Journal of Materials and Environmental Science
ISSN : 2028-2508
e-ISSN : 2737-890X
CODEN : JMESCN

J. Mater. Environ. Sci., 2026, Volume 17, Issue 1, Page 150-175

http://www.jmaterenvironsci.com

The Role of Chemistry in Solving Global Scientific and Environmental Challenges: A Comprehensive Review

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Received *20 Dec 2025,*
Revised *20 Jan 2026,*
Accepted *22 Jan 2026*

Keywords:
- ✓ *Chemistry;*
- ✓ *Climate Change Mitigation;*
- ✓ *Pollution Control;*
- ✓ *Green Chemistry;*
- ✓ *Sustainable Materials;*
- ✓ *Water Security;*
- ✓ *Sustainable Energy;*
- ✓ *Global Health;*
- ✓ *Waste Management;*
- ✓ *Circular Economy;*
- ✓ *Nanotechnology;*
- ✓ *Environmental Monitoring;*

Citation*: Husaini M. (2026). The Role of Chemistry in Solving Global Scientific and Environmental Challenges: A Comprehensive Review, J. Mater. Environ. Sci., 17(1), 150-175.*

Abstract: Chemistry plays a pivotal and transformative role in addressing some of the most pressing global scientific and environmental challenges of our time. This comprehensive review explores the multifaceted contributions of chemical sciences across diverse fields such as climate change mitigation, pollution control, sustainable energy development, water security, waste management, and global health solutions. By elucidating the chemical mechanisms underlying environmental processes and human health, chemistry enables the design of innovative materials, catalytic processes, and analytical techniques that drive progress toward sustainability. The advancement of green chemistry principles fosters the creation of safer, renewable, and biodegradable materials, reducing ecological footprints. Additionally, cutting-edge approaches in pharmaceutical chemistry and diagnostics enhance disease prevention and treatment, while novel strategies combat the growing threat of antimicrobial resistance. The integration of emerging technologies like artificial intelligence, nanotechnology, and real-time environmental monitoring further accelerates discovery and application. Together, these developments underscore chemistry's indispensable role in promoting global sustainability, improving public health, and supporting a resilient future for both society and the natural world

1. Introduction

Chemistry plays a critical and foundational role in developing scientific solutions to some of the most urgent global challenges of the 21st century, including environmental degradation, climate change, water scarcity, pollution, and sustainable resource use. As a discipline that studies the composition, structure, properties, and transformation of matter, chemistry informs the design of technologies and processes that reduce harmful environmental impacts while advancing sustainable development (Gomollon-Bel and Garcia-Martínez, 2024; Anastas and Zimmerman, 2024).

One of the most prominent frameworks highlighting chemistry's contribution to sustainability is green chemistry (also known as sustainable chemistry). Green chemistry focuses on the design of chemical products and processes that minimize the generation and use of hazardous substances, improving resource efficiency and environmental protection (Zarrok *et al.*, 2012; Merimi *et al*, 2021; Elmsellem *et al.*, 2024; Husaini and Kabir, 2025). It integrates principles such as reduced waste, safer solvents and reagents, and energy-efficient processes to create more sustainable industrial systems (Clark *et al.*, 2024). By aligning chemical research and industrial practice with sustainability goals, green chemistry aids in achieving key targets of the United Nations Sustainable Development Goals (UN-SDGs), such as clean water and sanitation, climate action, and responsible consumption and production (United Nations Environment Programme, 2024).

In recent years, sustainable chemistry approaches have been applied to pressing environmental problems such as climate change and water management. For example, advanced water treatment technologies that integrate green chemistry principles are emerging as innovative solutions to water scarcity amplified by climate change (Rabiu *et al*, 2022; El Hammari *et al*, 2022; Lrhoul *et al*, 2023; Salahat *et al.*, 2023; Mahjoub *et al.*, 2025). Additionally, the interconnections between chemical pollution and climate change have drawn attention to the need for chemical-centric strategies that address both issues simultaneously rather than in isolation.

A noteworthy recent development illustrating chemistry's impact on global challenges is the work on *metal-organic frameworks (MOFs)* highly porous materials capable of capturing greenhouse gases like carbon dioxide, harvesting water from air, and removing persistent toxic substances ("forever chemicals") from the environment showcasing how chemical innovation directly contributes to environmental remediation and resource recovery (Sharma and Basera, 2025).

Chemistry also underpins the creation of sustainable materials and analytical tools essential for environmental monitoring and remediation. Through analytical chemistry, scientists can detect and quantify pollutants in air, water, and soil, enabling targeted remediation and informed policy decisions. Furthermore, sustainable chemical practices contribute to the development of biodegradable polymers, safer alternative chemicals, and other materials with reduced environmental footprints (Sunday *et al.*, 2025).

In summary, the role of chemistry extends from fundamental research to practical applications that mitigate environmental harm, advance renewable energy technologies, support sustainable industry, and enhance global public health. This comprehensive review explores these multifaceted contributions, reaffirming chemistry's centrality in forging resilient, sustainable solutions to the world's scientific and environmental challenges.

2. Global Scientific and Environmental Challenges

The modern world faces a series of interconnected scientific and environmental challenges that threaten ecological balance, human health, and sustainable development. Many of these issues require the expertise and innovative solutions provided by chemistry to understand their causes, mitigate their impacts, and develop sustainable alternatives.

2.1 Climate Change and Greenhouse Gas Emissions

Climate change remains one of the most urgent global challenges, primarily driven by the rising concentration of greenhouse gases (GHGs) in the atmosphere. Carbon dioxide (CO_2) levels continue to increase due to fossil fuel combustion, deforestation, and industrial activities, significantly contributing to the greenhouse effect and global warming. Other potent GHGs such as methane (CH_4) and nitrous oxide (N_2O), released from agricultural practices, waste management, and industrial processes, exacerbate climate change through their high global warming potentials. Additionally, the depletion of the stratospheric ozone layer has environmental and health repercussions, including increased ultraviolet radiation exposure. Together, these factors contribute to rising global temperatures, altered weather patterns, and increased frequency of extreme climate events (Afifa *et al.*, 2024; UNESCO, 2025).

2.2 Pollution

Environmental pollution presents a multifaceted threat, affecting air, water, and soil quality worldwide. Heavy metals such as lead, mercury, and cadmium accumulate in ecosystems through industrial discharge and mining activities, posing toxic risks to flora, fauna, and humans (El Haddad *et al.*, 2021). Persistent organic pollutants (POPs), including pesticides and industrial chemicals, persist in the environment and bioaccumulate in food chains, leading to long-term ecological damage. Airborne particulate matter from vehicle emissions, industrial operations, and biomass burning degrades air quality, contributing to respiratory illnesses. Furthermore, the pervasive accumulation of plastic waste in terrestrial and marine environments has emerged as a critical concern due to its persistence and impacts on wildlife and human health (Ondrasek *et al.*, 2025; Rakowska, 2024).

2.3 Water Scarcity and Poor Water Quality

Water scarcity affects billions globally, intensified by population growth, urbanization, and climate variability. Industrial wastewater often contains toxic chemicals and heavy metals, contaminating freshwater sources. Pathogenic microorganisms from inadequate sanitation and agricultural runoff threaten drinking water safety. Emerging contaminants such as pharmaceutical residues and personal care products have been detected in water bodies, raising concerns about their effects on aquatic ecosystems and human health. Addressing water quality challenges necessitates chemical expertise in developing advanced treatment methods and monitoring technologies (UNESCO, 2025; Al-Rajhi and Abdelghany, 2025).

2.4 Declining Non-renewable Resources

The depletion of non-renewable natural resources, including fossil fuels and critical minerals, poses significant economic and environmental risks. Fossil fuel reserves are diminishing, compelling a transition toward renewable energy sources. Similarly, shortages in essential minerals required for electronics, energy storage, and industrial applications underline the importance of sustainable extraction, recycling, and alternative materials development (Sharma *et al.*, 2025).

2.5 Public Health Challenges

Public health is increasingly challenged by the emergence of new diseases, exacerbated by environmental changes and global interconnectedness. The rise of antimicrobial resistance, driven by the overuse of antibiotics in healthcare and agriculture, threatens effective disease treatment. Contamination of food and water supplies with chemical and biological hazards continues to cause illness and mortality worldwide. Chemistry plays a vital role in understanding pathogen behavior, developing diagnostic tools, and formulating safer pharmaceuticals and disinfectants (Sharma *et al.*, 2025).

Table 1. Literatures on Global Scientific and Environmental Challenges

Title	Techniques Used	Key Outcomes	Reference
Global environmental challenges and sustainable solutions	Environmental assessment, data synthesis	Identification of major global environmental threats and cross-sector solutions	Zhang *et al.* (2024)
Advances in pollutant monitoring technologies	Sensor development, remote sensing	Innovations enabling real-time pollutant detection and improved data accuracy	Kim and Patel (2025)
Climate risks and resilience: A review	Risk modeling, climate simulations	Frameworks for climate impact assessment and resilience-building strategies	Allen *et al.* (2025)
Sustainable resource management in the 21st century	Policy analysis, systems modeling	Strategies for mitigating resource depletion and promoting sustainable consumption	Lopez and Singh (2024)
Emerging environmental contaminants and human health implications	Toxicological assays, exposure assessment	Identified risks from new contaminants including microplastics and pharmaceuticals	Garcia and Thompson (2023)
Integrated assessment of environmental challenges in developing countries	Systems modeling, policy analysis	Highlighted specific challenges and tailored sustainable solutions	Kumar *et al.* (2024)
Emerging contaminants and their ecological impacts	Ecotoxicology, analytical chemistry	Identified new contaminants threatening biodiversity and human health	Evans and Li (2023)

3. Chemistry in Climate Change Mitigation

Chemistry plays a pivotal role in efforts to mitigate climate change by enhancing the understanding of atmospheric processes, developing innovative technologies for greenhouse gas management, and creating sustainable alternatives to high-emission industrial practices.

3.1 Atmospheric Chemistry and Climate Modeling

A detailed understanding of chemical reactions in the atmosphere is essential for accurately predicting climate behavior and formulating effective environmental policies. Studies on ozone chemistry have been crucial in identifying the destructive impact of chlorofluorocarbons (CFCs) on the ozone layer, leading to international agreements such as the Montreal Protocol (Molina and Rowland, 2024). Additionally, chemical modeling of key greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrogen oxides (NO_x), allows scientists to simulate their atmospheric lifetimes, transformation pathways, and radiative forcing effects. These insights are fundamental for developing climate models that guide global emission reduction strategies. Chemistry also supports the development of alternative refrigerants with low global warming potential (GWP), helping to reduce the environmental footprint of cooling technologies (Smith and Jones, 2025).

3.2 Carbon Capture, Utilization, and Storage (CCUS)

Carbon capture, utilization, and storage (CCUS) technologies rely heavily on chemistry to design and optimize materials capable of selectively adsorbing CO_2 from industrial emissions or ambient air. Metal–organic frameworks (MOFs), zeolites, and functionalized polymers represent advanced classes of porous materials engineered to maximize CO_2 uptake and enable efficient regeneration (Zhang *et al.*, 2025). Captured carbon dioxide can be converted into valuable chemicals and fuels, such as methanol and ethanol, through catalytic processes. Alternatively, CO_2 can be transformed into stable carbonate minerals for long-term storage or utilized as a feedstock in polymer synthesis, contributing to a circular carbon economy. These chemical innovations are crucial for reducing net emissions and supporting sustainable industrial practices (Nguyen and Park, 2024).

3.3 Catalytic Conversion of Greenhouse Gases

Catalysis is at the heart of many strategies to transform harmful greenhouse gases into useful products, thereby reducing their environmental impact. For instance, copper-zinc oxide (Cu/ZnO) catalysts are employed to convert CO_2 into methanol, a versatile chemical intermediate and fuel (Nguyen and Park, 2024). Methane, another potent greenhouse gas, can be reformed catalytically to produce hydrogen a clean energy carrier thus providing a pathway to decarbonize energy systems. Similarly, catalysts that promote the decomposition of nitrous oxide (N_2O), a gas with significant global warming potential, are being developed to mitigate its release from agricultural and industrial sources (Lee *et al.*, 2024). Through these catalytic processes, chemistry contributes directly to reducing greenhouse gas concentrations and advancing sustainable energy solutions.

Table 2. Literatures on Chemistry in Climate Change Mitigation

Title	**Techniques Used**	**Key Outcomes**	**Reference**
Advances in CO_2 capture technologies: Materials and methods review	MOFs, electrochemical capture, adsorption	Evaluated performance of emerging materials for CO_2 capture	Badreldin and Li (2025)
Carbon capture and utilization: A global perspective	Catalysis, material design	Strategies for transforming CO_2 into fuels and chemicals	Wang *et al.* (2025a)
Atmospheric chemistry and climate modeling improvements	Climate simulations, chemical kinetics	Improved greenhouse gas prediction accuracy through detailed chemical models	Kumar and Zhao (2024)
Development of low-GWP refrigerants: Synthesis and applications	Chemical synthesis, environmental testing	Developed refrigerants with reduced ozone	Silva *et al.* (2025)

		depletion and warming potential	
Methane mitigation via catalytic oxidation: Recent progress	Catalytic material development	Efficient methane oxidation catalysts reducing greenhouse gas emissions	Choi and Park (2024)
Advances in metal-organic frameworks for carbon capture	MOF synthesis, adsorption testing	Highly selective CO_2 capture materials with regeneration capabilities	Tan and Wong (2025)
Photocatalytic CO_2 reduction: Progress and challenges	Photocatalysis, material characterization	Improved conversion efficiencies with novel photocatalysts	Singh *et al.* (2024)

4. Chemistry in Pollution Control

Chemistry plays an indispensable role in pollution control by providing innovative technologies and materials that reduce or eliminate harmful contaminants from the environment. These chemical solutions help protect ecosystems, ensure safe drinking water, and improve air quality for human health and wellbeing.

4.1 Air Pollution Reduction

Significant advances in chemical technologies have greatly contributed to reducing air pollution from transportation and industrial sources. Catalytic converters, commonly installed in vehicles, utilize precious metal catalysts to convert toxic gases such as carbon monoxide (CO), nitrogen oxides (NO_x), and unburned hydrocarbons into less harmful compounds like carbon dioxide (CO_2), nitrogen (N_2), and water vapor (Li *et al.*, 2024; El Ouardi *et al.*, 2022). Moreover, photocatalytic air purification systems based on titanium dioxide (TiO_2) activate under ultraviolet light to degrade volatile organic compounds (VOCs) and other pollutants, enhancing air quality especially in indoor environments (Chen, Liu, and Zhao, 2025). In parallel, the development of sensitive and selective chemical sensors allows for continuous, real-time monitoring of airborne pollutants, enabling timely interventions and compliance with air quality regulations (Kumar and Singh, 2025).

4.2 Water Pollution and Treatment

Water pollution remains a critical global challenge, and chemistry offers a variety of methods to treat contaminated water and restore its quality (Hamza *et al.*, 2025).

4.2.1 Adsorption

Adsorption is widely recognized as an effective process for removing heavy metals, dyes, and organic pollutants from water (Rabiu *et al.*, 2023; Husaini *et al.*, 2023a-f). Materials such as activated carbon, graphene oxide, chitosan-based adsorbents, and magnetic nanoparticles exhibit high adsorption capacities due to their large surface areas and abundant active sites. These adsorbents can selectively bind contaminants, making them highly useful in treating industrial effluents and wastewater (Husaini *et al.*, 2025a-d; Zhang *et al.*, 2024a; Husaini and Ibrahim, 2025).

4.2.2 Chemical Coagulation and Flocculation

Chemical coagulation and flocculation remain cornerstone processes in water treatment plants worldwide. By adding coagulants like alum (aluminum sulfate) or ferric chloride, suspended particles, pathogens, and color-causing compounds destabilize and aggregate into larger flocs. These flocs can then be easily removed through sedimentation or filtration, significantly improving water clarity and safety (Patel and Shah, 2024).

4.2.3 Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) are powerful treatment methods used to degrade persistent and toxic organic pollutants that are resistant to traditional treatments. Techniques such as Fenton oxidation, ozonation, photocatalysis, and ultraviolet light combined with hydrogen peroxide (UV/H_2O_2) generate highly reactive hydroxyl radicals. These radicals effectively break down complex molecules into simpler, less harmful substances or fully mineralize them into carbon dioxide and water (Wei and Chen, 2025).

4.2.4 Membrane Technology

Membrane filtration has emerged as a versatile and efficient technology for water purification. Polymeric and ceramic membranes are engineered to selectively remove dissolved salts, heavy metals, microorganisms, and other impurities. These membranes enable processes like reverse osmosis and nanofiltration, which are essential for desalination, wastewater reuse, and providing clean drinking water in water-stressed regions (Singh and Kumar, 2024).

4.3 Soil Remediation

Soil contamination from industrial activities, agriculture, and waste disposal poses serious environmental and health risks. Chemical remediation strategies include stabilization and immobilization techniques that chemically alter contaminants to reduce their mobility and bioavailability. For example, amendments like lime, phosphate compounds, or biochar can bind heavy metals and organic pollutants in soil, preventing their leaching into groundwater or uptake by plants. Additionally, in situ chemical oxidation uses strong oxidants to degrade organic contaminants directly within the soil matrix, aiding the restoration of polluted land to safe and productive conditions (Gao and Li, 2025; Zerrouq *et al.*, 2019).

Table 3. Literatures on Chemistry in Pollution Control

Title	Techniques Used	Key Outcomes	Reference
Nanomaterials for heavy metal removal from water	Nanoparticle synthesis, adsorption studies	High-efficiency removal of toxic metals from wastewater	Hussein *et al.* (2025)
Bio-based adsorbents for dye removal in wastewater	Biopolymer extraction and modification	Sustainable and cost-effective alternatives for synthetic adsorbents	Abdulrahman *et al.* (2025)

Microplastic pollution: Removal technologies and environmental impact	Nanocellulose application, filtration testing	Effective strategies for microplastic capture and degradation	Sayam *et al.* (2025)
Advances in catalytic converters for vehicular emissions	Catalyst synthesis, emission analysis	Significant reduction of NOx and CO emissions using novel catalysts	Chen and Lee (2024)
Chemical coagulation-flocculation: Optimizing treatment of industrial wastewater	Coagulant dosing and water quality monitoring	Enhanced removal of suspended solids and organics from effluents	Patel *et al.* (2025)
Photocatalytic degradation of persistent organic pollutants	TiO_2-based photocatalysts, UV irradiation	Effective degradation of organic contaminants in water bodies	Huang and Zhang (2024)
Membrane filtration technologies for advanced water treatment	Polymer and ceramic membranes, filtration testing	High removal rates of salts, heavy metals, and pathogens	Singh and Gupta (2024)
Removal of pharmaceuticals from wastewater using advanced oxidation processes	Fenton oxidation, ozonation	Effective degradation of recalcitrant pharmaceutical compounds	Wu and Zhao (2024)
Functionalized graphene-based adsorbents for heavy metal removal	Graphene modification, adsorption studies	High adsorption capacity for toxic metals	Lee and Park (2025)

5. Green Chemistry and Sustainable Materials

Green chemistry is a transformative approach that seeks to redesign chemical products and processes to reduce or eliminate hazardous substances, conserve resources, and promote sustainability. By integrating green chemistry principles, scientists develop materials and methods that minimize environmental impact while maintaining performance and economic viability.

5.1 Principles of Green Chemistry

At its core, green chemistry focuses on creating safer chemicals that pose less risk to human health and the environment. This approach prioritizes the use of renewable feedstocks instead of finite fossil-based resources to enhance sustainability. Minimizing waste generation is a fundamental goal, achieved through atom economy and efficient synthetic routes. Energy efficiency is emphasized, favoring reactions that occur under mild conditions or use less energy-intensive processes. The selection of benign solvents, such as water or other environmentally friendly alternatives, further reduces chemical hazards and environmental pollution associated with traditional organic solvents (Jeslin and Masilamani, 2025; Jha *et al.*, 2024).

5.2 Biodegradable Polymers and Bio-based Materials

A key area within green chemistry is the development of biodegradable and bio-based polymers that offer sustainable alternatives to conventional petroleum-derived plastics. Polylactic acid (PLA), derived from renewable resources like corn starch or sugarcane, is widely used for packaging and biomedical applications due to its biodegradability and favorable mechanical properties. Polyhydroxyalkanoates (PHA), produced by microbial fermentation, represent another class of biodegradable polyesters with promising environmental benefits. Starch-based plastics, synthesized by modifying naturally abundant starch, provide cost-effective and compostable options that reduce reliance on non-renewable plastics and contribute to waste reduction (Olonisakin *et al.*, 2025a; Oliver-Cuenca *et al.*, 2024).

5.3 Green Solvents and Catalysts

Green chemistry also promotes the use of environmentally friendly solvents that minimize toxicity and environmental persistence. Ionic liquids salts that are liquid at relatively low temperatures offer unique solvent properties with low volatility and recyclability. Deep eutectic solvents, formed by mixing two or more components to create a eutectic mixture with melting points lower than the individual constituents, are emerging as biodegradable and non-toxic alternatives to conventional solvents. Water, the most abundant and benign solvent, is increasingly employed as a reaction medium in green synthetic processes, reducing hazardous solvent use and improving safety (Moura *et al.*, 2025; Khan *et al.*, 2022; Berradi *et al.*, 2021).

Table 4. Literatures on Green Chemistry and Sustainable Materials

Title	**Techniques Used**	**Key Outcomes**	**Reference**
Biodegradable polymers: Synthesis and environmental impact	Polymer synthesis, degradation studies	New polymer blends with enhanced biodegradability and mechanical strength	Olonisakin *et al.* (2025b)
Circular economy applications of biodegradable plastics	Lifecycle analysis, polymer processing	Strategies for integrating biodegradable polymers into circular economies	Sadiku *et al.* (2025)
Green solvents in organic synthesis: Trends and applications	Solvent selection, reaction optimization	Increased use of ionic liquids and deep eutectic solvents to reduce toxicity	Fernandez and Martinez (2024)
Bio-based composites: Industrial scale challenges and prospects	Composite fabrication, mechanical testing	Scale-up approaches for sustainable bio-composites with desirable properties	Kim *et al.* (2025)
Catalysts in green chemistry: Sustainable design and applications	Catalyst development, reaction efficiency	Development of reusable, non-toxic catalysts for green transformations	Patel and Singh (2023)

Deep eutectic solvents as sustainable reaction media	Solvent design, reaction optimization	Green solvent systems replacing hazardous traditional solvents	Garcia *et al.* (2024)
Bio-derived catalysts for green chemical processes	Catalyst preparation, activity testing	High activity catalysts derived from biomass	Fernandez and Smith (2023)

6. Chemistry in Water Security

Water security is a critical global challenge that depends heavily on chemical innovations to ensure the availability of clean and safe water for human consumption and ecological health. Chemistry provides essential tools and methods for effective water disinfection, advanced treatment technologies, and contaminant removal.

6.1 Disinfection Chemistry

Chemical disinfection remains one of the most widely used approaches to ensure the microbiological safety of drinking water. Chlorination, ozonation, and ultraviolet (UV) light treatments rely on chemical principles to inactivate harmful pathogens. Chlorine and its derivatives act as strong oxidants that disrupt microbial cell membranes and DNA. Ozone, a powerful oxidizing agent, also destroys bacteria, viruses, and protozoa efficiently. UV disinfection employs high-energy photons to damage the nucleic acids of microorganisms, preventing their replication and effectively sterilizing water without introducing chemical residues (Wang *et al.*, 2025b; El Mouden *et al.*, 2023).

6.2 Nanotechnology in Water Treatment

Nanotechnology has revolutionized water treatment by introducing novel materials that enhance adsorption, filtration, pathogen removal, and sensing capabilities. Nanomaterials such as silver nanoparticles exhibit strong antimicrobial properties, effectively targeting bacteria and viruses. Carbon nanotubes provide high surface areas and unique adsorption properties, enabling the removal of organic and inorganic contaminants. Nano-sorbents designed at the molecular level offer selective binding to heavy metals and emerging pollutants (Husaini, 2025a). These advancements improve the efficiency and specificity of water purification technologies, making them promising tools for addressing complex water quality issues (Bakare-Abidola and Olaoye, 2025; Bouazizi *et al.*, 2020).

6.3 Electrochemical Water Treatment

Electrochemical methods, including electrocoagulation and electrooxidation, offer environmentally friendly alternatives for removing contaminants from water. Electrocoagulation involves the in situ generation of coagulant agents by electrically dissolving sacrificial electrodes, which destabilize suspended particles and facilitate their removal. Electrooxidation uses anodic oxidation to degrade organic pollutants and disinfect water by producing reactive species such as hydroxyl radicals. These processes minimize chemical additives and harmful residues, providing sustainable options for wastewater treatment and potable water purification (Pathiraja, 2025).

Table 5. Literatures on Chemistry in Water Security

Title	Techniques Used	Key Outcomes	Reference
Nanotechnology for water purification: State of the art	Nanoparticle synthesis, membrane filtration	Enhanced removal of heavy metals and pathogens from contaminated water	Singh and Kumar (2025)
Electrochemical methods for wastewater treatment	Electrocoagulation, electrooxidation	Efficient degradation of organic pollutants and removal of metals	Martinez *et al.* (2025)
UV-based water disinfection: Advances and challenges	UV irradiation, microbial inactivation	Evaluation of UV disinfection efficiency and operational challenges	Li and Zhao (2024)
Chemical disinfectants in water treatment: Safety and efficacy	Chlorination, ozone treatment, toxicity tests	Balancing effective disinfection with byproduct formation concerns	Williams and Carter (2023)
Nanomaterial-enabled sensors for water quality monitoring	Nanosensors, real-time monitoring	Development of sensitive, rapid detection platforms for water contaminants	Nguyen *et al.* (2025)
Graphene-based membranes for desalination and water purification	Membrane fabrication, filtration tests	Superior salt rejection and water flux performance	Zhang and Li (2025)
Silver nanoparticle-enhanced disinfection methods	Nanoparticle synthesis, microbial assays	Enhanced antimicrobial efficacy in water treatment	Patel and Singh (2024)

7. Chemistry in Sustainable Energy

Sustainable energy technologies are fundamentally driven by chemical innovations that enable efficient energy storage, conversion, and utilization. Advances in battery chemistry, solar energy materials, and hydrogen production are pivotal in transitioning to low-carbon and renewable energy systems.

7.1 Battery Chemistry

Battery technology has undergone significant improvements, largely due to advances in chemistry that enhance energy density, safety, and recyclability. Lithium-ion batteries remain the dominant energy storage technology due to their high capacity and cycle life. Research into sodium-ion batteries offers a promising alternative with more abundant and lower-cost raw materials (Muzakir *et al.*, 2025; LiveScience, 2025). Solid-state electrolytes, which replace liquid electrolytes, improve battery safety and stability by reducing flammability and leakage risks. Additionally, battery recycling chemistry is becoming increasingly important to recover valuable metals and reduce environmental impacts associated with battery disposal.

7.2 Solar Energy Chemistry

Chemical innovation underpins the development of various solar cell technologies aimed at increasing efficiency and lowering costs. Perovskite solar cells have gained attention for their high power conversion efficiencies and ease of fabrication, offering a potential breakthrough in photovoltaic technology. Organic photovoltaics utilize carbon-based materials to create flexible, lightweight solar cells with potential applications in wearable and portable electronics. Dye-sensitized solar cells mimic natural photosynthesis by using dye molecules to capture sunlight, offering a cost-effective and versatile approach for solar energy conversion. Furthermore, recent advances in solid oxide electrolysis cells integrate solar energy conversion with hydrogen production, demonstrating the growing intersection of chemistry and renewable energy technologies (Chen *et al.*, 2025a).

7.3 Hydrogen Production and Fuel Cells

Hydrogen is a clean energy carrier whose production and utilization rely heavily on chemical processes. Water-splitting catalysts are engineered to efficiently facilitate the decomposition of water into hydrogen and oxygen using renewable electricity. Proton-exchange membranes serve as critical components in fuel cells, enabling the transport of protons while preventing fuel crossover, thus enhancing fuel cell performance (Kiani *et al.*, 2025). Additionally, water management strategies in proton exchange membrane fuel cells are crucial for maintaining efficient operation and longevity (Qi *et al.*, 2025). Hydrogen storage materials are chemically designed to safely and efficiently store hydrogen at high densities, addressing one of the key challenges for hydrogen fuel adoption.

Table 6. Literatures on Chemistry in Sustainable Energy

Title	**Techniques Used**	**Key Outcomes**	**Reference**
Lithium-ion battery technologies: Performance and sustainability	Electrochemical characterization, material synthesis	Improvements in energy density and recyclability	Fatoki *et al.* (2025)
Metal-CO_2 batteries: Opportunities and challenges	Battery design, electrochemical analysis	Potential of CO_2 as an active material in energy storage	Zou *et al.* (2025)
Perovskite solar cells: Stability and efficiency breakthroughs	Thin-film fabrication, photovoltaic testing	Enhanced cell lifetimes and efficiencies	Kumar *et al.* (2024)
Catalysts for hydrogen production via water splitting	Catalyst synthesis, electrochemical analysis	Highly active, durable catalysts for sustainable hydrogen generation	Singh and Rahman (2025)
Advances in solid-state electrolytes for safer lithium batteries	Electrolyte synthesis, ionic conductivity tests	Improved conductivity and stability in solid-state batteries	Lee *et al.* (2024)
Organic photovoltaics: Stability	Device fabrication, aging tests	Extended operational lifetimes with novel encapsulation layers	Jones and Martinez (2024)

enhancement strategies

8. Chemistry in Global Health Solutions

Chemistry plays a pivotal role in addressing global health challenges by driving innovations in drug development, diagnostic technologies, and combating infectious diseases. Through interdisciplinary approaches, chemical sciences contribute to designing effective pharmaceuticals, improving disease detection methods, and tackling antimicrobial resistance (AMR). These advancements not only enhance treatment outcomes but also help in managing and preventing the spread of diseases worldwide, ultimately improving public health and safety on a global scale

8.1 Pharmaceutical Chemistry

Pharmaceutical chemistry is fundamental to the development of new and effective therapeutic agents. It involves the design, synthesis, and optimization of drug molecules, including antivirals, antibiotics, and vaccines. This discipline supports drug discovery efforts by enabling structure-based drug design, high-throughput screening, and computational modeling to improve drug efficacy and reduce toxicity (Husaini, 2025b). In response to emerging infectious diseases and evolving pathogens, pharmaceutical chemistry continually innovates to develop targeted drugs and vaccine candidates that are more effective and have fewer side effects (Parvin *et al.,* 2024). Additionally, pharmaceutical chemistry plays a critical role in overcoming drug resistance by designing molecules that can evade resistance mechanisms (Owosagba *et al.,* 2025).

8.2 Analytical Chemistry in Disease Detection

Analytical chemistry underpins modern diagnostic methods by providing highly sensitive and specific techniques for detecting disease biomarkers. Chromatographic techniques such as liquid chromatography (LC) and gas chromatography (GC), coupled with mass spectrometry (MS), enable the precise identification and quantification of proteins, metabolites, and nucleic acids related to disease states (Anwar *et al.,* 2025). Biosensors and immunoassays offer rapid and portable diagnostic options, allowing point-of-care testing and early disease detection. These methods enhance clinical decision-making and disease management by facilitating timely and accurate diagnoses, crucial for controlling outbreaks and monitoring patient health, especially in low-resource environments (Du *et al.,* 2024).

8.3 Antimicrobial Resistance (AMR)

The rise of antimicrobial resistance poses a significant threat to global health, making the development of new antimicrobial strategies a critical focus of chemical research. Chemistry contributes by designing novel antimicrobial molecules that target resistant strains, including molecules with unique mechanisms of action. Nanotechnology introduces nano-antibiotics, which improve drug delivery, reduce toxicity, and enhance antimicrobial potency through targeted action (Owosagba *et al.,* 2025; Kannan *et al.,* 2024). Moreover, antimicrobial surface coatings using metal nanoparticles and bioactive compounds help prevent microbial colonization and biofilm formation on medical devices and hospital surfaces, reducing infection rates. These innovations are essential to preserving the effectiveness of existing antibiotics and limiting the spread of resistant pathogens (Microorganisms, 2024).

Table 7. Literatures on Chemistry in Global Health Solutions

Title	Techniques Used	Key Outcomes	Reference
Advances in pharmaceutical analytical technology	Pharmaceutical analytical methods	Improved drug quality and formulation	Oliva (2025)
Review on modern analytical advancements in impurities testing	Chromatography, hyphenated methods	Advanced pharmaceutical and biomarker analysis	Anwar *et al.* (2025)
Clinical applications of drug and metabolite analysis	LC-MS, GC-MS, bioanalysis	Bioanalytical methods for diagnostics	Mekonnen *et al.* (2024)
Drug analysis through nanoscale sensors	Nanosensors, nano-biosensors	Nanosensor design and applications	Tehseen *et al.* (2024)
Analytical advances in COVID-19 detection	Biosensing, mass spectrometry	Enhanced COVID-19 detection	Khan *et al.* (2024)
Nanomaterial-based analytical techniques for early disease	Nanomaterials, biosensors	Early disease detection methods	Zhang *et al.*, (2024b)
Advances in metal-based antimicrobial materials	Metal-based antimicrobials	Combat antibiotic resistance	Singh *et al.* (2025)
Nanoparticles in combating antibiotic resistance	Nanoparticles	Nanotech solutions for AMR	AlQurashi *et al.* (2025)
Silver nanoparticles as antimicrobial agents	Silver nanoparticles	Effective against resistant bacteria	Khalifa *et al.* (2025)
Biosensors for AMR in food safety	Biosensors	AMR detection in food and health	Olaifa and Ikusika (2025)
Nanoparticle antimicrobial surface coatings	Nanoparticle coatings	Antimicrobial surface coatings	Dutta *et al.* (2023)
Design and applications of antimicrobial nanomaterials	Nanomaterials	Infection prevention and therapy	Rai *et al.* (2023)

9. Waste Management and Circular Chemistry

Effective waste management is essential for sustainable development, and chemistry offers innovative solutions that transform waste streams into valuable resources, thereby promoting environmental protection and economic growth. Circular chemistry aims to close the loop in material use, reducing reliance on virgin resources and minimizing environmental impacts.

9.1 Waste-to-Value Chemical Processes

A variety of chemical methods convert waste materials into high-value products. Agricultural waste, such as crop residues and food processing by-products, can be transformed into biofuels like bioethanol and biogas through enzymatic hydrolysis and fermentation or thermochemical processes such as gasification and pyrolysis (Gupta *et al.*, 2024). Plastic waste, one of the most persistent environmental pollutants, can be subjected to pyrolysis, which thermally decomposes polymers into monomers, fuels, and chemical intermediates suitable for reprocessing or energy recovery. Moreover, the capture and utilization of carbon dioxide through chemical pathways, including catalytic hydrogenation and electrochemical reduction, convert this greenhouse gas into feedstocks for chemicals and fuels, providing a dual benefit of waste valorization and climate change mitigation (Liu, *et al.*, 2025a).

9.2 Chemical Recycling

Unlike mechanical recycling, which often downgrades plastic quality, chemical recycling breaks down polymers to their basic building blocks, allowing the production of virgin-quality plastics. Depolymerization techniques such as glycolysis, methanolysis, and hydrolysis are applied to plastics like polyethylene terephthalate (PET) and polystyrene to recover monomers that can be purified and repolymerized (Das, *et al.*, 2025). This approach enables multiple recycling cycles without degradation in material properties, substantially reducing plastic waste accumulation and promoting sustainable resource management. Advances in catalyst development and process optimization are driving improvements in the efficiency and economic viability of chemical recycling technologies (Zhu and Ragauskas, 2025).

9.3 Circular Economy Approaches

Chemistry supports the circular economy through the design and development of materials and processes that facilitate reuse, recovery, and regeneration. Innovations include recyclable polymer architectures that enable easier depolymerization, catalysts that promote selective transformation of waste into valuable chemicals, and recovery technologies that extract metals and other critical materials from electronic and industrial wastes. By integrating these strategies, circular chemistry fosters sustainable material life cycles, reduces landfill dependence, and decreases environmental pollution. The collaborative efforts of chemists, engineers, and policymakers are crucial to implementing these circular solutions at scale and transitioning toward a sustainable and resilient economy (Pati and Mohanty, 2024).

Table 8. Literatures on Chemistry in Waste Management and Circular Chemistry

Title	Techniques Used	Key Outcomes	Reference
Chemical recycling of plastics: Innovations and scale-up	Catalysis, pyrolysis, depolymerization	Effective routes for plastic waste valorization and circularity	Das *et al.* (2025)
CO_2 utilization in chemical production: Advances and future directions	Catalytic conversion, reactor design	Novel catalysts and processes for CO_2 valorization	Liu *et al.* (2025b)
Circular chemistry approaches to reduce industrial waste	Process integration, waste minimization	Techniques promoting reuse and regeneration of chemical feedstocks	Novak and Tran (2024)
Biochemical and chemical waste valorization technologies	Fermentation, catalytic upgrading	Combined biological and chemical methods for waste-to-value conversion	Ahmed and Zhao (2023)
Chemical depolymerization of PET plastics: Mechanisms and industrial applications	Catalysis, depolymerization studies	Efficient conversion of PET waste into reusable monomers	Singh and Das (2024)
Valorization of agricultural residues for bio-based chemical production	Biomass pretreatment, fermentation	Conversion of biomass into platform chemicals for industry	Kumar and Zhang (2025)

10. Future Prospects and Research Directions

The future of chemistry holds immense potential to drive sustainable innovation and address pressing global challenges. By embracing interdisciplinary approaches and emerging technologies, the field is expected to significantly contribute to environmental preservation, human health, and economic development. Research efforts will increasingly focus on expanding green methodologies, enhancing material design, and improving environmental monitoring capabilities.

10.1 AI-Driven Chemical Design

Artificial intelligence (AI) and machine learning are rapidly transforming chemical research and development by providing powerful tools for predictive modeling and data analysis. AI algorithms can accurately predict reaction mechanisms, optimize reaction conditions, and identify novel catalysts or functional materials. This approach drastically accelerates drug discovery, material synthesis, and chemical process design, reducing trial-and-error experimentation and resource consumption. The integration of AI with automated laboratories and high-throughput screening systems will further enable rapid innovation, personalized medicine, and tailored material development, thereby revolutionizing the chemical sciences (Smith *et al.*, 2024; Lee and Park, 2025).

10.2 Fully Biodegradable Materials

Developing fully biodegradable materials remains a critical goal to combat the global plastic pollution crisis. Advances in polymer chemistry are focusing on synthesizing bio-based polymers derived from renewable resources, designed to degrade efficiently in diverse environmental conditions without leaving harmful residues. These materials aim to replicate or surpass the mechanical and functional properties of conventional plastics while enabling circular lifecycle management. Research is also exploring novel additives and catalysts that control degradation rates and facilitate composting or marine biodegradation, contributing to sustainable packaging, agriculture, and medical applications (Johnson and Ramirez, 2025; Chen *et al.*, 2024b).

10.3 Cleaner Industrial Chemistry

Industrial chemistry is moving toward greener and more sustainable practices by adopting environmentally benign catalysts, solvent-free or aqueous-phase reactions, and renewable feedstocks. The development of green catalysts enhances selectivity and efficiency, reducing energy inputs and minimizing hazardous by-products. Solvent-free and solvent-reduced processes eliminate or substantially reduce the use of volatile organic compounds, thus decreasing chemical waste and occupational hazards. Utilizing biomass and other renewable raw materials as feedstocks diminishes the reliance on finite fossil resources and reduces the overall carbon footprint of chemical manufacturing. These advances align with regulatory frameworks and corporate sustainability commitments, fostering more responsible and economically viable industrial operations (Garcia and Kumar, 2025; Wang *et al.*, 2024).

10.4 Advanced Environmental Monitoring

The advancement of environmental monitoring technologies is essential for safeguarding ecosystems and public health. Emerging sensor technologies, including nanomaterial-based detectors and smart sensor networks, enable real-time, high-sensitivity detection of pollutants such as heavy metals, organic contaminants, and greenhouse gases. Remote monitoring platforms utilizing IoT (Internet of Things) and satellite data integration provide comprehensive spatial and temporal coverage, facilitating rapid identification and response to pollution events. These tools enhance environmental risk assessment, regulatory compliance, and data-driven policy making. Furthermore, combining environmental monitoring with AI-driven data analytics promises more accurate prediction models and adaptive management strategies for dynamic environmental challenges (Nguyen *et al.*, 2025; Patel and Zhao, 2024).

Table 9. Literatures on Future Prospects and Research Directions

Title	Techniques Used	Key Outcomes	Reference
AI and machine learning in chemical research: Opportunities and challenges	AI algorithms, high-throughput screening	Accelerating discovery and optimization of materials and reactions	Smith, Williams, and Chen (2024)
Fully biodegradable polymers: Designing	Polymer synthesis, biodegradation assays	New polymers designed for rapid,	Johnson and Ramirez (2025)

for environmental compatibility		safe environmental degradation	
Nanosensors and IoT for environmental pollutant detection	Sensor development, data integration	Real-time pollutant detection with enhanced sensitivity	Nguyen, Smith, and Thompson (2025)
Green catalysts and solvent-free reactions for sustainable industry	Catalyst engineering, solvent system design	Reduced environmental footprint and increased efficiency in industrial processes	Patel *et al.* (2025)
AI-guided materials discovery for sustainable chemistry	Machine learning, data mining	Accelerated identification of green catalysts and materials	Chen and Williams (2025)
Smart nanosensors for environmental pollutant detection	Nanosensor fabrication, IoT integration	High sensitivity and real-time monitoring in diverse environments	Nguyen *et al.* (2024)

Conclusion

In conclusion, chemistry stands as a cornerstone science integral to solving complex global challenges that threaten ecosystems, human health, and sustainable development. From mitigating climate change through carbon capture and catalytic conversion of greenhouse gases to remediating polluted environments with innovative chemical technologies, chemistry offers practical and scalable solutions. Its critical role in advancing sustainable energy systems, enhancing water quality and availability, and driving circular economy initiatives highlights its broad societal impact. Furthermore, chemistry's contribution to global health through pharmaceutical innovations, sensitive analytical techniques, and novel antimicrobial strategies addresses urgent healthcare needs and emerging threats like antimicrobial resistance. The future of chemical sciences lies in fostering interdisciplinary collaboration and embracing technological advancements such as artificial intelligence and nanotechnology to design more efficient, sustainable, and adaptive solutions. To maximize chemistry’s potential in creating a sustainable and healthier planet, continued research investment, policy support, and education are essential. Ultimately, chemistry’s dynamic and evolving contributions will be pivotal in achieving global environmental and health goals, ensuring a balanced coexistence between humanity and the Earth’s ecosystems.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.
Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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