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Green Chemistry in Renewable Energy Technologies: A Review of Materials Processes and Challenges

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Abstract
An energy technology should be judged by the service it provides and by the chemical burdens incurred in providing that service. This review applies that perspective to solar cells, hydrogen generation, biomass processing, electricity storage, and material recovery. Selected publications from 2008–2025 are examined through three questions: what chemical intervention was demonstrated, what limitation remained, and what evidence would support a broader sustainability claim? The examples reveal a recurring gap between a successful material or reaction and a demonstrably sustainable system. Lead capture in photovoltaics addresses release but still requires a recovery pathway. Improved water splitting must be considered alongside reactor conditions and gas separation. Renewable carbon feedstocks and aqueous electrolytes offer useful design options, yet their processing inputs and dissolved components remain relevant. The review brings these observations together in an assessment framework that links synthesis, operation, durability, and recovery to a specified energy output. It identifies transparent material balances, realistic operating tests, and sensitivity to service life as priorities for future studies. The resulting interpretation is that green chemistry contributes most effectively when a chemical improvement is evaluated within the complete energy pathway, rather than inferred from a single ingredient or laboratory performance value.

Keywords: *green chemistry; renewable energy; photocatalysis; biofuels; energy storage; sustainable solvents; circular economy.*

Introduction

The increasing demand for clean and sustainable energy has accelerated research on photovoltaic cells, solar-driven hydrogen production, biomass-derived fuels, electrochemical energy storage, and recycling of energy materials. Although renewable-energy technologies reduce dependence on fossil resources, their development and operation still require solvents, catalysts, electrolytes, precursor chemicals, and functional materials. Consequently, the environmental performance of an energy technology depends not only on its renewable energy source but also on the chemistry used during material preparation, processing, operation, and end-of-life treatment. Green chemistry provides a preventive approach for reducing hazardous substances, waste generation, resource consumption, and unnecessary energy requirements during chemical and materials development [1]. Solvent selection is an important component of green chemical design. The CHEM21 solvent-selection guide provides health, safety, and environmental criteria for choosing appropriate reaction media [2]. Material-efficiency concepts such as the E factor further help evaluate waste generation and resource utilization during chemical processing [3]. These principles are particularly relevant to renewable-energy materials because synthesis, purification, and processing can contribute significantly to their overall environmental burden.

Photovoltaic research illustrates the relationship between materials performance and environmental considerations. Kojima et al. demonstrated the potential of organometal halide perovskites as visible-light sensitizers for photovoltaic cells [4]. However, the presence of lead in many efficient perovskite compositions creates concerns regarding possible release during damage and disposal. Li et al. addressed this issue through an on-device lead-sequestration strategy [5]. Hydrogen research has similarly emphasized earth-abundant catalysts [6], efficient photocatalytic water splitting [7], and scalable systems for separated hydrogen and oxygen production [8]. Biomass provides a renewable carbon source for fuels and chemicals. Luterbacher et al. demonstrated solvent-assisted biomass conversion using γ-valerolactone-based processing [9], while Kouzu et al. investigated calcium oxide as a heterogeneous catalyst for biodiesel production [10]. In energy storage, Suo et al. developed a highly concentrated aqueous electrolyte with an expanded electrochemical stability window [11], while Wang et al. demonstrated biomass-derived carbon nanosheets for supercapacitor electrodes [12]. Battery

recycling represents another important application, with Harper et al. emphasizing the importance of collection, dismantling, separation, and material recovery in lithium-ion battery recycling [13].

Green chemistry provides a useful framework for evaluating renewable-energy technologies because the environmental benefit of an energy source can be affected by the chemicals and materials required to manufacture, operate, and recover the technology. Safer solvents, earth-abundant catalysts, renewable feedstocks, lower-energy processing, durable materials, and effective recovery can reduce environmental burdens across the technology life cycle. Therefore, renewable energy and green chemistry should be considered complementary approaches rather than independent concepts.

Review Scope and Approach

This paper is a selective narrative review, not a systematic review or meta-analysis. Targeted web searches conducted on 4 October 2026 used combinations of green chemistry, solvent selection, perovskite photovoltaics, water splitting, biomass conversion, aqueous electrolytes, supercapacitors, and battery recycling. Publisher pages, accessible research articles, and bibliographic abstracts were used to verify representative findings and citation details. The selected publications span 2008–2025 and include foundational reviews and experimental studies; they do not constitute an exhaustive survey through 2026.

Sources were selected for a direct connection between chemical design and energy conversion, storage, or material recovery. Where only an abstract or publisher preview was accessible, discussion is limited to the reported information. No pooled performance estimate or ranking is attempted because the studies differ in scale, operating conditions, and measurement boundaries. The evaluation framework and research priorities below are the analytical synthesis of this review, rather than new experimental results.

Experimental and Reported Work

Representative experimental studies covering photovoltaic materials, solar hydrogen, biomass conversion, energy storage, and battery recycling were considered. In photovoltaic research, an organometal halide perovskite solar cell achieved 3.8% conversion efficiency, demonstrating the potential of perovskite materials for solar-energy conversion. An on-device lead-sequestration approach was subsequently developed to reduce the potential release of lead from perovskite solar cells. For solar hydrogen production, photocatalytic water splitting was investigated using semiconductor and earth-abundant catalyst systems. An InGaN-based system achieved 9.2% solar-to-hydrogen efficiency under concentrated sunlight and 6.2% under natural sunlight at larger scale. A separate scalable system using separated hydrogen and oxygen production reported a weekly average solar-to-hydrogen efficiency of 1.21% with a 692.5 cm^2 active area. Biomass conversion studies demonstrated the use of γ-valerolactone, water, and dilute sulfuric acid for biomass processing, giving 70–90% soluble carbohydrate recovery. Calcium oxide was also investigated as a heterogeneous catalyst for soybean-oil transesterification to produce biodiesel. In electrochemical storage, a concentrated aqueous electrolyte provided an electrochemical stability window of approximately 3 V and enabled a lithium-ion cell operating at about 2.3 V. Biomass-derived interconnected carbon nanosheets prepared from hemp bast fiber were also investigated as supercapacitor electrode materials. For circular material use, lithium-ion battery recycling studies considered the sequence of collection, handling, dismantling, separation, and material recovery. Together, these reported works demonstrate different approaches for improving renewable-energy materials and processes through material selection, catalytic conversion, safer chemical systems, renewable feedstocks, improved electrolytes, and recovery of valuable materials.

Comparative Results and Discussion

Overall comparison of the reported studies shows that green-chemistry improvement is technology-specific. In photovoltaic systems, the major concern is the management of hazardous constituents, whereas hydrogen production requires attention to catalyst abundance, operating conditions, gas separation, and system scale. Biomass conversion emphasizes solvent selection, catalyst recovery, and separation requirements, while energy-storage systems require consideration of electrolyte composition, electrode preparation, and service life. Battery

recycling extends these considerations to the end-of-life stage, where recovery yield alone is insufficient without adequate purity and practical reuse. Thus, no single parameter can define the sustainability of a renewable-energy technology. A meaningful assessment should combine chemical inputs, energy demand, performance, durability, and material recovery.

Three recurring relationships emerge from the selected examples. First, changing a chemical input affects the downstream processing required to make it useful. Second, improving a material property affects sustainability only through the performance and lifetime of the assembled technology. Third, retaining or recovering a constituent depends on what happens before and after the treatment step. Table 1 maps the reported opportunities to the additional evidence needed. These relationships constitute the comparative interpretation of this review; the table does not claim an environmental ranking.

Table 1. Representative Renewable-Energy Technologies, Reported Results, and Green Chemistry Considerations

Technology	Material/Process	Reported result	Green-chemistry consideration
Photovoltaics	Perovskite solar cell	3.8% efficiency	Material performance and lead management
Photovoltaics	Lead sequestration	On-device lead capture	Hazard containment and recovery
Solar hydrogen	InGaN photocatalyst	9.2% solar-to-H_2 efficiency	Catalyst composition and operating conditions
Solar hydrogen	Scalable separated system	1.21% weekly average efficiency	Scale, gas separation and auxiliary energy
Biomass conversion	γ-Valerolactone process	70–90% carbohydrate recovery	Solvent recovery and separation energy
Biodiesel	CaO catalyst	Soybean-oil transesterification	Catalyst recovery and reuse
Energy storage	Concentrated aqueous electrolyte	~2.3 V cell	Salt loading and electrolyte sustainability
Supercapacitor	Hemp-derived carbon	Carbon nanosheet electrode	Renewable precursor and processing energy
Battery recycling	Material recovery	Collection–separation–recovery pathway	Recovery efficiency, purity and residues

A practical comparison should begin with the output being sought. Electricity delivered over a defined lifetime, hydrogen at a specified purity, and a recovered precursor suitable for manufacture are different outputs. Matching technologies to such outputs helps reveal whether an apparent advantage survives changes in replacement rate, recovery losses, or energy supply. This review recommends showing these dependencies explicitly. Combining unrelated percentages into one score would conceal the differences between reaction success, device performance, and system benefit.

Challenges and Future Research Directions

Future investigations should connect a proposed chemical substitution to its consequences throughout the process. For example, reducing solvent hazard is more persuasive when the same study records purification demand and product yield. Likewise, using less catalyst is more useful when stability and replacement requirements are known. Research designed around these linked measurements can identify the point at which a local improvement becomes a meaningful system improvement. Demonstrations should also test the conditions under which the intended product will be obtained. For hydrogen, those conditions include gas handling and auxiliary power. For solar modules and storage devices, they include aging and realistic configurations. For biomass processes, they include variable feedstocks and repeated operation. Scale introduces new transport, heating, and separation requirements, so it should be evaluated directly rather than treated as a proportional enlargement of a laboratory experiment. The assessment recommended here combines measured inventories with environmental and economic models. Each conclusion should show its dependence on the source of process energy,

expected service life, and material recovery. This avoids assigning a single fixed benefit to a technology whose outcome may change between applications. Costs and environmental burdens should be presented in their own units before trade-offs are discussed. Reproducibility requires enough information to reconstruct both the experiment and its accounting boundary. Useful reporting includes reagent quantities, feedstock composition, recovery fractions, operating time, and the basis used to calculate performance. A focused college laboratory study can contribute by documenting these details for one clearly defined process comparison. Such evidence would support a specific improvement without requiring unsupported claims about the entire renewable energy sector.

Conclusion

The reviewed examples show several ways in which chemistry can improve an energy pathway: managing a hazardous constituent, altering a reaction environment, designing product separation, using a renewable precursor, or recovering a useful material. Each intervention answers a particular technical question. Its broader environmental meaning depends on processing inputs, sustained performance, and the treatment of products and residues. The contribution of this review is to connect these questions through a common assessment sequence from preparation to energy delivery and recovery. Future work should establish those connections with measured inventories and realistic durability tests. Under this approach, green chemistry becomes a method for substantiating improvements in renewable energy technologies, rather than a label inferred from one favorable feature.

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