Chapter-16
Challenges of Green Chemistry and Sustainability

Dr. Pratibha Gopalrao Raundal[1],Bhaskar Keval Nikam[2],Sandesh Vasantrao Gaikwad[3]

[1,2,3] Department of Chemistry, K. A. A. N. M. S. Arts, Commerce and Science College, Satana

Email- pratibhabhadane14@gmail.com

Abstract

Green chemistry has emerged as a strategic approach to address the growing challenges of environmental degradation and resource depletion by promoting the design of chemical products and processes that reduce or eliminate hazardous substances. Despite its potential to support sustainable development, the adoption of green chemistry within the chemical enterprise remains limited due to economic, technological, regulatory, and organizational barriers. This chapter critically examines the key challenges hindering the widespread implementation of green chemistry, including issues related to measurement and metrics, industrial lifecycle integration, workforce readiness, and chemical substitution. It highlights the lack of standardized assessment frameworks, the complexity of modifying existing industrial systems, and the need for education and skill development to support safer alternatives. By aligning the principles of green chemistry with global sustainability goals, particularly the Sustainable Development Goals (SDGs), the chapter emphasizes the role of innovative technologies, systems thinking, and policy support in overcoming these barriers. Ultimately, minimizing irreversible and hazardous chemical reactions through sustainable design is identified as the most pressing challenge for advancing green chemistry toward a more resilient and environmentally responsible future.

Keywords:Green Chemistry; Sustainability; Environmental Degradation; Resource Depletion; Economic Barriers; Technological Challenges; Measurement and Metrics; Industrial Implementation; Chemical Substitution; Sustainable Development Goals (SDGs)

Introduction

In recent decades, the twin crises of environmental degradation and resource depletion have sparked widespread concern for global sustainability. Commensurate with this concern, the field of chemistry, with its attendant environmental impacts and resource demands, has also attracted increased scrutiny. Green chemistry, which promotes the design of molecules, materials, and processes with reduced environmental and resource footprints, has emerged as a result. As yet, however, green chemistry remains an underutilized approach within the chemical enterprise. The reasons behind this slow uptake are manifold and include economic, technical, and scientific barriers; cultural, regulatory, and policy constraints; innovation, research and development, and investment shortfalls; and inadequate measurement, assessment, and metrics (Jen

Mendelsohn Matus et al., 2013). In-depth examination of these barriers reveals a comprehensive, systems-level view of the green chemistry challenge.

Green chemistry encompasses both theory and practice, with theory guiding the principles and practice defining the compendium of examples. In addition to specific technical principles of implementation or guidance, there exists a broader, classically philosophical motivation and rationale reflecting on the wider implications for the sustainability debate and its relationship to environmental and economic considerations; societal, equity, and justice concerns; and the contribution of chemical authorities and the broader chemical community to the sustainability discourse showcase the scope that green chemistry occupies at the present time.

Foundational Principles of Green Chemistry

Green chemistry, a systematic approach to sustainable chemical design, evaluates environmental hazards, economic viability, and performance efficacy throughout the chemical lifecycle. The 12 Principles of Green Chemistry provide a comprehensive framework for innovation in product and process design. These principles explicitly address the need to minimize resource and energy consumption and avoid the use of hazardous or toxic materials; thus, they align with global sustainability goals by directly supporting several Economic, Environmental, and Social Objectives (Lynn Koster, 2014).The 12 Principles of Green Chemistry articulate practice-relevant targets and strategies for innovation and reinforce awareness of wider economic and environmental implications stemming from material selection, process choices, and design objectives. By proactively considering these interconnected issues, firms can achieve a competitive advantage and create added value for their customers, society, and the environment. Well-designed products and processes not only reduce harmful residues, effort, and remediation costs but also streamline compliance with registration, evaluation, and authorisation of chemicals (REACH) regulation (BHANDARI, 2018).

12 Principles of Green Chemistry

Prevention

It is better to prevent waste than to treat or clean up waste after it is formed.

Atom Economy

Synthetic methods should maximize the incorporation of all materials used into the final product.

Less Hazardous Chemical Syntheses

Wherever practicable, synthetic methods should use and generate substances with little or no toxicity to human health and the environment.

Designing Safer Chemicals

Chemical products should be designed to be effective while minimizing toxicity.

Safer Solvents and Auxiliaries

The use of auxiliary substances (solvents, separation agents, etc.) should be made unnecessary or innocuous when used.

Use of Renewable Feedstocks

Raw materials should be renewable rather than depleting whenever technically and economically practicable.

Reduce Derivatives

Unnecessary derivatization (blocking, protecting groups, temporary modification) should be minimized or avoided.

Catalysis

Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.

Design for Degradation

Chemical products should break down into harmless substances after use and not persist in the environment.

Real-time Analysis for Pollution Prevention

Analytical methodologies should allow real-time monitoring and control to prevent formation of hazardous substances.

Inherently Safer Chemistry for Accident Prevention

Substances and processes should minimize the potential for chemical accidents, including releases, explosions, and fires.

Economic and Policy Barriers

Economic barriers prevent the uptake of green chemistry by the chemical industry and other enterprises. Challenges arise from a countervailing financial framework, lacking materials and products to test, non-sustainability concerns, and the lack of available certification to assure concerned societies when implementation requires allocation of funds (Matus et al., 2017). Agents that acted previously to favour the principles of green chemistry are less conspicuous nowadays because economic consideration gains precedence in operator decision-making. The well-being of principals takes priority over prior concerns. With green chemistry entailing a process change to make human health less dubious, the lack of imminent death, the immediacy of economic return, and the preference for prioritizing return to the firm rather than society at large all plague the implementation of green chemistry (Jen Mendelsohn Matus et al., 2013).

Technological and Scientific Hurdles

Green chemistry is a preparation and methodology of making substances especially chemicals with minimum hazard to human health and the environment. Green chemistry was devised in the 1990s by Paul T. Anastas and John C.. Warner to cover all aspects of a chemical process: starting materials, reagents, solvents, final products, and degradation products (Matus et al., 2017). The 12 principles of green chemistry are designed to assist chemists begin a greener process which does not need to comply with these principles. Consequently, these principles should not appear as constraints, but as help in achieving greener chemical processes.Exemplary progress was made, e.g., a bio-based plastic for food packaging, pesticides targeting pests and harmlessly biodegrading, an effective fire extinguishing agent combining water and surfactants, solvents using liquid carbon dioxide for chip manufacturing, elimination of arsenic from wood preservatives, and replacement of lead with yttrium in coatings (Jen Mendelsohn Matus et al., 2013). Yet, the diffusion of green chemistry remains low due to its disruptive nature and various barriers.

Measurement, Metrics, and Assessment

Green Chemistry faces considerable adoption challenges due in part to the variable definitions and metrics used among stakeholders (Matus et al., 2017). The terms “green chemistry”, “chemical sustainability”, “green engineering”, and “sustainable development” are often used interchangeably, leading to misunderstandings. The lack of a clear metric for, or certification of, green chemistry further complicates matters, preventing effective environmental claims from being established or verified. Green Chemistry, properly understood, is a methodology for implementing systems thinking rather than a set of concrete, universally applied objectives. Its intrinsically complex, nature—comprising multiple interacting parameters that vary among projects—poses additional barriers to standardized definitions and assessment (Jen Mendelsohn Matus et al., 2013).The 12 Principles of Green Chemistry were developed to facilitate the application of Green Chemistry and to support the systematic assessment of chemical processes. However, as reflected in their terminology, both the principles and their associated metrics remain open to interpretation. To date, no integrated, multi-metric framework for measuring quantified progress across the twelve principles has been published. Hence, an assessment of the practical indicators proposed for, and the complementary methodologies employed to address, individual principles is timely.

Industrial Implementation and Lifecycle Considerations

Adopting green chemistry involves significant organizational and system-wide challenges, with hurdles beyond the technology and measures that enter mainstream discussions (Matus et al., 2017). Existing processes at pilot or commercial scale may not stay within safety, risk, or budget targets; infrastructural replacement or adaptation becomes difficult; and even a minor change to any given stage in the operation (input, output, machinery, etc.) impacts every unit across the operation’s footprint, period, and ecosystem (Jen Mendelsohn Matus et al., 2013) , thwarting the desired control and flexibility. Large supply chains, platforms, or ecosystems covering multiple operations, products, or activities introduce similar issues on a wider albeit similarly concentrated scale. Transfer to alternative outlets or upstream decentralization permits parallel pilot testing and the pursuit of further incremental improvements, enabling operations to shift only once rigorous validation at full scale confirms meeting every target remains achievable at that outlet. Pursuing only alternative throughput without maintaining the prior one complicates such transfer; a straightforward replacement can produce cascading failure throughout a large organization, as switching from one prime-product pathway to another in a large set of operations jointly relied on a single connected fuel pathway enduring unharmed proved only the first step. Even acquisitions by existing organizations with ostensibly compatible expansions may cascade further failures. The connectivity multiplied by scale amplifies the occurrence of cascading challenges, creating vulnerabilities against disruptive change that address typical organizational-level notions of inherent value. Further complexity arises if the existing organization operates on a mutual-collaboration model common in far larger-scale endeavors where individual organizations typically address only their immediate or local challenges.

Education, Skills, and Workforce Readiness

Sustainability science highlights the need to align human activities with the capacity of the biosphere to maintain a habitable environment. Chemicals are central to most life activities on Earth; yet, chemical handling is done unsafely, re-neglecting to perform green chemistry practice accordingly. Institutional practices lead to inefficient selection and substitution of safer alternatives; thus, fostering the supply of green chemistry chemical is required to substitute and then remove hazardous chemicals from further production. Approaching chemical substitution requires a three-step selective process: removal of undesirable properties; determination of suitable replacement; and screening of safer substitutes for the compound of concern. Actionable steps comprise inventorying hazardous environmental, health,, and safety (EHS) properties of globally marketed chemicals; providing a catalogue of commercially available substitutes; and developing a ranking model, aided by product-specific EHS screening guides. (A. Lasker et al., 2019)

Case Studies of Practice and Failure

As with the 12 Principles of Green Chemistry, nearly every activity—both scholarly and industrial—that is environmentally pre-sorted is subject to the human whims of case study selection and citation. It is easy to select cases that reinforce a prescriptive agenda or to focus on instances in which antecedent projects preclude the screen for subsequent initiatives. Many major institutional and corporate policy narratives contain one or more project examples that advance politically supported goals at the exhibited expense of other potentially superior measures. Certain economic incentives accrue unobserved when criteria-driven project and portfolio selections are radically constrained. A documented example of an industrial failure (Jen Mendelsohn Matus et al., 2013) remains relevant; it is hoped that a more sustainable selection also is feasible. Human consumption feeds upon energy and materials harvested from nature, and all remains subject to the fate of geological processes over tens of millions of years.

Emerging Trends and Opportunities

Green chemistry embraces new technologies that foster the flow of materials–energy–information without destructive transformations, providing society with sustainable solutions for clean water, clean air, clean energy, waste removal, food preparation, disease control, and information access. New sustainable technologies span wide disciplines–from optimization theory, network theory, expert systems, and operations research to modern biology, neuroscience, synthetic biology, nanotechnology, and carbon–neutral design, green chemistry represents only a small part of the vast horizon that civilized society will explore. Nevertheless, as each country, city, company, organization, and household sets out to achieve a Sustainable Development Goal (SDG), each can align its efforts with green chemistry. Because green chemistry minimizes environmental footprint, pollutant release, energy usage, and resource depletion while enhancing safety, reliability, and economic–social–technological development, its principles, concepts, and practices can play a major role in such endeavors.

Conclusion

The pace of global change is accelerating and to what extent can chemistry be used to positively influence change and the way in which chemistry can lead to sustainable, safe societal systems for humans and the environment is arguably the most challenging intellectual problem facing the discipline. However, in order to arrive at any solution, the question of why current practices are unsustainable or cause harm must first be established. The 21st century has been characterised by increasing urbanisation, proliferation of synthetic molecular systems and the exponential increase of harmful waste disposal especially as a consequence of societal and consumer legislation.

References:

1. Jen Mendelsohn Matus, K., C. Clark, W., T. Anastas, P., & B. Zimmerman, J. (2013). Barriers to the Implementation of Green Chemistry in the United States.
2. Lynn Koster, M. (2014). Green Chemistry.
3. BHANDARI, S. U. N. E. E. T. A. (2018). APPLICATIONS OF GREEN CHEMISTRY PRINCIPLES IN AGRICULTURE.
4. Matus, K., T. Anastas, P., C. Clark, W., & Itameri-Kinter, K. (2017). Overcoming the Challenges to the Implementation of Green Chemistry.
5. Lasker, G., E. Mellor, K., & J. Simcox, N. (2019). Green chemistry & chemical stewardship certificate program: a novel, interdisciplinary approach to green chemistry and environmental health education. ncbi.nlm.nih.gov