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Green and Sustainable Chemistry: Simple Approaches for a Cleaner Future

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Abstract

Green Chemistry has been viewed as a necessity to minimize the environmental and health effects that are normally linked to chemical processes. The necessity of incorporation of safer materials, energy-saving practices and reduction of waste has been ever-increasing with the growing intensity of global sustainability problems. This paper aligns green chemistry to be discussed in the context of a broadened set of national and global frameworks, specifically the Sustainable Development Goals (SDGs), the environmental focus of NEP-2020 and India's Viksit Bharat @ 2047 vision, which all contend towards a more responsible scientific approach and cleaner technologies. This paper is aimed at pointing out low-cost green chemistry strategies that are simple and practical, and can be encouraged in educational laboratory settings, community-based enterprises and small businesses. The study examines approaches like an example of using renewable feedstocks, bio-solvents, microscale chemistry, solvent recycling, and low-energy synthesis approaches, all using secondary literature, policy documents, and individual case examples. The most important discoveries illustrate a significant decrease in pollution, toxicity, material use and energy consumption, and better cost efficiency. The obtained findings indicate that green chemistry does not require the use of sophisticated laboratories, and one can productively apply interventions that can be easily found and used on any scale. The paper gives a roadmap of an implementation of green chemistry principles in various contexts, which strengthens the sustainability, innovation and environmental responsibility in the developmental path of India.

Keywords: *Green Chemistry, Sustainability, Renewable Feedstocks, Waste Reduction, Low-Energy Synthesis, NEP-2020, Viksit Bharat 2047*

Introduction

Green and sustainable chemistry refers to the art of developing chemical products and processes that reduce the production and application of toxic substances and enhance efficiency and less environmental degradation. In the past 30 years, this practice has transformed into a complex of useful laboratory rules in a systems approach to relating molecular design, process engineering and lifecycle thinking to global sustainability objectives. According to the recent reviews, this change of focus on hazard reduction to systems-level has been focused on the United Nations Sustainable Development Goals (SDGs) (Constable, 2021).

Figure 1: Principles of Green Chemistry

Source: (Amrita Vishwa Vidyapeetham, 2018)

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The context of global environmental concern, which inspires green chemistry, is also urgent: chemical pollution, untreated industrial and municipal waste, and greenhouse gas emissions are still a threat to the ecosystems and human health. In international evaluations and SDG reports, it can be noted that there are always gaps in waste management and emissions control that can be mitigated with the assistance of green chemical practices (United Nations, 2020).

For developing nations like India, green chemistry is particularly critical because low-cost, low-tech interventions can provide large-scale co-benefits, i.e., less toxic exposure, lowering the cost of disposing of wastes and energy savings, to education, small-scale industry and agriculture. The role of cleaner chemical practices in national development is supported by national strategies of a developed, sustainable India (Viksit Bharat @ 2047), making innovation and adoption of green technology as one of the pillars of economic transformation (Virmani, 2024).

This change is also supported by the education policy: the National Education Policy (NEP 2020) promotes experience-based learning and instruction of sustainability as a part of the curriculum, which could be seen as an obvious step toward incorporating green chemistry into laboratory work and institutional practice. Such alignment between the basic and affordable green chemistry principles and SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) thus serves the interests of both the environmental and the development perspective of the long-term goal of India.

Objectives

- To explore simple, low-cost approaches for promoting green chemistry - techniques that can be adopted in less-resource settings and offer substantial environmental benefit.
- To identify sustainable chemical practices suitable for institutions and small industries, focusing on alternatives such as bio-based solvents, renewable feedstocks, and waste-minimising reaction conditions.
- To analyse the environmental benefits of adopting renewable feedstocks and safer solvents, including reductions in hazardous-waste generation, energy consumption and greenhouse-gas emissions.
- To evaluate the alignment of these practices with global and national frameworks -namely, the SDG 12 (Responsible Consumption & Production), SDG 13 (Climate Action), and national policies such as the NEP 2020 and the vision of Viksit Bharat @ 2047 for a green economy.
- To propose practical recommendations for wider adoption, focusing on implementable steps for laboratories, educational institutions and small industries to integrate eco-friendly chemistry practices affordably and effectively.

Data and Methodology

This research employs the descriptive and qualitative research design in the analysis of feasible solutions to green chemistry, where practical solutions apply in institutions and small companies. The discussion is based on the extensive survey of secondary literature related to open-access peer-reviewed articles, sustainability reports, and international standards, which describes the effect of environmentally responsible chemical practices. It would be wise to take a scientific approach to place finding the low-cost, friendly alternatives through the recent reviews on renewable feedstocks, green solvents, and sustainable reaction pathways (Ganesh, 2021). The alignment of policies is achieved through reviewing the documents associated with the Sustainable Development Goals (SDG 12 and SDG 13) and the national strategies (the National Education Policy (NEP 2020) and the sustainability vision of India under Viksit Bharat @ 2047.

There are three important stages of analysis in the methodology. To begin with, the comparison is made between traditional chemical processes and organic ones, based on some indicators that include waste production, toxicity, efficiency of resources devoted to it, and energy consumed. This comparison is informed by open-access reports of the performance of bio-based solvents, renewable catalysts and low-energy synthesis procedures (Messire et al., 2024). Second, a systematic audit of environmental and operational effects is conducted through the synthesis of case studies of the academic institutions and small-scale industries that have established greener approaches and have been able to show quantifiable enhancements in sustainability results (Pathak, 2022). Third, the findings obtained are simplified into easy-to-implement green practices that could be implemented in laboratory operations, academic programs and industrial operations.

Combined, this methodology process will contribute to the formulation of viable recommendations with respect to the nature of scientific sustainability as well as national policy priorities.

Results and Discussion

Simple Green Chemistry Approaches

As highlighted in this research paper, the renewable feedstocks, especially those derived from biomass, could help as an alternative to the petroleum-based raw materials. The analysis of the recent studies demonstrates that the lignocellulosic biomass, agricultural waste and plant-based polymers are great contributors to the lifecycle emission and toxicity reduction as chemical precursors (Phung Hai et al., 2021). The feedstocks are also able to promote the circular economy as they develop renewable waste into useful intermediates.

Another important outcome is the substitution of the dangerous solvents with a safer group of bio-solvents like ethanol, glycerol and water. Research has documented that bio-solvents reduce the chances of flammability, enhance biodegradation and exposure to toxic organic volatile substances (Xu et al., 2017). They are cheap and generalised to suit small locales, thus appropriate in small laboratories and learning institutions.

Green synthesis energy-efficient techniques, including microwave-assisted and ultrasonic-assisted synthesis, were observed to reduce reaction time, give high yields and reduce energy requirements. Modern open-source studies prove a heating energy reduction of up to 80 percent compared to the traditional reflux systems (Gabano &

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Ravera, 2022). Similarly, green catalysts that are adopted, such as reusable metal catalysts and enzyme-based systems, reduce waste production and increase selectivity. In particular, enzymatic catalysis has proven to be highly efficient under mild conditions, without the use of any toxic reagents and harsh temperatures.

Table 1: Comparative Analysis of Key Green Chemistry Approaches

Green Chemistry Area	Representative Examples	Scientific Advantages	Environmental Benefits	Practical Relevance in Laboratories and Industry
Renewable Feedstocks	Lignocellulosic biomass, agricultural residues, plant-derived polymers	Provide sustainable carbon sources; enable the synthesis of platform chemicals through biochemical or thermochemical processes; reduce reliance on fossil-derived hydrocarbons	Lower lifecycle emissions; reduced precursor toxicity; support circular-economy transitions through valorisation of renewable waste streams	Applicable in biorefineries, polymer manufacturing, fine-chemical production and academic settings exploring sustainable synthetic pathways
Bio-Solvents	Ethanol, glycerol, water and other low-hazard solvent systems	Exhibit favourable physicochemical properties for reaction media; lower volatility and improved material compatibility compared to conventional solvents	Reduced volatile-organic-compound release; enhanced biodegradability; diminished fire and toxicity hazards	Suitable for teaching laboratories, small-scale industries and routine synthesis due to low cost, safety, and general availability
Energy-Efficient Synthesis Techniques	Microwave-assisted reactions, ultrasonic-assisted reactions	Shortened reaction times; improved yields and selectivity; efficient energy transfer mechanisms enabling reactions under milder conditions	Significant decrease in heating requirements; reduced overall energy consumption; minimisation of side-product formation	Usable in constrained laboratory environments; compatible with pharmaceutical, materials and organic-synthesis workflows; reduces operational costs
Green Catalysts	Reusable metal catalysts, enzyme-based catalytic systems	High selectivity and catalytic efficiency; ability to operate at ambient or near-ambient conditions; improved reaction control	Reduction of chemical waste; lower reaction temperatures; elimination of harsh reagents and by-products	Valuable for industrial reaction scaling, biotransformations and sustainable synthesis modules in educational institutions

Waste Reduction Practices

The effectiveness of microscale chemistry is also pointed out as the research applies considerably smaller amounts of reagents without affecting the quality of the experiment. There is evidence that microscale methods are capable of reducing chemical wastes by 50-90 percent, making the disposal of chemicals simpler and safer in scholarly labs (Murcia et al., 2023).

Reagent recycling and reusability became another viable option at the institutional and small-industry levels. Solvents used in recrystallisation, silica, catalysts, and media used in reaction can be reused, and the material costs decreased, as well as unfriendly waste can be minimised. Sustainable synthesis processes have case study examples of reused catalysts that are still active in subsequent cycles (Xiao et al., 2025).

Waste minimisation is further sustained by safe handling and disposal practices with the help of guidelines provided by UNEP (2022). These are segregated waste streams, detoxification procedures and water-efficient cleaning systems, all of which conform to SDG 12 on responsible production (UNEP, 2023).

Energy-Efficient Processes

Energy-focused results have shown that low-temperature reactions can lower the necessary energy requirements and have no impact on the efficiency of the reaction. The reports of green catalytic systems demonstrate impressive conversion rates in the ambient or mild conditions and do not need energy-consuming heating (Wang et al., 2025).

Another viable utilisation is the integration of the solar-powered lab installations, particularly in rural or resource-strained institutions. The solar heaters, photovoltaic systems and solar-assisted distillation units have been tested successfully in Indian academic settings, leading to the reduction of both the operational costs and carbon emissions (Martulli et al., 2022).

In the process of synthesis, unnecessary consumption is identified with the help of energy-measuring tools, including handheld meters and digital monitoring tools, which facilitate the optimisation process. Simple monitoring through recent low-cost energy audits in teaching labs demonstrates that it is possible to cut energy consumption by 20-30 percent simply by monitoring it (Hanifi et al., 2025).

Environmental and Economic Impacts

The combined implementation of these green ways leads to high levels of decreasing pollution, carbon emissions and toxicity. Greenhouse gases are emitted less by renewable feedstocks, as should be SDG 13 (Climate Action), and bio-solvents decrease the risks of chemical exposure. These findings are reinforced by the IPCC (2023), which states that dwindling fossil-fuel reliance will result in a direct decrease in carbon footprints.

Economic benefits also play an important role. In educational institutions practising microscale chemistry and solvent recycling, it has been stated that there are reagent, energy and waste-handling, service-related savings. Solvent-recovery system-based and catalytic-based small industries portend a net decrease in costs and better yields of products (Wen et al., 2022).

Individual case studies in India, particularly in teaching laboratories and cottage-industry production, indicate that green options can not only be made in large-scale manufacturing but also be effective in meeting national sustainability goals.

Table 2: Environmental and Economic Impacts of Key Green Chemistry Interventions

Intervention	Environmental Impact	Economic Impact
Renewable feedstocks	Lower greenhouse gas emissions and reduced fossil dependency	Reduced long-term raw material costs
Bio-solvents (ethanol, water)	Lower toxicity and reduced environmental contamination	Savings on solvent purchase and disposal
Microscale chemistry	Significant reduction in lab waste and emissions	Lower reagent and waste-management costs
Reusable catalysts	Less by-product formation and cleaner reactions	Higher yields and reduced reagent consumption
Solvent recycling	Reduced solvent discharge and contamination	Lower expenditure on fresh solvents
Low-energy synthesis (microwave/ultrasonic)	Reduced process-related emissions and energy use	Lower electricity costs and faster production

Policy and Education Linkages

The results are highly congruent with NEP 2020, which focuses on experiential learning, environmental responsibility and scientific inquiry. Implementing green chemistry units in laboratories will facilitate the NEP requirement of practical, sustainability-driven learning (Ministry of Human Resource Development, 2020). The green chemistry practices are also relevant to SDG 12 and SDG 13, and enhance the interest of India in the global system of sustainability (United Nations, 2023).

Lastly, institutions are also in the middle when it comes to the creation of environmentally responsible behavior.

Conclusion

The implementation of basic and easy-to-scale green chemistry practices portrays apparent environmental and financial benefits. The renewable feedstocks, less toxic solvents, less energy-intensive production and minimisation of waste reduce emissions, poisonousness and consumption as well as decreasing operation expenses. These strategies are feasible in both educational institutions and small industries to support the sustainability priorities of the country and enhance the transition of India to a cleaner chemical ecosystem that is resilient and ready to survive the future.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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