-y>
- Khan, H., Ullah, S., Khan, A. S., Nasrullah, A., Rehaman, A., Khan, P., Gilani, M. A., Kanan, S., Samara, F., Ahmed, N., & Mjalli, F. S. (2025a). 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(part B), 128496. <https://doi.org/10.1016/j.molliq.2025.128496>
- Khan, S., Hussain, Z., Ahmad, B., Ahmad, N., & Azizi, S. (2026a). 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., Kamika, I., Azizi, S., & Maaza, M. (2026b). MXene-based membranes for advanced desalination: Properties, engineering strategies, and emerging applications. *Desalination*, 624, 119860. <https://doi.org/10.1016/j.desal.2026.119860>
- Khan, S. Z., Khan, A. L., Yue, S., Jaafar, J. B., & Zaidi, A. A. (2025b). Introducing journal of energy, materials & sustainability (JENMAS). *Journal of Energy, Materials & Sustainability (JENMAS)*, 1, 1-3. <https://doi.org/10.66173/jenmas.2025.1>
- Liu, Z., Roosh, M., Lu, M., Arshad, A., Xian, W., Shen, Y., Liu, G., Bahadur, A., Iqbal, S., Mahmood, S., & Alotaibi, K. M. (2025). Empowering wastewater treatment with step scheme heterojunction photocatalysts degradation of nitrophenol. *Scientific Reports*, 15, 3299. <https://doi.org/10.1038/s41598-025-86975-z>
- 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. <http://dx.doi.org/10.1016/j.apenergy.2026.127892>
- Maatki, C., Bilal, M., Ahmad, N., Ahmad, F., Alshammari, B. M., Kriaa, K., & Kolsi, L. (2025). Numerical study of three-dimensional unsteady viscous fluid flow across parallel rotating discs with an upward fluctuation and thermal radiation. *Journal of Radiation Research and Applied Sciences*, 18(2), 101577. <https://doi.org/10.1016/j.jrras.2025.101577>
- Mansilha, C., Barbosa-Póvoa, A., Tarelho, L., & Fonseca, A. (2026). A comprehensive review of green hydrogen production technologies: current status, challenges, research trends and future directions. *Renewable and Sustainable Energy Reviews*, 225, 116119. <https://doi.org/10.1016/j.rser.2025.116119>
- Mashhadzadeh, A. H., Mashhadzadeh, A. H., Golman, B., Spitas, C., Faroughi, S. A., & Kostas, K. V. (2025). Recent advancements in mechanical properties of graphene-enhanced polymer nanocomposites: Progress, challenges, and pathways forward. *Journal of Molecular Graphics and Modelling*, 135, 108908.

<https://doi.org/10.1016/j.jmgm.2024.108908>

- Medina-Acosta, M., Chinchillas-Chinchillas, M. J., Garrafa-Gálvez, H. E., Garcia-Maró, C. A., Rosas-Casarez, C. A., Lugo-medina, E., Luque-Morales, P. A., & Soto-Robles, C. A. (2024). Photocatalytic degradation of four organic dyes present in water using ZnO nanoparticles synthesized with synthesis using Ambrosia ambrosioides leaf and root extract. *Processes*, 12(11), 2456. <https://doi.org/10.3390/pr12112456>
- Meskher, H., Thakur, A. K., Hazra, S. K., Ahamed, M. S., Saleque, A. M., Alsahly, Q. F., Shahzad, M. W., Ivan, M. N. A. S., Saha, S., & Lynch, I. (2025). Recent advances in applications of MXenes for desalination, water purification and waster 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., & 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., Challob, 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(part B), 136251. <https://doi.org/10.1016/j.fuel.2025.136251>
- Mousavi, S. A. H. S., & Dehaghani, A. H. S. (2024). Catalytic pyrolysis of plastic waste to gasoline, jet fuel and diesel with nano MOF derived-loaded Y zeolite: Evaluation of temperature, zeolite crystallization and catalyst loading effects. *Energy Conversion and Management*, 299, 117825. <https://doi.org/10.1016/j.enconman.2023.117825>
- Musa, A. A., Bello, A., Adams, S. M., Onwualu, A. P., Anye, V. C., Bello, K. A., & Obianyo, I. I. (2025). Nano-enhanced polymer composite materials: A review of current trends. *Polymers*, 17(7), 11991. <https://doi.org/10.3390/polym17070893>
- Muhsin, R. M. M., Manan, T. S. B. A., Bidai, J., Mangat, M. S. A., Hanafiah, Z. M., Hohari, A., Ahmad, N., Mustafa, M. R. U., Yusoff, M. S., & 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., Dogra, S., & Gupta, L. R. (2026). Leveraging machine learning for optimized microgrid management: Advances, applications, challenges, and future directions. *Renewable and Sustainable Energy Reviews*, 215(part C), 116345. <https://doi.org/10.1016/j.rser.2025.116345>
- Noureen, S., Ahmad, Z., Sirajuddin, M., Ahmed, A., Haider, A., Mahmood, S., Ayub, K., Yousuf, S., Ahmad, N., & 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.jorganchem.2025.123802>
- Nthwane, Y. B., Fouda-Mbanga, B. G., Thwala, M., & Pillay, K (2025). A comprehensive review of heavy metals (Pb²⁺, Cd²⁺, Ni²⁺) removal from wastewater using low-cost adsorbents and possible revalorization of spent adsorbents in blood fingerprint application. *Environmental Technology*, 46(3), 414-430. <https://doi.org/10.1080/09593330.2024.2358450>
- Paul, K., Jyothi, B., Kumar, R. S., Singh, A. R., Bajaj, M., Kumar, B. H., & Zaitsev, I. (2025). Optimizing sustainable energy management in grid connected microgrids using quantum particle swarm optimization for cost and emission reduction. *Scientific Reports*, 15, 5843. <https://doi.org/10.1038/s41598-025-90040-0>
- Qu, G., Zhong, F., Xu, J., Huang, X., & Sun, Z. et al. (2026). Intelligent enzyme design and hybrid catalytic systems: Driving innovation in biocatalysis. *Green Synthesis and Catalysis*, 7(2), 157-174. <https://doi.org/10.1016/j.gresc.2025.12.002>
- Ren, H., Labidi, A., Miao, Z., Chang, T., Padervand, M., Lichtfouse, R., & Wang, C.(2025). Dual S-scheme heterojunction nanocomposite-driven charge transport for photocatalytic green energy production and environmental implementations – where to go? *Advanced Composites and Hybrid Materials*, 8, 402. <https://doi.org/10.1007/s42114-025-01470-3>
- Ruan, Y., Hu, Y., & Cheng, H. (2025). Recent Progress in g-C₃N₄-based photocatalysts for organic pollutant degradation: Strategies to improve photocatalytic activity. *Catalysts*, 15(2), 148. <https://doi.org/10.3390/catal15020148>

- Rubina, S., Feby, K. A., & Anas, S. (2025). Advances in photodegradation of organic pollutants using polymer-supported Fenton catalysts. *Tetrahedron Green Chem*, 5, 100073. <https://doi.org/10.1016/j.tgchem.2025.100073>
- Saavedra, E. L., & Osmá, J. F. (2024). Impact of nanoparticle additions on life cycle assessment (LCA) of ceramic tiles production. *Nanomaterials*, 14(11), 910. <https://doi.org/10.3390/nano14110910>
- Saxena, S. (2025). Pyrolysis and beyond: Sustainable valorization of plastic waste. *Applications in Energy and Combustion Science*, 21, 100311. <https://doi.org/10.1016/j.jaecs.2024.100311>
- 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., Ali, Z., & 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(part 4), 143404. <https://doi.org/10.1016/j.ijbiomac.2025.143404>
- Shahwar, D-e, Usama, Khan, Z., Ahmad, N., Ali, A., & Imran, M. (2026). Molecular dynamics investigation of single nucleotide polymorphism-driven variations in GSTP1 phosphorylation and substrate interaction. *Journal of Biomolecular Structure and Dynamics*, 44(9), 4654-4665. <https://doi.org/10.1080/07391102.2026.2619869>
- Subhan, A., & Mourad, A-H I. (2025). Plasmonic metal nanostructures as performance enhancers in solar cells: A review. *Next Materials*, 251, 100509. <https://doi.org/10.1016/j.nxmte.2025.100509>
- Suleman, F., Muhsbat, 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(part 1), 107352. <https://doi.org/10.1016/j.jaap.2025.107352>
- Suleman, F., Muhsbat, S., Uddin, F., Hashmi, S., Borhan, A., Ahmad, F., & Ahmad, N. (2026). 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(part 1), 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. U. H., Khan, N. A., Ahmad, N., Ahmad, F., Alsayer, I. A., Altuwair, I. A., Ahmad, S. A., Zaheer, R., Khan, R., & 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>
- Syed, N. H., Khan, N. A., Ahamd, N., Khan, M., Ahmad, F., Humayun, F., Haq, S., Alsayer, I. A., & Altuwair, I. A. (2024a). A CFD analysis to investigate the effect of inserts on the overall heat transfer coefficient in a concentric tube heat exchanger. *Engineering Technology & Applied Science Research*, 14(6), 18077-18085. <https://doi.org/10.48084/etasr.8891>
- Syed, N. H., Haq, I., Ahmad, F., Khan, N. A., Habib, M., Ahmad, N., & Rind, I. K. (2024b). 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. <https://doi.org/10.48084/etasr.8066>
- Tanweer, A., Taqvi, S. A. A., Kazmi, B., Khatoon, S., Taha, M., Nadir, M., Ahmad, F., & 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>
- Tarlochan, F., Alduais, A., Chaban, Y., & Du, X. (2025). Integrating sustainability into STEM education and career. *International Journal of STEM Education*, 12, 62. <https://doi.org/10.1186/s40594-025-00582-y>
- Ullah, K., Abrar, M., Uddin, S., Ahmad, M., Ali, A., Ahmad, P., Alrefaww, S. H., Ahmad, N., Iqbal, N., 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 application. *Ceramics International*, 51(5), 5923-5929. <https://doi.org/10.1016/j.ceramint.2024.12.039>

- Varkolu, M., Gundekari, S., Omvesh, Palla, V. C. S., Kumar, P., Bhattacharjee, S., & Vinodkumar, T. (2025). Recent advances in biochar production, characterization, and applications. *Catalysts*, 15(3), 243. <https://doi.org/10.3390/catal15030243>
- Virender, V., Pandey, V., Singh, G., Sharma, P. K., Bhatia, P., Solovev, A. A., & Mohan, B. (2024). Hybrid metal-organic frameworks (MOFs) for various catalysis applications. *Topics in Current Chemistry*, 282, 3. <https://doi.org/10.1007/s41061-024-00486-5>
- Wang, Y., Sun, D., Zhao, B., Zhu, T., Liu, C., Xu, Z., Zhou, T., & Xu, C. (2025). Data-driven perovskite design via high-throughput simulation and machine learning. *Processes*, 13(10), 3049. <https://doi.org/10.3390/pr13103049>
- Yin, H-N., Chen, Z., Zhao, X., Liu, Z., Yu, F., Zheng, S., Huang, N., & Liu, Z. (2025a). Molecular-dynamics-simulation-guided directed evolution of flavoenzymes for atroposelective desaturation. *Nature Synthesis*, 4, 1621-1629. <https://doi.org/10.1038/s44160-025-00882-9>
- Yin, I. X., Udduttulla, A., Xu, V. W., Chen, K. J., Zhang, M. Y., & Chu, C. H. (2025b). Use of antimicrobial nanoparticles for the management of dental diseases. *Nanomaterials (Basel)*, 15(3), 209. <https://doi.org/10.3390/nano15030209>
- Yuan, L., Du, P., Yin, L., Yao, J., Wang, J., & Liu, C. (2024). Metal-organic framework-based S-scheme heterojunctions for photocatalytic. *Nanoscale*, 16(11), 5487-5503. <https://doi.org/10.1039/d3nr06677k>
- Zia, R., Nazir, M. S., Rouf, H., Ahmad, N., Ahmad, F., Ali, Z., & Ul Hassan, S. (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(part 4), 146503. <https://doi.org/10.1016/j.ijbiomac.2025.146503>
- Zohaib, A., Akram, F., Khalid, S., Nawaz, H., & Ur Rehman, M. (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>

Funding

Not applicable.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Copyrights

Copyright for this article is retained by the author(s), with first publication rights granted to the journal.

This is an open-access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/4.0/>).