Green Chemistry and Renewable Energy: Innovations in Sustainable Materials and Clean Energy

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Abstract
The increasing demand for energy, depletion of conventional fossil fuel resources, and growing environmental concerns have intensified the need for sustainable chemical processes and renewable energy technologies. Green chemistry provides a scientific framework for designing chemical products and processes that minimize hazardous substances, reduce waste, improve energy efficiency, and promote the use of renewable feedstocks. When integrated with renewable energy technologies, green chemistry can contribute to cleaner energy production, efficient energy conversion, and sustainable energy storage. This review discusses important developments at the interface of green chemistry and renewable energy, with particular emphasis on green hydrogen production, solar energy conversion, biomass-derived fuels, sustainable catalysts, and environmentally responsible battery materials. It also examines the role of nanomaterials, photocatalysis, electrocatalysis, and waste-derived materials in improving energy-related processes. Although these technologies offer substantial environmental and technological benefits, challenges remain concerning material durability, production costs, resource availability, scalability, and end-of-life management. A holistic assessment of energy consumption, environmental impacts, and material life cycles is therefore essential. The integration of green chemistry principles with renewable energy research offers a promising pathway toward resource-efficient chemical manufacturing, lower-carbon energy systems, and sustainable development.
***Keywords**: Green chemistry, renewable energy, sustainable materials, green hydrogen, biomass, photocatalysis, electrocatalysis, energy storage, sustainability.*

1. Introduction

Energy is fundamental to industrial development, transportation, agriculture, and modern living. However, the continued dependence on fossil fuels has contributed to greenhouse gas emissions, air pollution, resource depletion, and environmental degradation. Renewable energy sources such as solar, wind, hydropower, and biomass offer alternatives to conventional energy systems. Nevertheless, the sustainable deployment of these technologies requires more than the replacement of fossil fuels with renewable electricity. It also requires environmentally responsible methods for manufacturing materials, producing fuels, storing energy, and managing chemical waste. Green chemistry is the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances. Its principles encourage waste prevention, improved atom economy, safer solvents, catalytic efficiency, energy conservation, and the use of renewable feedstocks [1,2]. These principles are directly relevant to the development of sustainable energy technologies. For example, solar cells require functional semiconductor materials, hydrogen production requires efficient catalysts and electrolyser components, and batteries depend on electrochemically active materials. The extraction, synthesis, processing, and disposal of these materials may create environmental burdens. Green chemistry can help reduce these impacts through cleaner synthesis routes, renewable raw materials, safer chemical alternatives, and improved recycling methods. The relationship between green chemistry and renewable energy is therefore mutually beneficial. Renewable energy can supply cleaner electricity and heat for chemical manufacturing, while green chemistry can improve the environmental performance of materials and processes used in renewable energy systems. This review examines the major areas of this relationship, the associated challenges, and opportunities for future research.

2. Objectives:

The main objectives of this paper are:

- To explain the role of green chemistry in the development of renewable energy technologies.
- To examine sustainable materials used in solar energy conversion, hydrogen production, biofuels, and energy storage.
- To discuss the contribution of catalysis, nanotechnology, and waste valorisation to clean energy research.

- To identify environmental, economic, and technological challenges associated with these approaches.
- To outline future research directions for integrating green chemistry with renewable energy systems.

3. Green Chemistry as a Foundation for Sustainable Energy

The twelve principles of green chemistry provide a useful framework for evaluating chemical processes and materials [1,2]. Several principles are particularly important in renewable energy research.

3.1 Prevention of waste:

Waste prevention involves designing processes that generate fewer unwanted by-products and use raw materials efficiently. In energy-material synthesis, this may involve reducing purification steps, recovering solvents, and converting agricultural or industrial waste into useful products.

3.2 Use of renewable feedstocks:

Renewable feedstocks include biomass, cellulose, lignin, agricultural residues, and other biological resources that can be replenished sustainably. These materials can serve as precursors for biofuels, carbon-based electrodes, and other functional materials. Their benefits depend on responsible sourcing and the avoidance of competition with food production or ecosystems.

3.3 Energy efficiency:

Chemical synthesis and material processing may require substantial heat, pressure, or electricity. Catalytic reactions, optimized reaction conditions, and suitable alternative synthesis techniques can reduce energy demand. When processes are powered by renewable electricity, their overall greenhouse gas emissions may be reduced further.

3.4 Catalysis:

Catalysts improve reaction rates or selectivity without being consumed in the overall reaction. Efficient catalysts can reduce the energy requirements of hydrogen production, biomass conversion, and electrochemical energy storage. Their sustainability must also be evaluated in terms of toxicity, abundance, durability, and recyclability.

4. Green Chemistry and Solar Energy Technologies:

Solar energy is an abundant renewable resource that can be converted into electricity through photovoltaic devices or into chemical energy through photochemical and photocatalytic processes.

4.1 Sustainable photovoltaic materials:

Photovoltaic cells convert incident sunlight directly into electrical energy. Their performance depends on light absorption, charge separation, charge transport, and the stability of the active materials. Research has explored silicon, thin-film semiconductors, organic photovoltaic materials, and perovskite solar cells.From a green chemistry perspective, solar-cell development should consider the toxicity of constituent elements, solvent use during fabrication, manufacturing temperatures, material recovery, and operational lifetime. Some emerging photovoltaic materials offer promising efficiency and processing advantages, but concerns about toxic constituents, long-term stability, and recycling remain.Greener manufacturing approaches include reducing solvent consumption, improving material utilization, using safer processing chemicals, and designing cells for easier disassembly and material recovery. These strategies may reduce the environmental footprint of photovoltaic technologies.

4.2 Photocatalysis for clean fuel production:

Photocatalysis uses light-absorbing materials to drive chemical reactions. Semiconductor photocatalysts absorb photons and generate electrons and holes. Under suitable conditions, these charge carriers participate in oxidation and reduction reactions.One important application is photocatalytic water splitting, which aims to produce hydrogen and oxygen using solar energy. The process involves oxidation of water and reduction of protons, with the overall reaction represented as:

$2H_2O \rightarrow 2H_2 + O_2$

In practice, the process requires appropriate catalysts, sufficient light absorption, effective charge separation, and control of competing reactions. Many reported systems still face limitations involving efficiency, stability, and scalability. Photocatalysis can also be applied to carbon dioxide conversion and environmental remediation. However, claims of practical performance must be supported by reliable measurements, appropriate controls, and complete energy balances. Green chemistry contributes by encouraging abundant and less hazardous catalysts, efficient reaction conditions, and reduced waste generation.

5. Green Hydrogen Production and Catalysis:

Hydrogen is an important chemical feedstock and can also serve as an energy carrier. It may be used in fuel cells, industrial processes, and selected transportation and energy-storage applications. Its environmental benefits depend strongly on how it is produced.

5.1 Water electrolysis

Water electrolysis uses electricity to split water into hydrogen and oxygen. When the electricity is supplied by low-carbon renewable sources, the resulting hydrogen can have substantially lower life-cycle emissions than hydrogen produced from unabated fossil fuels.

The overall reaction is:

$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$

Electrolysis involves two electrode reactions: the hydrogen evolution reaction at the cathode and the oxygen evolution reaction at the anode. Both reactions require suitable electrode materials and operating conditions.

5.2 Role of electrocatalysts

Electrocatalysts reduce kinetic barriers and improve reaction rates at the electrodes. Platinum-group metals are effective for certain hydrogen-producing reactions, while iridium- and ruthenium-based oxides are used in some oxygen-evolution systems. Their cost and limited availability encourage research into alternatives based on more abundant elements, including nickel, iron, cobalt, and molybdenum.

Green chemistry supports catalyst development through efficient synthesis, reduced use of hazardous reagents, lower-energy processing, and improved material recovery. The performance of alternative catalysts must be evaluated in terms of activity, selectivity, durability, and performance under practical operating conditions.

5.3 Challenges in hydrogen technology

Important barriers include the cost of renewable electricity, electrolyser capital costs, water availability, catalyst durability, hydrogen storage, and transport infrastructure. Hydrogen is not a primary energy source; it is an energy carrier whose production requires an energy input.Consequently, a sustainable hydrogen system should assess the complete chain from electricity generation to electrolysis, compression or conversion, storage, transport, and final use. Green chemistry can contribute to safer materials and more efficient reactions, but system-level analysis is necessary to establish the overall environmental benefit.

6. Biomass, Biofuels, and Waste Valorisation:

Biomass is a renewable source of carbon-containing materials derived from plants, biological residues, and other organic matter. Agricultural residues, forestry by-products, and certain organic wastes can be converted into useful fuels and chemicals.

6.1 Bioethanol and biodiesel:

Bioethanol can be produced through fermentation of suitable sugar- or starch-containing feedstocks, while advanced processes can convert lignocellulosic biomass into fermentable sugars. Biodiesel is commonly produced by transesterification of suitable oils or fats with an alcohol in the presence of a catalyst. These fuels can provide alternatives to some petroleum-derived fuels. Their sustainability, however, depends on the feedstock, land-use effects, fertilizer and water requirements, process energy, and treatment of by-products.

6.2 Conversion of agricultural waste

Agricultural residues contain cellulose, hemicellulose, lignin, and other useful components. These materials can be processed into biofuels, platform chemicals, activated carbon, and other functional materials.Green chemistry encourages the use of waste streams as valuable raw

materials. For example, biomass-derived carbon may be investigated for use in electrodes for batteries and supercapacitors. Such applications can add value to residues that might otherwise be discarded or burned.Nevertheless, the use of biomass must not compromise soil health, biodiversity, food security, or the existing beneficial uses of residues. Collection, pretreatment, conversion, and transportation must also be included in environmental assessments.

6.3 Waste-to-energy and circular resource use

Waste valorisation aims to recover useful materials or energy from waste streams. Organic waste can be processed through anaerobic digestion to produce biogas, while selected waste-derived materials can be converted into chemical feedstocks or electrode precursors.A circular approach prioritizes preventing waste, extending material life, and recovering resources before final disposal. It should not encourage unnecessary waste generation merely to supply a conversion process.

7. Sustainable Materials for Batteries and Energy Storage:

The intermittent nature of solar and wind energy increases the importance of effective energy storage. Batteries, supercapacitors, thermal storage systems, and other technologies can help balance electricity supply and demand.

7.1 Green chemistry in battery materials

Rechargeable batteries contain electrodes, electrolytes, separators, current collectors, and other components. Their environmental impacts arise from mining, refining, material synthesis, manufacturing, operation, and disposal.

Green chemistry can improve battery sustainability by promoting lower-hazard electrolytes, more efficient electrode synthesis, longer-lasting materials, and recycling processes that recover valuable components. Material choices must balance energy density, power capability, cost, safety, cycle life, and resource availability.

Lithium-ion batteries are widely used in portable electronics and electric vehicles, but their supply chains can involve significant resource and environmental concerns. Alternative technologies, including sodium-ion batteries, aqueous batteries, and selected solid-state systems, are being investigated for different applications. No single chemistry is optimal for every use.

7.2 Biomass-derived carbon electrodes

Agricultural and forestry residues can be converted into carbon-rich materials through controlled thermal or chemical treatment. Depending on the precursor and processing method, these materials may exhibit useful porosity, conductivity, and surface chemistry. Such properties make biomass-derived carbon promising for supercapacitors, battery electrodes, and other electrochemical applications. However, performance varies considerably with feedstock composition and processing conditions. High-temperature treatment, chemical activation, and purification can consume energy and generate waste. A genuinely green synthesis route should therefore be evaluated for chemical consumption, energy demand, product yield, electrode performance, and the possibility of recycling or safely disposing of the final material.

7.3 Recycling and end-of-life management

Battery recycling can recover valuable metals and reduce the need for some primary raw materials. Conventional recycling approaches may require high temperatures or strong chemical reagents, while emerging processes investigate selective leaching, direct recycling, and biologically assisted methods. Green chemistry can help improve selectivity, reduce reagent consumption, and minimize secondary waste. Effective recycling also requires battery designs that facilitate disassembly and material separation.

8. Nanotechnology and Green Synthesis of Energy Materials

Nanomaterials possess size-dependent optical, electrical, catalytic, and surface properties. They are used in research on solar cells, photocatalysis, fuel cells, hydrogen production, and electrochemical energy storage. Conventional nanomaterial synthesis may involve hazardous reducing agents, organic solvents, high temperatures, or multiple purification stages. Green synthesis methods explore water-based processing, biological extracts, renewable precursors, and lower-energy reaction conditions. Plant-mediated synthesis, for example, uses biomolecules present in plant extracts to assist the formation or stabilization of selected nanoparticles.

Biomass-derived carbon and biopolymer-supported catalysts are other promising research areas. However, the term “green synthesis” should be applied cautiously. Natural extracts can vary in composition, and the resulting materials may require extensive washing, calcination, or chemical treatment. Nanoparticle toxicity, release into the environment, and end-of-life management also require investigation. A comprehensive evaluation should compare the full synthesis process with conventional alternatives rather than judging sustainability from the use of a biological reagent alone.

9. Integration of Renewable Energy with Green Chemical Manufacturing:

Renewable electricity can support chemical manufacturing through electrified heating, electrochemical synthesis, hydrogen production, and other processes. Such integration may reduce dependence on fossil fuels when the electricity supply is sufficiently low-carbon.

9.1 Renewable-powered electrochemistry

Electrochemical methods can produce hydrogen and selected chemicals using electricity rather than relying exclusively on conventional thermal or reagent-intensive routes. Their sustainability depends on electrode efficiency, electricity source, electrolyte management, separation requirements, and equipment lifetime.

9.2 Solar-driven chemical transformations

Solar thermal and photochemical processes can supply energy for selected reactions. Photocatalytic systems may enable transformations under relatively mild conditions, although their practical efficiency and ability to scale up must be established for each application.

9.3 Low-carbon industrial processes

Industries can reduce their environmental impacts through energy-efficient equipment, heat recovery, renewable electricity, improved catalysts, and recycling of solvents and process water. Green chemistry helps identify opportunities to reduce hazardous inputs and unwanted by-products, while renewable energy can lower emissions associated with process energy.The greatest benefits are likely when cleaner raw materials, efficient chemistry, renewable energy, and circular resource management are designed together from the beginning.

10. Environmental and Economic Assessment:

A technology should not be considered sustainable solely because it uses renewable energy or a naturally derived material. Its environmental performance must be assessed across its life cycle. Life-cycle assessment can evaluate resource extraction, manufacturing, transportation, operation, and end-of-life treatment. Relevant indicators may include greenhouse gas emissions, energy consumption, water use, toxicity, resource depletion, and waste generation. Green chemistry metrics can complement life-cycle assessment. Examples include atom economy, reaction yield, the environmental factor (E-factor), and process mass intensity. These metrics measure different aspects of chemical efficiency and should be interpreted together rather than used in isolation. Economic feasibility is also important. The cost of raw materials, energy, catalysts, equipment, maintenance, recycling, and waste treatment affects the commercial viability of sustainable technologies. A process that uses a less hazardous reagent may offer occupational and environmental advantages, but its full economic and technical performance must still be demonstrated. For this reason, comparisons between technologies should use consistent system boundaries, clearly stated assumptions, and reliable experimental or industrial data.

11. Major Challenges:

Despite substantial progress, several challenges limit the integration of green chemistry and renewable energy.

11.1 Material availability and critical elements

Some energy technologies depend on elements with limited supply, geographically concentrated production, or environmentally damaging extraction routes. Research into abundant-element catalysts, alternative electrode chemistries, material substitution, and recycling is therefore important.

11.2 Stability and durability

Catalysts, electrodes, photovoltaic materials, and other functional materials can degrade during operation. Short lifetimes increase replacement needs and may offset environmental benefits. Research must focus on stability under realistic operating conditions, not merely initial laboratory performance.

11.3 Energy-intensive synthesis

Some advanced materials require high-temperature treatment, complex purification, or multiple processing stages. These requirements can reduce the benefits of an otherwise promising material. Lower-energy synthesis and renewable-powered processing deserve greater attention.

11.4 Scale-up and reproducibility

A successful laboratory experiment may not translate directly into industrial production. Large-scale systems require consistent quality, safe operation, reliable supply chains, and manageable costs. Green synthesis methods must be tested for reproducibility and performance at relevant scales.

11.5 Water use and environmental trade-offs

Hydrogen production, biomass processing, and material manufacturing may require substantial water or generate contaminated wastewater. The environmental consequences depend on local water availability, process design, and treatment methods.

11.6 Recycling and circularity

Many renewable energy technologies are designed primarily for performance and cost, with limited attention to repair, disassembly, and recycling. Future material design should consider the entire life cycle from the initial selection of raw materials to recovery at end of life.

12. Future Perspectives:

Future progress will depend on closer collaboration among chemists, materials scientists, chemical engineers, environmental scientists, and energy researchers. First, research should prioritize catalysts based on abundant and less hazardous elements while improving activity and durability. Second, waste biomass and other renewable feedstocks should be investigated as sources of chemicals, carbon materials, and energy carriers, with careful attention to competing uses and life-cycle impacts. Third, advances in electrochemistry and photocatalysis may improve the conversion of renewable electricity or sunlight into fuels and useful chemicals. Fourth, battery and solar-cell design should increasingly incorporate repairability, recyclability, and reduced dependence on critical raw materials. Artificial intelligence and computational chemistry may also accelerate the identification of promising catalysts and functional materials. However, computational predictions must be validated experimentally and assessed for practical manufacturability. Finally, future studies should report transparent and comparable sustainability metrics. Standardized evaluation of energy demand, material efficiency, toxicity, water consumption, and greenhouse gas emissions would make it easier to identify technologies that deliver genuine environmental improvements.

13. Conclusion

Green chemistry and renewable energy represent complementary approaches to sustainable development. Renewable energy technologies can reduce dependence on fossil fuels, while green chemistry can improve the environmental performance of the materials and processes used to produce, convert, and store energy. This review has examined the relevance of green chemistry to solar energy, green hydrogen, biomass conversion, catalysis, nanomaterials, and electrochemical energy storage. The use of renewable feedstocks, safer reagents, efficient catalysts, waste valorisation, and recycling can help reduce environmental burdens associated with these technologies. Nevertheless, the sustainability of an energy system cannot be established by a single feature, such as renewable electricity or a biomass-derived material. Material availability, process energy, toxicity, water consumption, durability, economic feasibility, and end-of-life management must all be considered. Future research should integrate green chemistry principles with life-cycle assessment and practical engineering requirements. Such an approach can support the development of cleaner chemical processes, more sustainable materials, and reliable low-carbon energy technologies. Ultimately, the integration of green

chemistry and renewable energy offers a valuable scientific pathway toward a resource-efficient and environmentally responsible future.

References

1. Anastas, P. T., & Eghbali, N. (2010). Green chemistry: Principles and practice. Chemical Society Reviews, 39, 301–312. https://doi.org/10.1039/B918763B
2. United States Environmental Protection Agency. Basics of Green Chemistry. https://www.epa.gov/greenchemistry/basics-green-chemistry
3. Beach, E. S., Cui, Z., & Anastas, P. T. (2009). Green chemistry: A design framework for sustainability. Energy & Environmental Science, 2, 1038–1049. https://doi.org/10.1039/B904997P
4. Kharisov, B. I., Kharissova, O. V., & Méndez, U. O. (2019). Greener synthesis of chemical compounds and materials. Royal Society Open Science, 6, 191378. https://doi.org/10.1098/rsos.191378
5. Kurul, F., Doruk, B., & Topkaya, S. N. (2025). Principles of green chemistry: Building a sustainable future. Discover Chemistry, 2, Article 68. https://doi.org/10.1007/s44371-025-00152-9
6. Bhatt, M. (2026). Integrating green chemistry into electrochemical energy storage: A review of bio-synthesized transition metal oxides. Electron. https://doi.org/10.1002/elt2.70031
7. Carbon-based materials derived from green and sustainable chemistry: Current perspectives for electrocatalysis and energy applications. (2025). Renewable and Sustainable Energy Reviews, 222, 116001. https://doi.org/10.1016/j.rser.2025.116001
8. Ding, Y., Li, Z., Zheng, R., Zhao, H., and colleagues. (2026). Advanced photocatalysts for synergistic pollutant elimination and clean energy evolution. Journal of Energy Chemistry, 116, 875–892. https://doi.org/10.1016/j.jechem.2026.01.045