

FROM LAB TO NATURE

ADVANCEMENTS IN GREEN SYNTHESIS METHODS IN CHEMISTRY

Editors:
Smriti Dewangan
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From Lab to Nature: Advancements in Green Synthesis Methods in Chemistry

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FOREWORD

It is a privilege to write the foreword for *From Lab to Nature: Advancements in Green Synthesis Methods in Chemistry*, a remarkable contribution to the field of sustainable chemistry. In today's world, when environmental awareness is critical, this book is an invaluable resource for researchers, academics, and industry experts looking to incorporate eco-friendly ideas into chemical synthesis.

Green synthesis is transforming the way we approach chemistry by replacing hazardous ingredients with ecologically friendly alternatives while maintaining efficiency and sustainability. This book delves into modern green synthesis techniques, including biomimetic synthesis, catalytic improvements, solvent-free reactions, and renewable feedstocks. It emphasizes the importance of green chemistry in creating a cleaner, more sustainable future by connecting lab research with real-world applications.

This book's capacity to close the gap between theoretical understanding and real-world applications is one of its strongest points. For researchers, academics, and business executives dedicated to implementing environmentally responsible practices in chemical synthesis, it is a priceless resource. In addition to educating readers, this book encourages greater creativity in green chemistry by showcasing the latest developments and case studies. The author has painstakingly gathered a wealth of information, providing readers with both foundational ideas and the most recent developments in the subject. This book is a source of inspiration for future advancements in sustainable chemical techniques and an academic resource.

I want to express my gratitude to the author for this important contribution and hope that it will motivate and direct scientists, researchers, and students toward more environmentally friendly scientific pursuits.

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PREFACE

Chemistry has always been a driving force in scientific progress, industrial development, and improvements in life. However, traditional chemical synthesis often relies on hazardous chemicals, produces toxic byproducts, and employs energy-intensive processes that endanger the environment and human health. In response to these issues, green chemistry has evolved as a transformational strategy that prioritizes sustainability, efficiency, and responsible resource use.

From Lab to Nature: Advances in Green Synthesis Methods in Chemistry is a thorough examination of the most recent developments in environmentally friendly chemical processes. This book explores several elements of green synthesis, such as solvent-free reactions, biomimetic techniques, catalytic improvements, and the utilization of renewable feedstocks. By emphasizing these sustainable solutions, the book hopes to bridge the gap between traditional practices and modern eco-friendly methodologies. The inspiration for this effort derives from the growing global need to reduce the environmental imprint of chemical companies while retaining the efficiency and efficacy of synthetic processes. This book will help researchers, academics, and professionals grasp the principles and applications of green synthesis. The debates here not only offer theoretical insights but also emphasize practical applications that can be incorporated into academic research and industrial practice.

I truly hope that this book will serve as an inspiration to scientists, students, and professionals seeking new, long-term solutions in chemistry. By embracing green synthesis, we can work together to make the world cleaner, safer, and more sustainable.

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CHAPTER 1

Introduction to Green Chemistry and its Environmental Imperative

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Abstract: Green chemistry is a transformative field focused on designing products and processes that minimize or eliminate the generation and use of hazardous substances. Its primary goal is to enhance resource efficiency, reduce environmental impact, and promote sustainability across industrial practices. Guided by twelve core principles, green chemistry encourages the use of renewable raw materials, safer solvents, mild reaction conditions, and waste minimization. It also emphasizes atom economy—maximizing the incorporation of starting materials into final products, to reduce by-products and resource loss. Rather than “constructing chemical reactions with weaker bonds,” green chemistry focuses on designing efficient, selective reactions under milder conditions, using catalysts and renewable feedstocks. These strategies help industries reduce emissions, avoid toxic intermediates, and move toward circular economy models. By integrating energy efficiency and safer chemical design, green chemistry provides innovative pathways to address global challenges such as pollution, climate change, and resource depletion.

Keywords: Bio-based chemicals, Biocatalysis, Catalyst, Environmental impact, Feedstock, Green chemistry, Green synthesis, Green solvents, Hazardous substance reduction, Mild reaction conditions.

INTRODUCTION

Green synthesis is focused on developing chemical reactions so that they are less harmful to the environment, yet effective and economical. Through all these principles, atom economy, catalysis, and optimization of reactions, clean

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production pathways are reinforced to accommodate the increasing need to be sustainable with regard to industrial activities [1]. Advances in green technologies—such as microwave-assisted synthesis, supercritical fluids, and biocatalysis—have enabled the production of specialty materials, agrochemicals, and pharmaceuticals while reducing environmental impact. Green synthesis provides guidelines for the chemical industry to address major issues such as resource depletion, global warming, and environmental degradation [2, 3]. Green chemistry is an emerging paradigm that tries to find optimal synthetic pathways, minimize waste, and conserve resources by using benign reagents, safer solvents, and renewable feeds [4, 5].

Concept of Green Synthesis

This has influenced the creation of environment friendly, efficient, and safe processes [6]. (Fig. 1) illustrates the basics of green synthesis. The figure highlights key points, including preventing waste formation, maximizing reactant utilization through atom-economy, and safer chemical design to reduce toxicity without affecting product performance. It also considers the principle of energy efficiency and highlights chemical reactions under mild conditions or the use of alternative energy sources, such as microwave or ultrasonic irradiation. Combined, these principles show the extent to which green synthesis can align with sustainability and pollution prevention objectives.

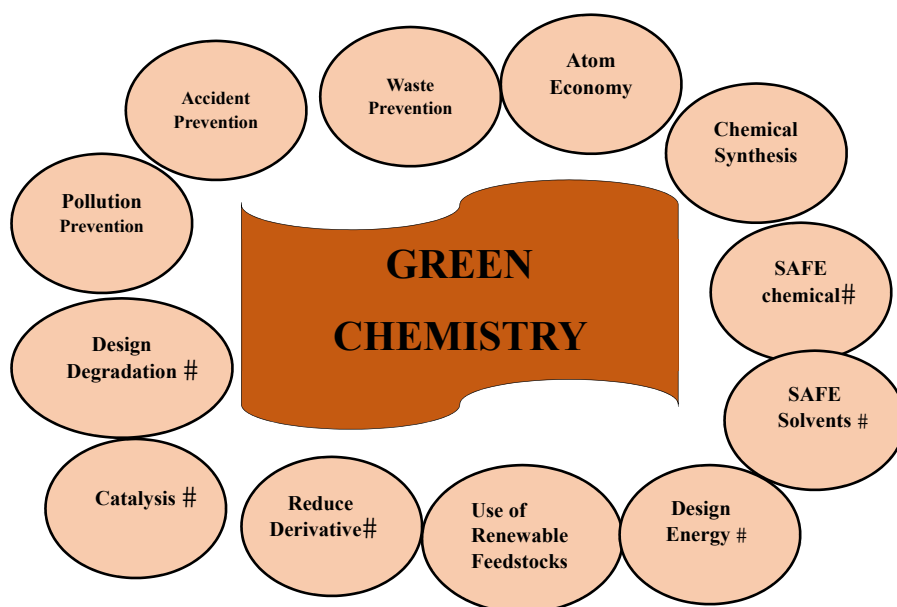


Fig. (1). Concept of green synthesis.

- Prevention: Design efficient synthetic pathways that generate minimal by-products and have minimal environmental impact to prevent waste [7].
- Atom Economy: Use reactants as efficiently as possible to maximize product yield while minimizing waste [8].
- Less Hazardous Synthesis of Chemicals: Use reaction paths and intermediates that are less toxic to human beings and the environment [9].
- Designing Safer Chemicals: Reduce the toxicity of products and maintain their functionality and performance [9].
- Safer Solvents and Auxiliaries: Reduce or substitute hazardous solvents with more greener solvents like water, ionic liquids, or supercritical CO₂ [10].
- Energy Efficiency: Conduct reactions at ambient temperature and pressure whenever feasible or employ other forms of energy like solar, microwave, and ultrasonic energy [11].
- Renewable Feedstock: Use Biomass or another renewable resource as a source of raw material to decrease dependence on fossil resources [11].
- Reduce Derivatives: Avoid unnecessary derivatization steps that generate additional derivatives [12].
- Catalysis: Catalytic reagents should be used instead of stoichiometric reagents to increase efficiency and reduce waste [12].
- Design to Degradation: Design products that can be dismantled into non-toxic, biodegradable products [13].
- Real-Time Analysis of Pollution Prevention: Introduce monitoring devices that detect and prevent the formation of by-products during reactions [11].
- Safer Chemistry (Accident Prevention): Designing processes to minimize the risks of explosions, fires, and hazardous releases [14].

IMPORTANCE OF GREEN SYNTHESIS

Green synthesis is a contemporary approach to chemical synthesis that aims to design and produce chemical compounds with minimal adverse ecological effects by utilizing environmentally friendly procedures [15]. The initiative enhances sustainability of chemical operations through the incorporation of green chemistry ideas that aim at reducing the number of toxic substances, maximizing use of energy, and using renewable materials. Green synthesis aims to optimize reaction efficiencies, minimize waste and other environmental hazards through safer and greener alternatives, including bio-based materials, catalyst, and energy-efficient procedures, as opposed to the hazardous reagents and other conventional solvents [16]. It is a sustainable and environmentally friendly approach to the synthesis of chemicals and is required in the current field of chemistry [17]. The project is expected to reduce potential hazards to the environment and human health arising from chemical processes by following green chemistry guidelines. This is done by using renewable raw materials, reducing energy use, and producing less harmful

CHAPTER 2

Fundamentals of Green Synthesis: Laboratory to Industrial Perspective

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Abstract: Green synthesis prioritizes reliable and environmentally friendly methods characterized by mild reaction conditions, non-toxic precursors, and minimal waste generation. By applying the principles of green chemistry, it becomes possible to design novel, safe, reusable, and biodegradable products. Solvent-free techniques and green solvents, particularly water, have been successfully employed for the synthesis of drugs and nanoparticles. Natural extracts from plant parts (leaves, roots, flowers, and fruits) and biomolecules derived from bacteria, algae, and fungi act as reducing and stabilizing agents in nanoparticle synthesis, enhancing both safety and sustainability. This chapter provides an overview of green synthesis, assessing laboratory performance in terms of yield, purity, and environmental impact, while also addressing scalability, cost-effectiveness, and industrial feasibility. Additionally, it discusses the role of eco-friendly methods in drug delivery systems, where controlled or sustained drug release improves patient compliance and reduces side effects. By identifying new opportunities for collaboration, emerging markets for green products, and potential research directions, this chapter highlights how green synthesis supports sustainable development and reduces the environmental footprint of chemical processes.

Keywords: Algae, Bacteria, Biometabolites, Catalytic mechanisms, Green chemistry, Green synthesis, Microwave-assisted synthesis, Nanoparticles, Natural extracts, Renewable feedstocks.

INTRODUCTION

Green Synthesis (GS), a core pillar of green chemistry, represents an environmentally sustainable approach to chemical manufacturing that reduces or

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eliminates hazardous substances in the production of compounds, particularly nanomaterials, while promoting resource efficiency, minimizing energy consumption, and reducing waste [1]. In pharmaceutical contexts, GS often involves the use of green solvents and plant-derived extracts, aligning with the broader Green Chemistry (GC) framework, which seeks safer, more sustainable alternatives to conventional processes [2]. The key philosophy of GC is pollution prevention at the source rather than mitigation after waste is generated. GS fulfills this goal through environmentally benign techniques that utilize non-toxic, renewable, and biodegradable feedstocks, often derived from microorganisms (bacteria, fungi, algae) or plant materials (leaves, roots, seeds, fruits, stems, flowers) [3]. Compared with traditional synthesis methods—reliant on toxic solvents, high energy inputs, and hazardous reagents—GS offers safer reaction pathways with reduced environmental risk. A significant industrial application of GS is in nanomaterial synthesis, where biological systems serve as reducing and stabilizing agents. Such methods produce nanoparticles with improved biocompatibility, lower energy requirements, and minimal harmful by-products. Given increasing concerns over resource depletion, climate change, and industrial pollution, GS has become a strategic route for sustainable development [4]. Integration of GS with chemical engineering innovations, such as waste-free processing, bio-based materials, and renewable energy, supports global sustainability targets while improving industrial productivity and cost efficiency.

This chapter emphasizes the translation of GS from laboratory research to large-scale manufacturing, detailing its core technologies, industrial adoption pathways, and its transformative role in reducing the environmental footprint of chemical production [5]. These twelve principles of green chemistry, as applied in laboratory synthesis, are summarized in Fig. (1).

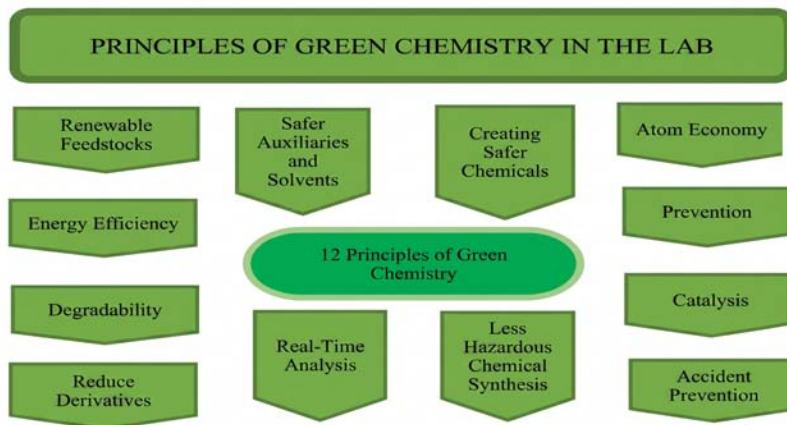


Fig. (1). Twelve principles of green chemistry in the laboratory.

CHAPTER 7

Photocatalysis and Electrocatalysis in Green Chemistry

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Abstract: A new age of green chemistry has started with the introduction of photocatalysis and electrocatalysis, giving us safe and green methods for various chemical reactions. This chapter explains the important ideas, tools, and methods these catalytic technologies use to promote green chemistry. It covers the important basics of photocatalysis, including producing active oxygen species and using them for tasks like cleaning polluted water, breaking water into hydrogen and oxygen, and forming chemicals in a green way. This section also focuses on electrocatalysis and presents specific methods, particularly electrochemical reduction and oxidation processes, that help reactions perform effectively and accurately. The combination of electrocatalysts with renewable power sources highlights their importance for sustainability. A description of industrial applications that focus on removing pollutants and making new, valuable chemicals, as well as progress made in the field of making catalysts from both single and multiple materials, is given. In addition, the chapter explains problems associated with catalyst stability and with scaling up the process, and proposes future approaches for further development. The work shows that combining photocatalysis and electrocatalysis can significantly reduce pollution in chemical manufacturing. This chapter outlines everything you need to know and provides useful insights for those wanting to advance sustainable practices in chemistry.

Keywords: Adsorption, Band gap, Catalyst, Charge separation, Electrocatalysis, Electrode, Energy-efficient, Green chemistry, Heterogeneous catalysis, Hydroxyl radicals.

INTRODUCTION

Sustainable and eco-friendly chemical methods have grown enormously over the past few decades due to global efforts to reduce environmental damage, mitigate climate change, and protect scarce natural resources. Designing both products and

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KEY PRINCIPLES OF GREEN CHEMISTRY IN SYNTHESIS

The 12 Principles of Green Chemistry guide the design of processes and products that minimize environmental harm and promote sustainability and are particularly relevant when transitioning GS from laboratory to industrial contexts [6]:

1. Prevention: Avoid waste generation at the source.
2. Atom Economy: Maximize incorporation of all reactants into the final product.
3. Less Hazardous Chemical Synthesis: Use and produce substances with low toxicity.
4. Designing Safer Chemicals: Ensure function with reduced hazard potential.
5. Safer Auxiliaries and Solvents: Minimize or eliminate auxiliary substances.
6. Energy Efficiency: Favor ambient temperature and pressure when feasible.
7. Renewable Feedstocks: Source materials from renewable origins.
8. Reduce Derivatives: Avoid unnecessary derivatization steps.
9. Catalysis: Prefer catalytic over stoichiometric processes.
10. Design for Degradation: Create products that break down into harmless substances.
11. Real-Time Analysis: Monitor processes to prevent by-product formation.
12. Inherently Safer Chemistry: Reduce risks of accidents such as fires or explosions.

GREEN SYNTHESIS IN THE LABORATORY

In a laboratory setting, green synthesis involves using environmentally friendly materials, techniques, and methodologies to carry out chemical reactions or syntheses. The primary objective of this approach is to minimize waste generation, eliminate or reduce the use of hazardous substances, and optimize energy consumption, thereby significantly reducing the environmental footprint of chemical processes. By adhering to sustainability and green chemistry principles, green synthesis ensures safer experimental conditions while promoting resource efficiency and cost-effectiveness. Several key parameters play a crucial role in green synthesis, contributing to its effectiveness and sustainability [7]. A holistic design approach to green synthesis involves planning reactions from the start to integrate renewable feedstocks, safer reagents, energy optimization, and waste minimization in a single workflow, ensuring both environmental and economic sustainability.

CHAPTER 3

Biocatalysis and Enzyme-Based Green Synthesis

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Abstract: Enzyme-based biocatalysis has become an advanced approach that has been demonstrated to be more sustainable. It is considered one of the most economical, efficient, and eco-friendly processes for the production of active pharmaceutical intermediates and pharmaceuticals. The basic principle of biocatalysts in green chemistry is to use enzymes instead of chemical catalysts to target molecules that support the sustainable green chemistry industry. The biocatalyst performs a biocatalytic cascade reaction, in which each chemical step is catalyzed by an enzyme. The mechanism involved in biocatalysis is to utilize biological macromolecules to catalyze small molecular transformations. This review presents the principles, mechanisms, and applications of biocatalysis, with a focus on its role as a transformative technology in making industrial processes more sustainable, as well as its potential to develop revolutionary green innovations in the future. This chapter highlights the history of biocatalysis and recent developments in the production of advanced therapeutic drugs in the pharmaceutical industry, as well as current limitations in technology, cost, and sustainability.

Keywords: Acid-Base catalysis, Activation energy, Atom economy, Biocatalyst, Catalysis, Energy efficiency, Enzymatic processes, Environmental impact, Fermentation, Green chemistry.

INTRODUCTION

A biocatalyst is generally an enzyme, a living organism, or a substance of a biological system that promotes or accelerates biochemical reactions. Biocatalysts are environmentally friendly and energy efficient. They play an important role in almost all biological processes and have numerous economic uses in industries

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such as food, pharmaceuticals, and fuels. Biocatalysts reduce the energy required to initiate a chemical reaction [1]. Biocatalysts are highly selective and are capable of performing difficult chemical processes in fewer synthesis stages, without producing waste in multi-step reactions. Biocatalysts often use water as a solvent, thereby avoiding waste from organic solvents. They also make it easier to synthesize chemicals and goods in a safer, less dangerous manner. Biocatalysts are biodegradable, some are edible, and the feedstocks used to make them are renewable. Overall, biocatalysts contribute to the trend toward developing more environmentally friendly and process-intensive manufacturing systems [2, 3].

Enzyme-based green synthesis complies with green chemistry principles by reducing waste, improving biodegradability, and increasing reaction selectivity. The use of enzymes in organic synthesis, biotransformation, and polymerization has gained popularity due to their catalytic activity, recyclability, and potential industrial scalability. Advances in enzyme engineering and immobilization methods have increased its stability and applicability in green synthesis, rendering it a viable tool for sustainable innovation [4, 5].

HISTORY OF BIOCATALYSIS AND ENZYME-BASED GREEN SYNTHESIS

The use of biological catalysts, or enzymes, to facilitate chemical reactions has a long and fascinating history, dating back to ancient civilizations. The evolution of biocatalysis has been driven by the need for efficient, selective, and environmentally sustainable chemical processes. The integration of enzymes in green synthesis represents a significant advancement in sustainable chemistry, minimizing hazardous waste and energy consumption while enhancing reaction specificity [6].

Early Applications of Biocatalysis

Ancient Civilization

The earliest recorded use of biocatalysts dates back to ancient Egypt, Mesopotamia, and China, where microorganisms were unknowingly employed for the fermentation of beverages, bread, and dairy products. The production of beer, wine, and cheese was dependent on enzymatic processes, though the scientific mechanism was not yet understood.

Ancient Applications of Enzymes (Before the 17th Century)

Even before the discovery of enzymes by science, ancient societies unknowingly utilized the catalytic role of enzymes in food preparation. Rennin (present in animal stomachs) was used to curdle milk to make cheese, and fruit enzymes were

used to tenderize meat. These practices reflect the early use of enzymatic activity in day-to-day life, although the mechanisms were not known.

Discovery of Biological Catalysis (17th – 18th Century)

The study of enzymes began in the 17th and 18th centuries through investigations into fermentation. Jan Baptista van Helmont, in the 1600s, introduced a process called "ferment" that transforms starch into sugar. In 1783, Lazzaro Spallanzani came up with the idea that digestive fluids contain active ingredients that disintegrate food. These discoveries were the first sign of biological catalysis and formed the basis for understanding enzymes in chemical and biological processes [7].

Discovery of Enzymatic Activity (19th Century)

The foundation of modern biocatalysis was laid in the early 1800s when scientists began to investigate the chemical nature of fermentation. In 1833, Anselme Payen and Jean-François Persoz isolated the first enzyme, amylase, from malt extract. Later, Louis Pasteur (1857) demonstrated that fermentation was driven by living yeast cells, marking a significant milestone in enzymology [8].

Emergence of Enzyme Chemistry (Late 19th – Early 20th Century)

Enzymes as Catalysts (1897)

The concept that enzymes were separate from living cells was established when Eduard Buchner discovered that cell-free yeast extracts could ferment sugar, proving that enzymes function independently. This led to the recognition of enzymes as biochemical catalysts [9].

Lock and Key Model (1894)

Emil Fischer proposed the lock-and-key model, explaining enzyme specificity and how enzymes interact with substrates. This understanding was crucial for later developments in enzyme engineering and biocatalysis [10].

Industrial Enzyme Applications and the Rise of Green Synthesis (Mid-20th Century – Present)

Enzymes in Industrial Processes (1950s–1970s)

With advancements in protein purification and biochemistry, enzymes like proteases and lipases have found widespread applications across industries such as textiles, detergents, pharmaceuticals, and food processing [11, 12].

CHAPTER 4

Green Solvents: Ionic Liquids, Deep Eutectic Solvents, and Aqueous Media

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Abstract: Green solvents play a crucial role in advancing sustainable and environmentally friendly chemical practices by reducing the toxicity, volatility, and persistence associated with conventional organic solvents. This chapter highlights three major classes of green solvents, Ionic Liquids (ILs), Deep Eutectic Solvents (DESs), and aqueous media, and compares their environmental benefits, physicochemical properties, and industrial applicability. Ionic liquids, characterized by negligible vapor pressure, thermal stability, and tunable polarity, have been widely explored in catalysis, electrochemical processes, and organic synthesis. However, their high production cost, potential toxicity, and limited scalability remain significant challenges to their broad adoption. Deep eutectic solvents, formed through simple hydrogen-bonding interactions, are inexpensive, biodegradable, and useful in natural product extraction, catalytic transformations, and bioprocessing. Despite these advantages, their thermal stability under extreme conditions and limited industrial validation restrict widespread implementation. Aqueous media, being abundant, inherently safe, and compatible with many enzymatic and organic reactions, remain a cornerstone of green chemistry, although their low solubility for hydrophobic substrates and the energy-intensive purification methods required to achieve it limit their universal applicability. Together, these solvent systems represent complementary approaches to designing safer, more efficient reaction environments that reduce environmental impact and align with global goals for carbon reduction and circular economy practices. By critically assessing their strengths and limitations, this chapter provides guidance on integrating green solvents into mainstream chemical processes, enabling innovation in both laboratory and industrial settings. The discussion establishes a clear link between solvent design, sustainable chemistry, and the broader transition toward environmentally responsible technologies.

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Keywords: Aqueous media, Biodegradability, Catalytic applications, Deep eutectic solvents, Electrochemical processes, Enzymatic biocatalysis, Environmental sustainability, Green solvent design, Hydrogen-bonding interactions.

INTRODUCTION

The history of green solvents is closely linked to the Pollution Prevention Act of 1990, which marked a transition toward green chemistry principles aimed at reducing the environmental impact of chemical processes [1, 2]. Green solvents were developed to replace traditional solvents that often pose serious risks to human health and the environment due to toxicity, volatility, and persistence. Early solvents derived from natural sources, such as alcohol, water, and essential oils, were less toxic [3, 4], but their use was limited by cost and availability. With the expansion of industrial chemistry, synthetic solvents such as chloroform, benzene, and carbon tetrachloride became widely used due to their high efficiency. However, their widespread use raised concerns regarding severe ecological and health hazards [5, 6]. By the mid-20th century, it became evident that a shift to safer solvents was essential. The concept of green chemistry emerged in the 1990s with the seminal book *Green Chemistry: Theory and Practice* by Paul Anastas and John C. Warner (1998) [7], introducing the 12 Principles of Green Chemistry. These principles emphasized designing safer, less volatile, and more biodegradable solvents. In the early 2000s, ionic liquids (ILs) gained attention as promising green solvents due to their negligible vapor pressure, thermal stability, and tunable polarity [8]. They have been extensively explored in catalysis, extraction processes, and electrochemical applications (Fig. 1), though cost and large-scale synthesis challenges remain significant barriers [9, 10]. Biocatalysts, including enzymes and whole cells, have recently been combined with ILs, DESs, and aqueous media, representing a new frontier in sustainable chemistry [11]. These solvents stabilize enzymes and enhance catalytic efficiency under mild conditions, reducing energy consumption and toxic waste generation [12]. The tunable polarity and non-volatility of ILs and DESs make them particularly suitable for complex organic transformations and biopolymer processing [13, 14]. Additionally, their biocompatibility and reduced environmental footprint align with the goals of the pharmaceutical and fine chemical industries, embodying the principles of the circular economy and reduced carbon emissions [15 - 17].

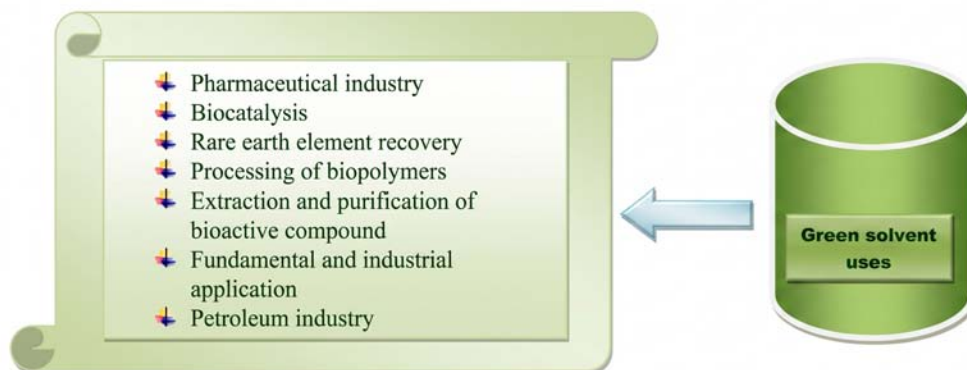


Fig. (1). A pictorial representation of the uses of green solvents.

GREEN SOLVENTS: TYPES AND PROPERTIES

To meet the increasing demand for sustainable chemistry, there is a need for novel strategies that balance environmental impact with scalability and efficiency [18, 19]. Biocatalysts and green solvents play a significant role in this transition because they enable cleaner chemical processes under mild conditions, thus reducing energy use and resource waste [20]. Advances in biotechnology, such as protein engineering and recombinant DNA technology, have stabilized, improved efficiency, and made enzymes less costly and more practical for large-scale industrial applications [21, 22]. Green solvents, such as ionic liquids and deep eutectic solvents derived from renewable materials, are now effective and sustainable alternatives to toxic traditional solvents [23]. These, therefore, call for a stronger inter-industry, research-and-policy collaboration to drive innovation, establish eco-friendly supply chains, and create supporting regulatory frameworks. With these in place, sustainable chemistry can satisfy the growing demand and advance global environmental and economic goals [24].

Ionic liquids

Ionic liquids are salts that are in a liquid state at room temperature or slightly above and are usually formed of organic cations and inorganic or organic anions [25]. They have properties that are not usual, including low volatility, high thermal stability, and the ability to dissolve a wide range of compounds, making them valuable for many industrial and chemical applications [26].

Properties of Ionic Liquids

- **Low Volatility:** Ionic liquids have very low vapor pressures and are, therefore, safer and more environmentally friendly than volatile organic solvents [27].
- **Thermal Stability:** They do not decompose when heated at high temperatures,

CHAPTER 5

Solvent-Free Green Synthesis

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Abstract: Developing "green" synthetic strategies—particularly solvent-free protocols—represents a primary methodology for mitigating the environmental impact of chemical manufacturing. By avoiding hazardous volatile organic solvents, optimizing atom economy, and minimizing energy consumption and waste production, solvent-free synthesis significantly enhances process sustainability. These methods frequently result in enhanced product recovery and a substantial reduction in undesirable by-products, rendering them both economically and ecologically sustainable.

Recently, the domains of organic synthesis and medicinal chemistry have increasingly focused on various solvent-free methodologies, including mechanochemical, microwave-assisted, ultrasonic, and electrochemical synthesis. Mechanochemical processing is an established approach in materials science and inorganic synthesis that uses mechanical energy, typically from ball milling or grinding, to induce chemical transformations. Microwave-assisted approaches enhance reaction kinetics through efficient dielectric heating, leading to significant reductions in processing time and energy usage. Alternative specialized configurations, including high-shear mixing, thin-film processing, and spray drying, have emerged as effective approaches for rapid and fundamentally safer reactions. Nonetheless, the extensive industrial application of these technical advancements is constrained by challenging economic, operational, and engineering scalability issues. As the chemical industry increasingly integrates green chemistry principles into its fundamental practices, ongoing advancements in solvent-free techniques are well positioned to drive significant innovations, ultimately facilitating the sustainable production of safe, next-generation chemical products.

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Keywords: Atom economy, Dielectric heating, Electrochemistry, Eco-friendly manufacture, High-shear mixture, Industrial scale-up, Organic synthesis, Process intensification, Reaction kinetics, Waste minimization.

INTRODUCTION

Most chemical reactions are carried out in the liquid phase; solutions are the best medium for heat transfer during endothermic and exothermic reactions [1]. Solvents dissolve the solid reactants and break up the crystal lattice. Solvents have a significant effect on reaction rates and the position of chemical equilibrium. Agitation methods, such as stirring, shaking, or other methods, are routinely used to ensure reactants interact efficiently in a homogeneous solution. However, the function of a solvent in an organic reaction is more complex than just providing a uniform environment for interaction [2]. A solvent can significantly influence the rate of a reaction, either accelerating or decelerating it. Various factors, including electrostatic, steric, and conformational influences, influence the interactions between the solvent and the reaction partners. Despite its significant role, the solvent remains distinct from the invention and is recovered in its original form after the reaction. On the other hand, solvent-free procedures use no liquid medium at all to react. Rather than liquefying the reactants, these variants depend on solid or molten particles directly contacting one another to complete the reaction. This renders solvent-free methods more environmentally friendly and economical, but also, at least in some cases, less controllable than those in solution. Solvent-free chemical synthesis is not well known compared to solvent-based processes, which makes it difficult to recognize [3]. Solid-state reactions occur when two macroscopically solid materials interact directly to form a third solid product without generating any liquid or vapor phases. Some authors consider these reactions to be solventless and treat solid-supported reactions as a separate type [4]. In this analysis, reactions between solid phases are considered in the absence of solvent, and reactions involving liquid in the liquid-solid and solid-solid regimes are considered. Many solvent-free reactions involve macroscopic organic solids, but many occur through a liquid or melt phase. The reactants are heated to form a temporary molten (eutectic) phase with respect to the solid reactants, which can cause these substances to form even in the absence of an added solvent. This solvent-free reaction can find numerous applications across different classes and types of compounds, including condensations, cycloadditions, alkylation, aromatic substitutions, additions, cyclizations, eliminations, rearrangements, C–C coupling cascade reactions, and catalyzed reactions. Important transformations include condensations of carbonyl compounds, cycloadditions, alkylations, and aromatic substitutions, among others. While solvent-free reactions present certain drawbacks, these challenges can be effectively addressed through advancements in reactor engineering technology [5]

- 6]. The emergence of “hot spots” and, in the worst case, runaway reactions are among the potential hazards that need to be addressed in solvent-free reactions. Unlike conventional working methods, in which the reaction medium (or solvent) serves only as a heat sink or heat transfer agent, new reactor development should be more focused [7].

PRINCIPLE OF SOLVENT-FREE REACTIONS

The molecular movement of reactants is crucial for solvent-free conditions. In liquid-phase reactions, molecular motion is understood through solution dynamics. In solid-phase reactions, molecular reactions become more complex. Recent findings show that molecular movement is essential for solid-solid reactions [8]. Agitation modalities such as mechanochemistry, microwave irradiation, ultrasound, and magnetic stirring facilitate molecular transitions between crystalline phases. In solution-based reactions, substrate concentrations may be reduced, and reactions may not occur due to factors such as reactive cross-sections and molecular orientation [9]. Several fundamental principles govern solvent-free reactions, as shown in Fig. (1).

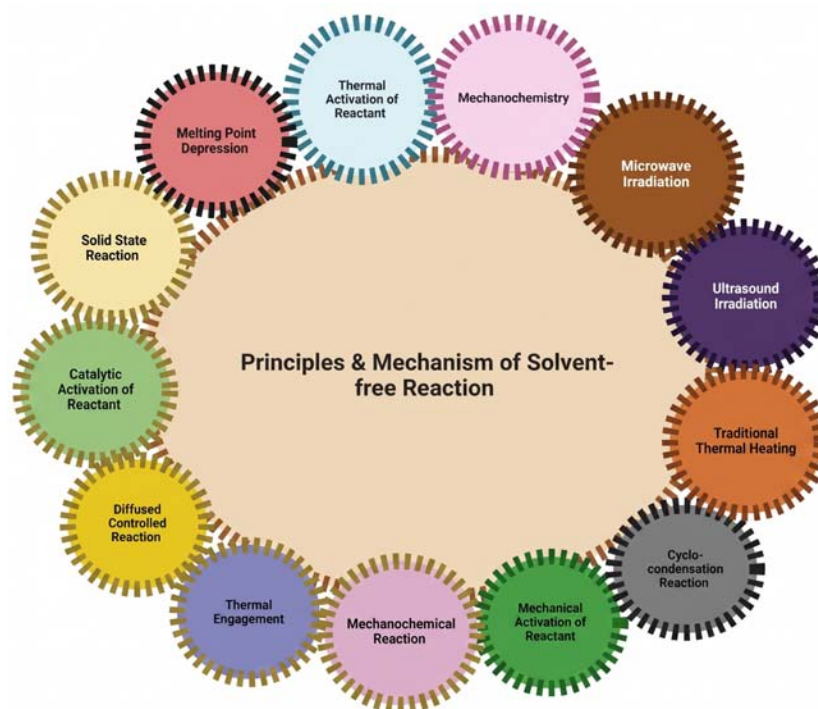


Fig. (1). Representation of various principles and mechanisms of solvent-free reactions.

CHAPTER 6

Microwave, Ultrasound, and Sonochemistry-Assisted Synthesis in Green Chemistry

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Abstract: The use of microwave-assisted synthesis has become an effective tool in synthetic chemistry, providing an option for quick, efficient, and, most importantly, environmentally friendly chemical conversions. This method uses less energy and less solvent, minimizes the time taken to complete the reaction, maximizes the yield of products, and provides homogeneous heating via dielectric heating with microwave radiation. The use of ultrasonic waves in sonochemistry to enhance the rate of reactions and production of materials at the nanoscale complements microwave methods and supports green chemistry objectives. These approaches allow reaction purification, reduce waste, and apply to both homogeneous and heterogeneous reactions. Microwave and ultrasound-assisted technologies for synthesizing pharmaceutical formulations, conducting extraction processes, and producing nanocomposites and nanoparticles have proven to be more efficient and environmentally friendly. Mechanochemical methods, microwave-assisted hydrothermal synthesis, and the use of industrial waste streams are other alternative methods that have led to sustainable development in chemical synthesis.

Keywords: Biocatalysis, Cavitation, Dielectric heating, Energy efficiency, Environmental remediation, Green chemistry, Heterogeneous catalysis, Homogeneous catalysis, Ionic liquids, Microwave-assisted synthesis.

INTRODUCTION

Microwave chemistry is a niche of chemistry that utilizes microwave radiation as an efficient source of energy to catalyze chemical reactions. This new technology has transformed the traditional methods of chemical synthesis since it offers a more energy-efficient, faster, and more eco-friendly alternative to conventional heating methods. Microwave-assisted synthesis is a breakthrough of considerable

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importance in synthetic chemistry, offering the possibility of cutting reaction time down to minutes, hours, or days. For example, a Diels-Alder reaction that normally takes 10-12 hours under normal heating conditions can be performed under microwave irradiation in as little as 10-15 minutes [1].

This process does not only increase the productivity of laboratories but also gives scientists more time to work on innovative research challenges. With high-throughput experimental capabilities, scientists are able to systematically optimize reaction conditions and test numerous variables simultaneously. The ability of microwave energy to provide homogeneous and consistent heating reduces the temperature gradient, allowing reaction products to be obtained with higher yields, greater selectivity, and increased reproducibility. It has been shown that microwave-driven reaction yields can reach up to 3050% higher than with conventional conditions, with less than 5090% of the energy input, which has played a major role in achieving greener chemistry [2].

Microwave chemistry, in particular, is finding some applications in pharmaceutical, materials, and organic studies. Actually, it has helped scientists to quickly synthesize biologically relevant materials and create nanoparticles. Due to this technology, the process of chemical synthesis has continued to evolve as sustainable and progressive procedures are introduced in the contemporary fields of science [3].

Ultrasound-assisted synthesis is an efficient and environmentally clean method that facilitates chemical reactions by increasing mass transfer and forming a localized high-energy environment in applications in the pharmaceutical and materials industries [4]. This is done using electrical equipment that produces sound pulses, which are passed through tissues and reflected according to the density of the structures encountered. The images are created on a computer, and the reflection is then processed. First of all, the ultrasound does not involve the use of ionizing radiation, making it safer in terms of monitoring fetal development in pregnancy [5]. Doppler ultrasound is a special technique to measure blood circulation in arteries and veins to diagnose issues of deep vein thrombosis and arterial obstructions. The latest methods include contrast-enhanced ultrasound, elastography to measure tissue stiffness, and Point-Of-Care Ultrasound (POCUS) to perform bedside diagnostics [6].

Also, sonochemistry refers to the study of the effects of ultrasound on chemical systems, which lead to high reaction rates, high yields, and unique reaction pathways. The sonochemistry principle is based on acoustic cavitation, which is the creation and disintegration of bubbles in a liquid exposed to ultrasound [7]. Applications of sonochemistry in organic synthesis, materials science,

pharmaceuticals, and environmental cleanup include enhancing heterogeneous catalysis, producing nanoparticles, and degrading contaminants in wastewater treatment. Sonochemistry will be part of green chemistry since it reduces the use of harmful solvents and increases energy efficiency [8].

MICROWAVE ASSISTED SYNTHESIS

Microwave radiation allows microwave-assisted synthesis to take place much faster than regular chemical synthesis. The method has greatly transformed synthetic chemistry by decreasing the time needed for reactions, boosting how much product is formed, and making reactions more precise. It finds regular use in organic, inorganic, and medicinal chemistry, as well as in the production of nanomaterials.

Principle of Microwave-assisted Synthesis

Microwave-assisted synthesis is based on the principle of dielectric heating, in which microwave radiation (300 MHz–300 GHz) interacts with polar molecules or conducting ions in a reaction mixture, leading to rapid and uniform heating. The main components and mechanisms involved in microwave heating are:

Microwave Radiation

Microwaves are categorized as non-ionizing radiation, and their frequency spectrum spans 300 MHz to 300 GHz. The frequency bands are as follows: 300 MHz to 3 GHz is UHF (ultra-high frequency), 3-30 GHz is SHF (super-high frequency), and 30-300 GHz is EHF (extremely high frequency). High-power microwaves are those that operate at a frequency of 1 to 300 GHz and have a peak power of more than 100 MW, which allows them to interact well with polar molecules, including water; this is what makes them find widespread use in their applications [9 - 12]. Unlike other forms of energy at higher energies, such as ultraviolet or X-ray radiation, microwaves lack the energy to break chemical bonds [13]. Laboratory-scale microwave reactors typically operate at 100-1000 W (usually 300-800 W), which is insufficient to support large-scale batch and continuous-flow operations, and larger industrial-scale microwave units may run more efficiently in the 1 kW to over 10 kW range. As shown in Fig. (1), the electromagnetic spectrum is broadly classified as ionizing and non-ionizing radiation. Microwaves are considered non-ionizing radiation, meaning they do not have sufficient energy to ionize atoms or molecules; however, they may cause unknown vibrations in water molecules, particularly, and are essential in cooking and communication. Microwaves that do not fall within the infrared spectrum cannot be seen, but they are critical in many technologies, including radar, satellite communications, and medical procedures. The frequency and wavelength

processes to reduce hazardous chemicals and waste has become known as green chemistry and is now seen as an important strategy for sustainability. Of all the different techniques and technologies supporting green chemistry, photocatalysis and electrocatalysis have performed best and are perfectly suited to its main principles [1].

The use of photocatalysis, which involves light energy acting on a catalyst to initiate chemical reactions, offers significant benefits. The method allows light's abundant energy to produce reactive hydroxyl radicals and photoexcited electrons, supporting many chemical conversions [2]. Applications of photocatalysis include reducing carbon dioxide and producing green pharmaceuticals and fine chemicals. Photocatalytic activities are energy-saving, operate safely, and reduce the release of harmful substances, making them a key part of sustainable chemistry [3].

Just like fuel cells, electrocatalysis uses electrical energy to drive chemical reactions with special catalysts. Because electrocatalysis provides precise control over how reactions occur, it can be applied to fuel cell technologies, converting CO₂ into useful chemicals and producing organic compounds [4 - 7]. When paired with solar and wind energy, electrocatalysis can make chemical manufacturing both sustainable and carbon-free. Thanks to new types of nanomaterials, hybrid catalysts and reactor systems, electrocatalytic processes now work more efficiently and selectively, making them useful for large-scale operations [8 - 12].

Both technologies work to minimize environmental harm from chemical industries and offer opportunities to tap into renewable energy. At the same time, implementing them involves certain problems. Catalyst stability, scalability, cost-effectiveness, and the development of efficient reaction systems are vital for large-scale application of these catalysts. There have been substantial developments in creating photocatalytic and electrocatalytic materials, especially those that combine their advantages, driven by increased scientific work in this field [13 - 15]. Photocatalysis and electrocatalysis represent transformative technologies that are reshaping the landscape of green chemistry. By enabling energy-efficient, selective, and environmentally benign chemical processes, these methodologies have the potential to address pressing global challenges, from pollution control to renewable energy utilization [16 - 18]. A comparison between photocatalysis and electrocatalysis based on few characteristics is depicted in Table 1.

Table 1. Comparison between Photocatalysis and Electrocatalysis [19 - 24].

		Photocatalysis	Electrocatalysis
Features of catalysts	Type	Composite thin films or 2D nanomaterial powders	Powders loaded on an electrode surface or 2D nanomaterial thin films
	Nature	Hydrophilic	Hydrophilic or lipophilic
	Reprocess ability	Suitable for thin films, complex for powders	Highly suitable
Condition of reaction systems	Energy inputs	Solar energy/Visible energy	Externally applied electric bias
	Configuration	Single reaction chamber	Single or double reaction chamber separated by a membrane
	Charge transfer route	Relatively short	Relatively long
Benefits	Economy	Low cost and easily affordable due to the utilization of visible light.	High cost due to the utilization of expensive electrodes and electric energy
	Efficacy	Low efficiency	Relatively high efficiency

BASICS OF PHOTOCATALYSIS: MECHANISMS AND GREEN APPLICATION

In the presence of compounds known as photocatalysts that absorb light quanta and participate in the chemical transformations of the reactants, photocatalysis is defined as a change in the pace of chemical processes or their creation under the influence of light [1]. Photocatalysis is a versatile technique used in wastewater treatment, hydrogen generation, air purification, and antibacterial applications, including the breakdown of different organic contaminants in wastewater, the generation of hydrogen, air purification, and antibacterial activity. Due to its many advantages, such as high efficiency and low cost, photocatalysis is growing rapidly and garnering more research attention. A novel approach to solving environmental and energy problems is photocatalysis.

The mixture of photochemistry and catalysis is called photocatalysis. The Greek word for "photocatalysis" is made up of two parts. The prefix "*photo*" denotes light. The process by which a material increases the rate at which reactants undergo a chemical change without itself changing is known as "*catalysis*".

A catalyst is a material that lowers the activation energy of a reaction, increasing its pace. The simultaneous usage of light and catalysts to promote or quicken a chemical reaction is known as photocatalysis. Thus, the definition of photocatalysis is "catalysis-driven acceleration of a light-induced reaction" [2 - 3].

CHAPTER 8

Green Nanotechnology and Sustainable Nanomaterials

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Abstract: Nanotechnology has gained significant interest in environmentally friendly procedures, also referred to as ‘green chemistry’, to produce Nanoparticles (NPs) due to growing concerns about the environmental impact of traditional chemical approaches. A variety of NPs preparation techniques, including physical, chemical, and green synthesis, have been described. Since physical and chemical processes for Nanomaterials (NMs) have several drawbacks, green synthesis has gained more attention as it is safe, clean, and affordable, allowing for easy production scaling. Due to their cost-effectiveness, biodegradability, biocompatibility, simplicity of modification, continuous release into systems, reproducibility, and reduced toxicity, NPs derived from microbes, plants, and biomolecules are utilized in the production and processing of novel formulations at the nanoscale. Since nanoparticles created by green synthesis are useful in fields such as biomedicine, electronics, agriculture, cosmetics, and textiles, they are being recognized by scientists and research laboratories worldwide. Using green nanotechnology to develop new NMs is important today because it contributes to an environmentally conscious, positive future and a green, circular economy.

Keywords: Bio-nanomaterials, Circular economy, Eco-friendly, Environmental remediation, Energy production, Green chemistry, Green economy, Nanocomposites, Nanomedicine, Nanoscience.

INTRODUCTION

Before the term ‘nanotechnology’ was introduced, physicist Richard Feynman delivered a lecture entitled ‘There's Plenty of Room at the Bottom’ on December

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29, 1959, during a conference of the American Physical Society at the California Institute of Technology (CalTech) [1 - 3]. For many years, nanotechnology has been an important topic in science and technology. The continuous progress in technology is pointing out the value of nanotechnology, leading to a lot of talk in different communities. This area of study concerns itself with making and manipulating components and systems at the nanoscale, which is anything from 1 to 100 nanometers in size [4 - 10]. Thanks to nanomaterials, we are able to manufacture lightweight, durable, and flexible materials, and nanotechnology in electronics makes computing devices both faster and smaller. If a material is to be named as a nanomaterial, at least one of its dimensions must range below 100 nanometers [11 - 14]. With both size dimensions and surface effects determining their properties, nanomaterials demonstrate distinct features that differ greatly from those of bulk and micromaterials. Various categories of nanomaterials exist for researchers to classify them based on chemical composition and specific properties [15 - 16]. The combination of green chemistry principles and nanotechnology research continues to evolve the implementation of sustainable nanomaterials and green nanotechnologies. Research requires environmentally sustainable and eco-friendly synthesis methods for nanoparticles, as demand for such techniques is increasing [17 - 20]. Environmental protection should remain the priority in these methods, as they require non-harmful chemicals and renewable solvents in addition to ecological resources. Various NMs are listed in Table 1.

Table 1. Various types of NMs and their uses.

Type of NMs	Overview	References
Inorganic-based	These nanomaterials are usually characterized by their different properties, such as non-toxicity, hydrophobicity, biocompatibility, and stability. Examples include metal and metal oxide nanoparticles. Their applications include different areas such as biomedicine, catalysis, and sensor technology.	[21 - 23]
Organic-based	These particles exhibit properties of biocompatibility, biodegradability, and non-toxicity. Examples include liposomes, layered biopolymers, dendrimers, protein aggregates, lipid bodies, and milk emulsions. Their applications span various fields, including drug delivery, cosmetics, and food science.	[23 - 25]
Carbon-based	Characteristics of these nanomaterials are minimal toxicity, excellent electrical conductivity, adaptability, and optical clarity. Examples include graphene, fullerenes, and carbon nanotubes. Their applications are in various fields, including electronics, sensing technologies, drug delivery systems, composite materials, and protective coatings.	[26 - 29]
Composite-based	Characteristics of these nanomaterials include flexibility, elevated strength, electrical conductivity, thermal resistance, and improved barrier properties. Examples include hybrids of carbon nanotubes and quantum dots, as well as graphene-polymer composites. Their applications are in various fields, including sensors, energy storage solutions, and structural reinforcement.	[30 - 32]

ECO-FRIENDLY APPROACHES IN NANOPARTICLE SYNTHESIS

Nanoparticle systems synthesized using environmentally friendly methods and biological organisms, such as plants, fungi, and bacterial species, have gained recognition in the scientific literature for their cost efficiency, reduced toxicity, and natural compatibility. These environmentally friendly synthesis methods are gaining popularity for making nanomaterials because they offer sustainability, reduced toxicity, lower production costs, superior control over particle size, and enhanced biocompatibility. The overarching aim of nanotechnology is to establish a dependable and improved production methodology that effectively manages the chemical composition, morphology, and uniformity of nanoparticle systems for large-scale nanomaterial production [33 - 34]. Some eco-friendly sources and their advantages and disadvantages are shown in Table 2. Various NPs and their biomedical applications are shown in Fig. (1).

Table 2. Source of origin of NPs, their advantage and disadvantages.

Source	Advantage	Disadvantages	References
Plant extract	Easily and freely available, harmless, easy to handle, and cheap for nanoparticle synthesis	Loss of original physico-chemical characteristics, like color, shape, and size of the plant part used in the synthesis process	[35 - 37]
Bacteria	Ability to reduce the metal ions	Control of various biological factors is needed, such as cell wall functional groups and temperature control	[38 - 40]
Fungi	The high concentration of intracellular enzymes and various morphological forms of competent fungi enable them to synthesize a vast quantity of nanoparticles	There is considerable variability in the choice of starting biosynthetic materials, with some processes utilizing fungal biomass, while others rely on fungal cell filtrates	[41 - 45]
Algae	Algae with microalgae possess the ability to synthesize a variety of metallic nanoparticles	Loss of many materials takes place because of washing seaweeds and drying them in the sunlight.	[44 - 46]

Eco-friendly synthesis of Ag NPs

Silver is a key element in systems that show strong antimicrobial potential. Even so, how effective Ag NPs are at killing bacteria is related to their chemical and physical characteristics. Additionally, Ag NPs produced through biosynthetic or green approaches have some very interesting characteristics. Because these nanoparticles are stable, affordable, safe for the environment, and created with less dangerous chemicals, they have sparked major interest. By using plant materials and biomolecules, this approach ensures that diverse nanosize metal particles are successfully created [47 - 49].

Innovations in Catalysis for Green Synthesis

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Abstract: Catalysis is one of the foundations of sustainable chemical production, which increases the effectiveness of reactions, reduces the amount of waste, and saves energy. The significance of it is justified by global environmental problems, increasing energy consumption, and the need to achieve the Sustainable Development Goals (SDGs). The chapter summarizes diverse catalytic systems, such as heterogeneous, homogeneous, biocatalytic, organocatalytic, and photocatalytic, and their roles in advancing chemical transformations toward a greener state. Emerging technologies, including nanocatalysts, Metal-Organic Frameworks (MOFs), and magnetically recoverable catalysts, enhance selectivity, stability, and reusability. An environmentally friendly approach to the synthesis process, such as solvent-free reactions, microwave- and ultrasound-assisted catalysis, and mechanochemical reactions, is discussed in the context of industry, with examples from pharmaceutical, agrochemical, and fine chemical syntheses. Examples include Pd-catalyzed hydrogenation for the synthesis of active pharmaceutical ingredients, MOF-catalyzed oxidation for the production of agrochemicals, and enzymatic conversions in food manufacturing. Despite significant advancements, catalyst deactivation, recyclability, and scale-up continue to present major challenges. The chapter ends by presenting views on AI-assisted catalyst design, integrated hybrid systems, and policy frameworks to accelerate the transition to next-generation sustainable processes.

Keywords: Biocatalysts, Biomass conversion, C-C bond formation, Catalyst reusability, Catalysis, Green oxidation, Green chemistry, Heterogeneous catalysts, Homogeneous catalysts, Metal-Organic Frameworks (MOFs).

INTRODUCTION

The growing environmental demands, natural resource depletion, and more rigorous regulatory systems have made sustainable chemical production a global concern [13]. The growing need for green, economically feasible chemical processes has increased pressure to develop new solutions for chemical

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manufacturing. Green chemistry offers principles for formulating processes that help reduce waste, minimize energy use, and enhance overall safety [4 - 6]. Catalysis is one of the principles that have led to sustainability, the facilitation of chemical reactions under less vigorous conditions, atom economy, and eco-friendly reaction pathways [7 - 9]. Catalysis enables reactions to proceed more efficiently, with catalysts accelerating the desired transformations without being consumed and often generating fewer byproducts [10, 11]. Conventionally, catalysis has been advanced through nanostructuring, surface engineering, and the implementation of smart materials [12, 13]. Recent innovations include nanocatalysts, Metal-Organic Frameworks (MOFs), photocatalysts, and biocatalysts, which can be optimized through computational modeling and biotechnology to yield optimal reaction conditions and catalytic performance [14 - 17]. The need to create green catalytic systems arises from challenges facing the global environment, such as climate change, carbon emissions, and chemical pollution, which require urgent intervention in the design of chemical processes [18]. Not only do catalytic solutions provide efficient reaction pathways, but they also enable the integration of renewable resources, minimize toxic byproducts, and incorporate principles of the circular economy, thereby meeting the requirements of both environmental and industrial sustainability [19, 20]. The utilitarian aspect of catalytic green synthesis can be seen in industrial practice. For example, Pd/C-catalyzed reduction of cinnamaldehyde to cinnamyl alcohol has been shown to be more productive and safer in Active Pharmaceutical Ingredient (API) production [21]. Oxidation of alcohols is a catalyst-based process (MOF) by which agrochemical intermediates can be manufactured industrially [22]. Examples in the food industry include the use of enzymatic transformations in starch-to-high-fructose-syrup processes [23]. These demonstrations show that catalytic strategies can be directly implemented at both commercial and laboratory scales and offer practical solutions to the chemical, pharmaceutical, agrochemical, and food industries [24, 25]. Catalytic systems also help in global climate action and the United Nations Sustainable Development Goals (SDGs). They enable the use of CO₂, the production of hydrogen through the division of water, and the fixation of nitrogen under eco-friendly conditions, thereby contributing to SDG 7 (clean energy), SDG 9 (industry, innovation, and infrastructure), and SDG 13 (climate action) [26 - 29]. The integration of catalytic solutions into policy frameworks and industrial standards, along with green chemistry regulations, can accelerate the adoption of sustainable manufacturing practices [30]. At the same time, despite significant improvement, there are still problems. The deactivation of catalysts, the lack of recyclability, and the scale-up problems of laboratory reactions require interdisciplinary expertise from chemists, engineers, and materials scientists [31 - 34]. The combination of Artificial Intelligence (AI), machine learning in catalyst design, and hybrid catalytic cycles

is expected to enhance sustainable chemical synthesis at minimal environmental cost [35, 36]. This chapter offers a valuable perspective on innovations in catalytic strategies, the advent of new technologies, industrial applications, and the future of green synthesis, with much attention paid to the importance of catalysis in creating a sustainable, environmentally responsible chemical industry [37 - 39].

TYPES OF CATALYSTS IN GREEN SYNTHESIS

Catalysis is the primary driver of green chemistry, enabling sustainable transformations by enhancing reaction efficiency, selectivity, and atom economy. By providing alternative reaction pathways with lower activation energies, catalytic systems facilitate operations under milder conditions, thereby mitigating the formation of hazardous byproducts. The physical properties, operational mechanisms, and structural configurations of catalysts allow for their classification into several distinct categories. Each class presents unique advantages and specific operational challenges in the context of green synthesis [35]. A comprehensive summary of these catalytic systems, including their structural attributes and industrial relevance, is provided in Table 1.

Table 1. Comparison of different types of catalysts in green synthesis.

Catalyst type	Characteristics	Application	Advantages	Limitations	Ref
Homogeneous Catalysts	Soluble in the reaction medium	Fine chemicals, pharmaceuticals	High selectivity, ease of control	Difficult to separate and reuse	[37 - 40]
Heterogeneous Catalysts	Insoluble, often solid phase	Petrochemical industry, biomass conversion	Easy recovery and reuse, long lifespan	Lower selectivity, side reactions	[41 - 43]
Biocatalysts	Enzymes, microorganisms	Biotransformations, pharma, food industry	Environmentally benign, high specificity	Limited temperature and pH stability	[44 - 48]
Organocatalysts	Small organic molecules	Asymmetric synthesis, polymerization	Metal-free, green synthesis	May require harsh conditions	[49 - 52]
Photocatalysts	Utilizes light energy	Photochemical reactions, CO ₂ conversion	Sustainable, uses renewable energy	Requires a light source, efficiency issues	[53, 54]
Electrocatalysts	Catalysts in electrochemical processes	Water splitting, fuel cells	Energy-efficient, environmentally friendly	Expensive materials, slow kinetics	[55, 56]

CHAPTER 10

Toxicity Studies and Life Cycle Assessments in Green Synthesis Methodology

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Abstract: Green synthesis emphasizes the development of environmentally friendly and sustainable chemical processes by reducing the use of hazardous substances, conserving energy, and utilizing renewable resources. It aims to minimize the ecological footprint of chemical production while ensuring efficiency and safety. However, evaluating the true environmental benefits of such processes requires a more comprehensive approach that extends beyond the laboratory synthesis. Toxicity studies are essential for assessing the biological and ecological safety of raw materials, reagents, intermediates, and by-products, ensuring that the entire process poses minimal risk to human health and the environment. Complementing this, Life Cycle Assessment (LCA) provides a systematic evaluation of environmental impacts across all stages of a product's life cycle, from raw material extraction and synthesis to use and disposal. The integration of toxicity data with LCA enables a more accurate and holistic assessment of the sustainability of green synthetic methods. This combined approach helps identify potential trade-offs, optimize reaction conditions, improve process safety, and support the design of genuinely green alternatives. This paper underscores the importance of coupling toxicity studies with LCA to validate and enhance the green credentials of chemical processes, ultimately contributing to the advancement of sustainable and responsible chemistry.

Keywords: Assessment, By-products, Chemical processes, Ecological footprint, Energy conservation, Environmental impact, Green chemistry, Intermediates, Life cycle assessment, Optimization.

INTRODUCTION

Green chemistry has grown alongside the increasing global emphasis on sustainability and environmental protection, which has acted as a catalyst for its transformation from a research domain into a means of ensuring sustainable,

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environmentally friendly practice in chemical research and industry. Green synthesis is at the heart of this movement because it focuses on designing chemical processes and products based on chemicals that reduce or even eliminate the use and generation of toxic substances. Green synthesis emphasizes atom economy, the use of safer solvents and renewable feedstocks, and energy efficiency, with the aim of making chemical production less environmentally damaging. Nevertheless, a process is often perceived by the broader public as inherently sustainable when it involves the use of 'green' reagents or methodologies; this is a simplistic and misleading view [1 - 3].

Real sustainable chemical processes require a comprehensive assessment framework that evaluates a process's sustainability from material acquisition through all operational stages to final waste disposal. Toxicity studies need to be conducted to assess biological and environmental risks posed by reagents, intermediates, solvents, catalysts, and final products. These investigations are vital because they examine acute and chronic human health risks, as well as ecological risks and environmental preservation, across all aspects of 'green' processes. Equally important, the use of Life Cycle Assessment (LCA) to measure environmental impact at every stage of a product's lifecycle is robust and quantitative. As LCA takes into account energy consumption, carbon footprint, water use, waste production, and pollutant emissions, it offers a cradle-to-grave view. Applied in conjunction with the toxicity data, LCA can determine which of the competing green synthesis strategies is the most sustainable.

Both toxicity profiling and LCA support a case-by-case approach to green chemistry initiatives through a scientifically based, holistic platform. In addition to ensuring regulatory compliance and environmental safety, this combined approach also helps rationalize the design of safer, cleaner chemical processes. This paper reviews methodologies used in toxicity studies and LCA, their complementary nature in green chemistry, and illustrative case studies of their practical applications. We finally outline emerging trends, challenges, and directions for further improving sustainable assessment in the field of green synthesis, with emphasis on both academic research and industrial development [4 - 6]. The schematic representation of life cycle assessment is shown in Fig. (1).



Fig. (1). Life Cycle Assessment in Green synthesis.

TOXICITY STUDIES IN GREEN SYNTHESIS

To ensure that chemical innovations align with ecological and human safety, as well as environmental sustainability, toxicity studies are essential to the green chemistry framework. The inherent toxicity of intermediates, by-products, or even the finished product can pose serious risks, despite green synthesis's emphasis on safer reagents, renewable feedstocks, and energy-efficient techniques. Therefore, if toxicological factors are not carefully evaluated, a synthesis pathway that seems green on the surface could still pose health or environmental risks. Every phase of the chemical lifecycle, from raw materials and reaction conditions to waste streams and product applications, requires toxicity evaluation in green chemistry [7].

Some naturally occurring or "bio-based" reagents, for example, may be renewable but still exhibit high biological activity or persistence in ecosystems, leading to bioaccumulation or ecotoxic effects. Similarly, new catalysts or reaction media, such as ionic liquids or deep eutectic solvents, might offer environmental benefits, such as low volatility or recyclability, but it is possible that little is known about their long-term toxicological profiles.

CHAPTER 11

Case Studies in Green Chemistry: Pharmaceutical and Industrial Applications

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Abstract: Green chemistry has emerged as a sustainable approach for addressing the environmental and economic challenges associated with conventional chemical synthesis and industrial manufacturing processes. The incorporation of innovative synthesis technologies, including biocatalysis, microwave- and ultrasound-assisted methods, and nanotechnology, enables industries to adopt sustainable practices. Green chemistry principles have been successfully implemented through key case studies across pharmaceuticals, agriculture, textiles, and materials science. Through enzymatic techniques combined with solvent-free procedures, the pharmaceutical industry has improved drug development, and green nanotechnology has enabled sustainable nanocomposite manufacturing. The textile industry now uses plant-based dyes alongside energy-efficient dyeing techniques, as additional advancements in agrochemicals lower environmental toxicity through biopesticides. Green synthesis technology is applied in practice in this chapter, as the research describes its role in pharmaceutical drug development, environmentally friendly material production, and industrial improvement. The chapter includes comparative research demonstrating the major advantages of green synthesis approaches, including reduced waste output, increased energy efficiency, and lower environmental pollution. This chapter demonstrates the growing significance of sustainable chemistry in both industrial and academic research by presenting real-world examples and data analysis. Green chemistry demonstrates significant potential for future development through innovative strides that align with regulatory progress and broad industrial implementation, which leads to sustainable economic systems worldwide.

Keywords: Biocatalysis, Green chemistry, Green nanotechnology, Industrial sustainability, Life cycle assessment, Microwave-assisted synthesis, Pharmaceutical applications, Sustainable synthesis, Solvent-free synthesis, Ultrasound-assisted synthesis.

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INTRODUCTION

Traditionally, the pharmaceutical and chemical industries used hazardous solvents for synthesis, inefficiently utilized energy, and produced harmful compounds. The application of traditional methods results in significant environmental pollution, poses a threat to workplace safety due to exposure to hazardous materials, and increases manufacturing costs by requiring waste handling and increased energy use [1 - 4]. The industries have begun to consider environmentally friendly alternatives due to increased awareness of sustainability, improved regulations, and rising business benefits. Green chemistry and sustainable chemistry are used interchangeably by scientists to refer to current chemical designs that reduce the use of hazardous materials [5 - 8]. The main objectives of green chemistry are to ensure maximum atom economy and energy savings and to use renewable raw materials to reduce environmental harm caused by industry, without compromising operational efficiency and profitability [9 - 10]. Green chemistry cannot be complete without one of its fundamental elements: scientists developing green synthesis methods that substitute dangerous reactants with safer ones. It uses water-based and bio-based solvents rather than toxic organic chemicals and allows catalytic reaction systems that reduce energy requirements and waste generation [11 - 13]. Modern industries have begun implementing microwave-assisted, solvent-free synthesis to achieve higher reaction efficiency while reducing environmental impacts by minimizing hazardous emissions. Through green chemistry principles, industries now use enzymes and microorganisms for biocatalysis, as these biological agents drive chemical transformations under mild conditions while enhancing reaction selectivity and minimizing the production of unwanted by-products [14 - 18]. Green chemistry plays a vital role in more than just pharmaceutical development, affecting other sectors, including agrochemicals, materials science, and industrial manufacturing [19 - 21]. Research and development in pharmaceuticals has begun implementing sustainable drug synthesis approaches, as these methods improve operational efficiency while reducing production costs and complying with environmental regulations. Recycling enzymes serve as the primary tool in drug production to maximize efficiency and minimize waste [22 - 24]. Green nanotechnology approaches now allow scientists to create eco-friendly nanocomposites for material applications by designing enhanced material properties, including stronger structures and longer durability, as well as automated degradation features. The chapter examines current progress in green chemistry through applications in major industries with concrete case studies illustrating its success. The chapter provides an in-depth analysis of how green chemistry optimizes pharmaceuticals, agrochemicals, and industrial materials by improving efficiency, reducing waste, and minimizing environmental impact, as demonstrated in

Fig. (1). The examples illustrate the revolutionary nature of green synthesis, which is essential for creating sustainable industrial activities [25].

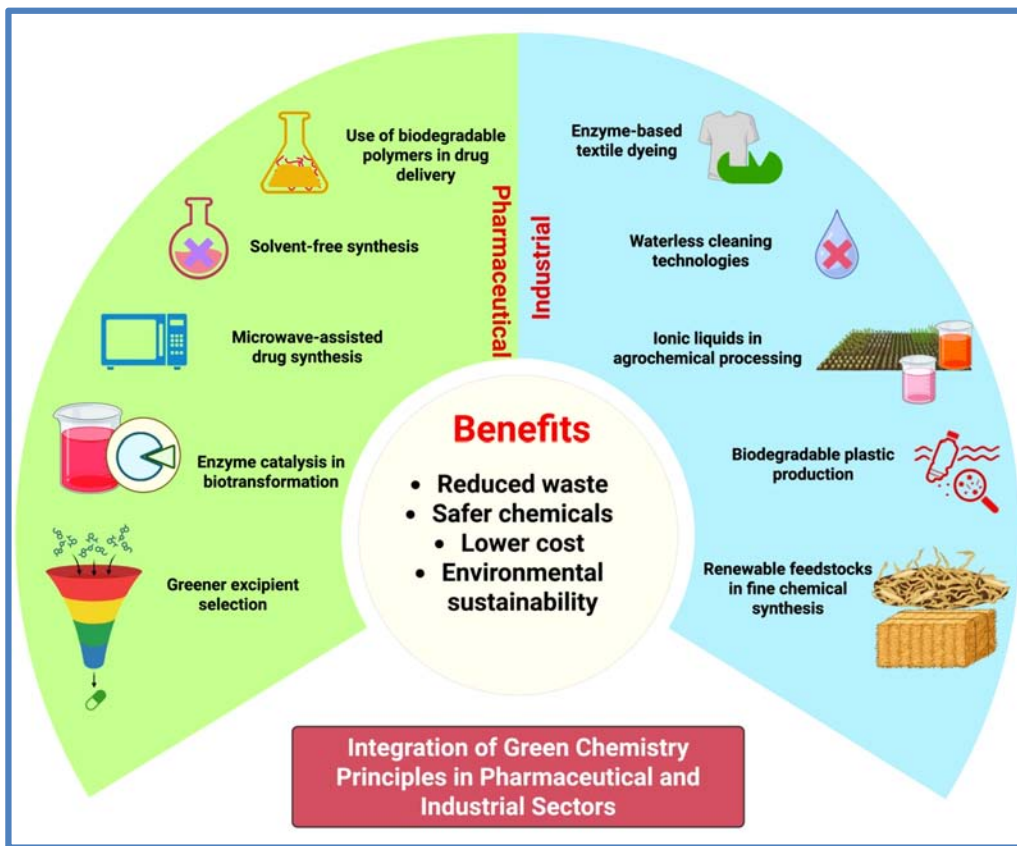


Fig. (1). Integration of principles of green chemistry in the industry and pharmaceutical sectors.

GREEN SYNTHESIS IN DRUG DEVELOPMENT

Green synthesis is necessary in drug development, as it offers eco-friendly approaches to replace conventional chemical synthesis processes. The pharmaceutical industry applies the principles of green chemistry in active drug development to reduce hazardous waste, improve reaction performance, and use renewable resources [26]. Today, the pharmaceutical industry is a pioneer in adopting green chemistry standards to reduce hazardous residues, enhance transformation, and introduce sustainable raw materials. Green synthesis is a technique in drug production that uses enzyme catalysis, microwave-mediated reactions, and solvent-free conditions to enable drug developers to reduce the use of toxic reagents and maximize drug yield. These methods make the production of

CHAPTER 12

Green Chemistry in Academia and Industry: Current Status and Future Vision

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Abstract: Over the last ten years, green chemistry has demonstrated basic scientific approaches to safeguarding the environment and human health in an economically viable way. Notable advancements are being made in several key scientific fields, including the development of renewable feedstocks, safer chemicals, environmentally friendly solvent design, and catalysis. The potential of chemistry to address many of the current environmental problems facing the world is demonstrated through outreach initiatives within the green chemistry community. A path to the economic and environmental prosperity that comes with living in a sustainable society is outlined in the history and foundations of green chemistry, and the revolution presents many difficulties for chemists working in research, industry, and education. Despite these difficulties, there are plenty of chances to learn and use new chemistry, boost the profitability of chemical production, and change the formerly negative perception of chemistry. This chapter thoroughly summarizes the state of green chemistry research today and how it has been incorporated into business operations. The obstacles to industries implementing green chemistry methods are examined, and the main areas of innovation in this field, including sustainable materials, green solvents, and green catalysis, are evaluated. To promote sustainable chemical practices worldwide, we also outline a future vision for green chemistry that emphasizes the value of interdisciplinary cooperation, policy creation, and education, and that depends on

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further developments in basic research, improved regulatory frameworks, and the expansion of sustainable technologies.

Keywords: Academia, Artificial intelligence, Bio-based materials, Biocatalysts, Catalysis, Circular economy, Drug synthesis, Environmental impact, Green chemistry, Sustainability.

INTRODUCTION

Green chemistry, also referred to simply as sustainable chemistry, is a scientific approach that seeks to develop chemical processes and products with the least possible negative environmental impacts, promote waste reduction, and support sustainability. Concentrating on stopping pollution at its source instead of addressing its effects is a proactive approach as opposed to a reactive one. Green chemistry is really important these days because it helps us address issues like resource depletion, climate change, and pollution. It is an essential part of going forward with science education [1]. The importance of green chemistry education increased as governments and businesses around the world began adopting greener approaches. It equips students with the knowledge and skills they need to design safer, greener chemical processes. By incorporating green chemistry into their program, future scientists and professionals can be taught to engineer materials and processes that are less environmentally and human-toxic, cost-effective, and more energy-efficient. Especially for non-chemists in allied disciplines (*e.g.*, Environmental science and engineering or pharmaceutical development) as well as chemists, attention needs to be paid to educating about green chemistry. This makes sustainability a central factor in scientific breakthroughs by enabling interdisciplinary creativity.

Academics are leading the way in green chemistry, making important contributions to research, education & industry partnerships, and policy advocacy. Educational institutions shall help advance green chemical methods for a cleaner, more sustainable future by fostering innovation that prioritizes sustainability. In recent years, the importance of green chemistry education has grown significantly. Academic institutions and educators have recognized the advantages of integrating green chemistry into their programs. Before teaching students how to measure waste, it is important for them to recognize what constitutes waste. This can be challenging, as trash is not just solid waste; it also includes dispersed pollutants in the form of liquids and vapors. This leads to the more intricate topic of effective waste management practices and the need to separate waste from non-harmful substances that can be safely released into the environment. Educational institutions are now concentrated on developing new educational resources and hands-on activities that highlight the benefits of green chemistry practices and stimulate consumer interest. It is feasible to incorporate green chemistry into the

existing curriculum. To create systems that are more effective, secure, fair, and sustainable than ever before, teachers ought to educate the next generation of scientists and engineers through training. The majority of the changes essential to a truly sustainable environment, like solar panels, carbon capture, and prevention rather than remediation, are within the Science, Technology, Engineering, and Mathematics (STEM) sectors[2]. Green chemistry must be fully integrated into the undergraduate curriculum to educate students for a sustainable future. Students should be exposed to an education that equips them with the vision, ethical values, and skills to conceive and design the disciplines that will be essential for their future and to enter into science as it stands. Toxicology and the preservation of human health and the environment must also be emphasized in chemistry classes.

The Importance of Green Chemistry

Green chemistry, a set of principles and framework that has been developed by and for chemists, represents a different way of thinking about chemistry that is more focused on the environment and the people involved in the process rather than the chemicals. The key factors are a new way of thinking about and practicing chemistry through protecting the environment and human health in chemistry research and application. Fashion shoes were largely developed decades ago with little consideration for environmental impact or human health [3 - 6].

Green chemistry courses and curricula are very beneficial to students because they learn how chemistry can solve some of the world's most pressing sustainability-related issues; this makes the chemistry classroom matter and relevant. Systems thinking has been gaining more ground in preparing chemistry students with the skills to integrate sustainability into green chemistry applications [7, 8].

By the twenty-first century, chemists became fully aware of the dangers, effluents, and toxicity inherent in their profession. The community made laboratory work much safer with fume hoods and Personal Protective Equipment (PPE) such as safety glasses, gloves, closed shoes, and flame-retardant laboratory coats [9, 10]. Every time an obsolete approach must be replaced by a new one, the educator will realize that teaching a more moral application of chemistry is very difficult [11 - 13].

Resources Requirement in Laboratories and Classrooms

There are, however, many important prerequisites for integrating green chemistry into undergraduate curricula, the most significant of which is the time required for faculty to develop these programs. Senior faculty must be freed from their current teaching duties to develop wholly new introductory textbooks and/or to design

CHAPTER 13

Policy Implications, Economic Assessments, and Public Engagement

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Abstract: The increasing demand for sustainable and environmentally friendly chemistry has driven significant advancements in green synthesis methods. These approaches aim to minimize hazardous substances, reduce energy consumption, and utilize renewable resources, aligning with global sustainability goals. Traditional chemical processes often incur high environmental and economic costs due to waste generation and dependence on non-renewable resources. Green synthesis addresses these challenges through cleaner technologies, including biomimetic catalysis, microwave-assisted synthesis, and solvent-free processes. These innovations offer substantial benefits such as reduced carbon footprints, cost savings from waste minimization, and compliance with stringent environmental regulations. Market analyses indicate a growing consumer preference for green products, opening new economic opportunities. However, successful adoption requires a multidisciplinary approach involving scientific innovation, policy support, and public engagement. Incentives for green R&D, standardized certifications, and educational initiatives can accelerate implementation and acceptance. Addressing challenges like scalability, resource availability, and financial constraints is crucial for mainstreaming these methods. This chapter highlights the necessity of bridging scientific progress with policy and societal engagement to advance green synthesis. The integration of sustainable chemical practices promises a future that is environmentally responsible, economically viable, and aligned with global sustainability objectives.

Keywords: Advanced chemical methods, Alternative energy sources, Biodegradable materials, Biomimetic catalysis, Circular economy, Eco-friendly processes, Economic assessments, Energy efficiency, Environmental impact, Green chemistry.

INTRODUCTION

In tackling urgent global issues like sustainability, resource depletion, and environmental degradation, green synthesis techniques in chemistry represent

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a major advancement. Green chemistry is crucial for mitigating the negative effects of chemical processes by reducing waste, energy consumption, and the use of hazardous chemicals. To ensure these technologies effectively address sustainability goals, broader considerations like policy, economic viability, and public engagement are essential. The goal of green synthesis is to shift from risky, energy-intensive processes to eco-friendly methods that use renewable resources and generate fewer byproducts. While scientific advancements have revolutionized the field, supportive legislative frameworks are necessary for widespread adoption. Governments play a key role by enforcing environmental standards, enacting laws that promote sustainable practices, and offering financial incentives for research and innovation [3]. Economic factors also influence the adoption of green synthesis. While initial costs for specialized personnel, catalysts, and infrastructure may be high, long-term savings result from easier regulatory compliance, lower waste disposal costs, and reduced energy use [4, 5]. Companies adopting green synthesis can gain a competitive edge as demand for eco-friendly products rises. However, high costs and limited renewable feedstocks may hinder smaller businesses, making scalability and market conditions crucial considerations [6]. Public involvement is essential to advancing green synthesis. Awareness of its benefits, such as improved health and environmental impact, can drive demand for sustainable goods and encourage businesses to adopt greener practices. Open communication about green technologies builds trust among scientists, companies, and the public. Engaging stakeholders, including policymakers and community organizations, ensures that sustainability efforts align with societal values [7, 8]. The interplay between policy, economics, and public engagement shapes the success of green synthesis. While scientific advancements provide the foundation, their impact depends on supportive policies, economic feasibility, and societal readiness. Policymakers must establish regulations and incentives, while economic evaluations should consider financial and indirect benefits, such as reduced environmental damage and improved public health. Public engagement creates societal demand, fostering innovation and a commitment to sustainability [9]. Despite its potential, the shift to green synthesis faces obstacles. Varying resources, technological access, and financial capacity affect adoption rates, particularly in developing countries and smaller businesses. International collaboration, knowledge sharing, and funding are crucial to overcoming these barriers and ensuring a global transition to sustainable practices [10 - 12].

POLICY DEVELOPMENT FOR SUSTAINABLE CHEMICAL PRACTICES

The chemical industry is vital to the global economy, providing essential materials for manufacturing, agriculture, healthcare, and energy sectors [13]. However, traditional chemical processes have contributed to environmental degradation, resource depletion, and health risks [14]. Addressing these concerns has increased focus on sustainable chemical practices [15]. Green chemistry aims to reduce the environmental and health impacts of chemical processes by improving efficiency, minimizing waste, and transitioning to renewable resources [16, 17]. Policymaking plays a key role in facilitating this transition by creating

frameworks, regulations, and incentives that drive innovation, enhance industry adoption, and achieve sustainability objectives (Table 1).

Table 1. Policy approaches and their impacts on sustainable chemical practices.

Policy Approach	Description	Potential Impacts
Regulations and Standards	Limits on emissions, waste, and hazardous chemicals (e.g. REACH, TSCA).	Ensures environmental protection, compliance with safety standards [18]
Incentives for Innovation	Financial support, such as tax credits or grants, for green chemistry R&D.	Encourages adoption of sustainable technologies and lowers barriers to innovation [19]
Education and Awareness	Campaigns and training programs to promote green chemistry principles.	Enhances public and industry knowledge, fostering acceptance and implementation [20]
International Cooperation	Aligning global policies under frameworks like the UN's SDGs.	Facilitates unified global efforts to tackle sustainability challenges [21]
Public-Private Partnerships	Collaboration between the government and industries for green chemistry advancement.	Leverages combined resources for large-scale innovation and implementation [22]
Circular Economy Policies	Encouraging recycling and reuse to minimize waste and reliance on virgin resources.	Promotes resource efficiency and supports long-term sustainability goals [23 - 25]

The Case for Sustainable Chemical Practices

The chemical industry has been fundamental to contemporary society, manufacturing products such as medications, polymers, fertilizers, and solvents. Nonetheless, the detrimental environmental and health impacts of conventional chemical manufacturing have become increasingly apparent. Activities within this sector frequently entail toxic substances, substantial energy usage, and hazardous waste, resulting in pollution, ecological degradation, and resource depletion [26 - 27]. Amidst climate change and increasing sustainability concerns, the chemical industry faces intensified pressure to implement environmentally friendly methods. Sustainable chemistry prioritizes minimizing adverse environmental effects, enhancing resource efficiency, and decreasing dependence on non-renewable resources [28]. This transition is fundamentally based on green chemistry concepts, which encompass the utilization of renewable feedstocks, the development of safer chemicals, and the implementation of energy-efficient technologies [29]. Policymakers are instrumental in this transformation by establishing regulations and incentives that propel industries towards sustainable practices. Effective rules may mitigate detrimental emissions, foster safer materials, and develop cleaner technology, all while accommodating scientific

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