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Green chemistry in medicinal chemistry: A review on sustainable approaches to the synthesis of biologically active compounds

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Abstract

The pharmaceutical industry's commitment to sustainability is reshaping drug development, centering on green chemistry principles to minimize environmental impact without compromising drug efficacy. This review explores transformative green chemistry approaches, emphasizing atom economy, waste reduction, and renewable feedstocks in synthesizing biologically active compounds. Key advancements such as biocatalysis, flow chemistry, and safer solvent alternatives demonstrate a path to efficient, lower-impact drug synthesis. These sustainable strategies, while challenged by regulatory and industrial constraints, showcase significant potential to reduce the pharmaceutical carbon footprint and environmental toxicity. Through the integration of green methodologies, the industry can address pressing ecological challenges, improve public health, and foster a paradigm shift toward sustainable pharmaceutical production.

Keywords: Sustainability; Drug discovery; Green chemistry; Waste reduction; Renewable feedstocks; Environmental impact

1. Introduction

1.1. Overview of Green Chemistry principles

Designing chemical processes and products with the least possible negative effects on the environment and maximum sustainability is the goal of green chemistry. This strategy is defined by twelve fundamental principles that emphasize efficiency and waste reduction, as articulated by (Anastas & Werner, 2000). Atom Economy promotes optimizing the integration of raw materials into the finished product, thereby minimizing waste, whereas prevention emphasizes the need to prevent waste from being created rather than managing it after it has been created (Anastas & Werner, 2000). Designing reactions with less toxic compounds promotes safety for the environment and human health, which is the idea behind Less Hazardous Chemical Syntheses (Cannon et al., 2012). Ensuring that the finished products are efficient with low toxicity, protecting users and ecosystems, is the emphasis of another principle called Designing Safer Chemicals (Sheldon, 2014). Green chemistry's objectives for safety and the environment are in line with the practical use of safer solvents and auxiliary materials, which helps minimize the use of hazardous solvents in chemical manufacture (Anastas & Werner, 2000). Another essential component of green chemistry is energy efficiency, which promotes the creation of chemical processes with lower energy consumption and that function at room temperature and pressure, thereby leaving a less carbon imprint (Constable et al., 2022). Furthermore, whenever feasible, renewable feedstocks—which use raw materials generated from sustainable resources rather than depletable ones—are favoured (Sheldon, 2014).

Reducing Derivatives is another important idea. It prevents needless changes to chemical compounds that call for extra reagents and procedures, which would otherwise result in waste and resource consumption (Jiménez-González & Constable, 2011). By increasing chemical reaction efficiency and lowering energy and reagent requirements, catalysis

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helps to minimize waste in chemical reactions (Tao et al., 2011). Furthermore, the goal of Design for Degradation is to guarantee that chemical products, upon reaching the end of their useful life, transform into innocuous compounds, so averting long-term environmental damage (Anastas & Werner, 2000). With the use of real-time analysis for pollution prevention, chemical interactions can be observed as they happen, improving control and lowering the production of dangerous compounds (Sheldon, 2014). Lastly, to safeguard both the environment and workers, Inherently Safer Chemistry for Accident Prevention promotes the design of chemicals and processes that limit risks, such as explosions or unintentional releases (Cannon et al., 2012).

Every pharmaceutical corporation has always pledged to supply cutting-edge medications to raise living standards everywhere. In order to synthesize biologically active molecules, this research study investigates sustainable green chemistry methodologies in medicinal chemistry. Companies must move from classic synthetic techniques to a modern, inventive mechanism to achieve this goal in an environmentally responsible manner (Singh & Pandey, 2020). Large companies and small businesses alike have already made progress toward sustainable adaptation by changing their chemical production processes to produce products using green synthesis based on green chemistry principles (Figure 1).

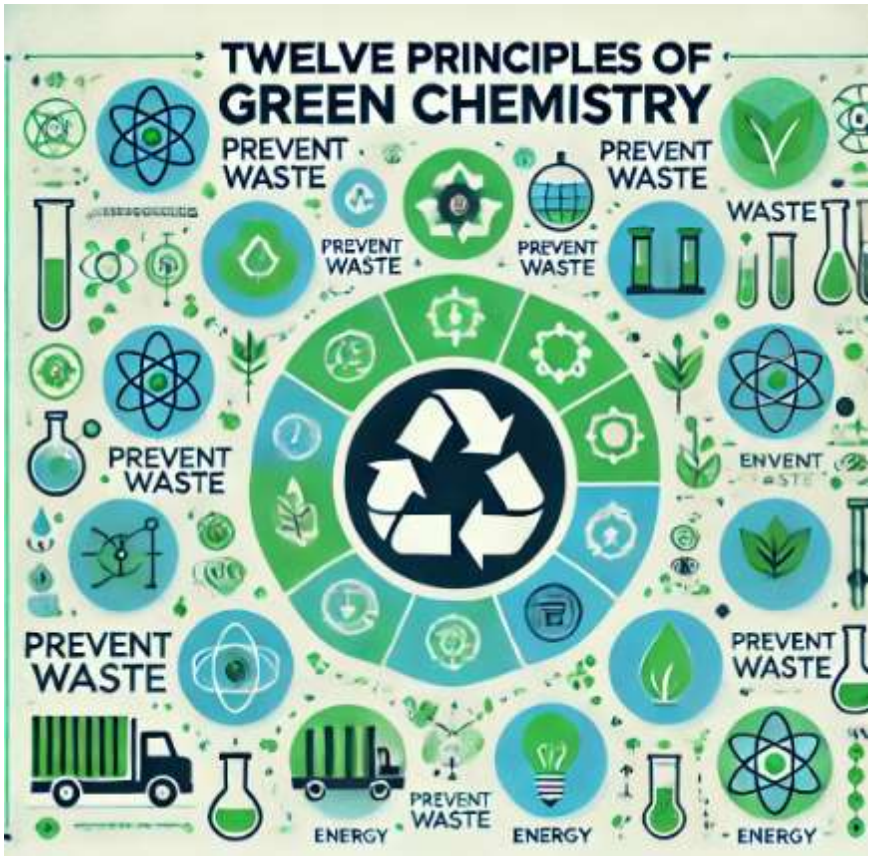

Figure 1 Twelve Principles of Green Chemistry

Research Objectives

The main aim of this study is to investigate and assess sustainable, green chemistry methods in medicinal chemistry, particularly regarding the synthesis of biologically active molecules. This review seeks to evaluate contemporary green chemistry concepts utilised in the synthesis of pharmacologically active molecules by examining recent advancements, techniques, and sustainable practices.

1. Identify essential techniques, reagents, and catalysts that reduce environmental impact and promote sustainability in drug synthesis.
2. Assess the effectiveness, scalability, and market potential of environmentally friendly synthetic methods to produce biologically active chemicals.
3. Promote the broader implementation of sustainable practices by showcasing successful instances and exemplary methods in green chemistry within the pharmaceutical sector.

1.2. Research Objectives

This review is structured on the subsequent research questions:

a) What are the principal green chemistry principles presently utilised in the production of physiologically active compounds?
b) Which green procedures and techniques are most efficacious in mitigating environmental impact in medicinal chemistry?
c) In what ways do green synthetic methodologies contrast with conventional techniques regarding efficiency, cost-effectiveness, and viability for large-scale pharmaceutical manufacturing?
d) What are the constraints and obstacles related to the adoption of green chemistry methodologies in the pharmaceutical sector?
e) In what ways might innovations in green chemistry enhance the future of sustainable pharmaceutical development?

1.3. Rationale of the review article

This review is necessitated by the pressing need to mitigate the environmental consequences of conventional drug manufacturing techniques. The pharmaceutical sector has historically been linked to significant waste generation, resource utilisation, and the application of hazardous substances, which provide environmental and health hazards. Integrating green chemistry concepts enables the sector to adopt more sustainable procedures that minimise waste, reduce harmful by-products, and lower energy consumption. This review aims to connect theoretical green chemistry ideas with their practical implementation in medicinal chemistry. This examination of sustainable techniques aims to offer significant insights and evidence to foster the wider adoption of green methodology, thereby facilitating a transition to environmentally responsible drug synthesis practices.

2. Relevance of Green Chemistry in Medicinal Chemistry

2.1. Importance of sustainable synthesis of biologically active compounds

Green synthesis seeks to minimize energy waste, maximize consumption, and supply power from renewable sources. Pharmaceutical businesses are the largest contributors to the global economy, bringing in a total of 1.27 trillion dollars annually, but they are also a major contributor to the carbon footprint, producing over 1.9 million tons of CO_2 annually (Bandichhor, 2018). Although the idea of environmental preservation was first proposed ten years ago, many of the initiatives failed because industry cooperation was lacking. The Industrial Nations have always sought to control output and pinpoint procedures to lessen their environmental impact, but these industries were never pleased with the previous concepts (Mishra et al., 2021).

2.2. Relevance of Green Chemistry in Medicinal Chemistry

By encouraging sustainable methods in the synthesis, design, and manufacturing of pharmaceutical substances, green chemistry plays a critical role in medicinal chemistry (Constable, 2007). Efficiency is increased and the environmental effect of medication synthesis is decreased through the use of renewable feedstocks and atom economy. Additionally, creating safer solvents and chemicals results in less harmful medications, which enhances patient safety and environmental results (Constable, 2007). Green chemistry aids in the development of more hygienic synthetic pathways for active pharmaceutical ingredients (APIs) in medicinal chemistry. The industry reduces undesirable byproducts by using catalysis to increase reaction efficiency and substituting safer reagents for those that are more hazardous (Clark & Tavener, 2007).

Furthermore, the application of flow chemistry and biocatalysis makes API production more sustainable by lowering the need for fossil fuels and improving production scalability (Sheldon, 2014). The synthesis of the HIV medication Efavirenz is a prime example, where the use of Green Chemistry principles resulted in a 90% decrease in waste production, reduced energy expenses, and enhanced yield. The incorporation of Green Chemistry into medicinal chemistry results in more environmentally friendly medication production procedures without sacrificing performance, as the need for sustainable pharmaceutical practices rises (Anastas & Eghbali, 2010; DeVito et al., 2015).

2.3. Environmental and health impacts of traditional synthetic methods in medicinal chemistry

Hazardous compounds are frequently used in traditional synthetic methods of medical chemistry, which provide serious threats to human health and the environment. Toxic reagents and solvents are used in many pharmaceutical operations, which can result in hazardous byproducts. For example, the use of organic solvents such as dichloromethane

and benzene not only increase the risk of cancer and other health problems for workers but also leads to pollution of the air and water. When these dangerous materials are not properly disposed of, the ecosystem deteriorates more quickly and soil and water resources get contaminated (Cooper et al., 2011; Schlosser et al., 2015; Irena et al., 2011).

These problems are exacerbated by the trash that is produced via standard synthetic approaches. A large percentage of the reactants in a pharmaceutical synthesis generally have low atom economy, which means they don't contribute to the desired outcome. This can result in a significant quantity of waste. Due to this inefficiency, there is a significant amount of hazardous waste that needs to be managed and disposed of carefully (Sheldon, 2014). For instance, it has been demonstrated that the synthesis of some antibiotics can result in waste ratios of up to 100:1, meaning that only a small portion of the input materials are transformed into active pharmaceutical ingredients (API) (Roschangar et al., 2021). This not only raises operating expenses but also presents a problem for environmental sustainability and regulatory compliance.

Furthermore, these actions taken together may have a significant impact on public health. Pollutants from pharmaceuticals can upset ecosystems, injure wildlife, cause bioaccumulation, and perhaps expose humans downstream in the food chain (Connors et al., 2013). Research has connected the presence of pharmaceutical pollutants in drinking water to a number of health problems, such as antibiotic resistance and hormone imbalances (Deo & Halden, 2013; Furlong et al., 2017). These results highlight the necessity for the pharmaceutical sector to shift to synthetic methods that are more sustainable and greener.

3. Synthesis Methods, Types of Biologically Active Compounds, and Their Applications

Medicinal chemistry employs a wide range of synthesis techniques, including combinatorial chemistry, chemical synthesis, and biocatalysis. Conventional organic synthesis uses a variety of chemical reactions to create complex molecules, whereas biocatalysis uses enzymes or entire cells to speed up chemical reactions. Rapid synthesis of a variety of chemical libraries for high-throughput screening is made possible by combinatorial chemistry (Margetić & Štrukil, 2020). The biologically active substances that are produced using these techniques include antivirals, anticancer agents, and antibiotics, all of which are vital for the treatment of different illnesses. For example, paclitaxel, a medication derived from the Pacific yew tree, is an efficient chemotherapy agent, while penicillin, an antibiotic, has transformed the treatment of bacterial infections (Newman & Cragg, 2007).

3.1. Contribution to the Reduction of Hazardous Waste in Pharmaceutical Production

The adoption of greener synthesis methods significantly contributes to the reduction of hazardous waste in pharmaceutical production. For example, the use of flow chemistry and microwave-assisted synthesis has been shown to enhance reaction efficiency, thus minimizing waste generation. Flow chemistry enables precise control over reaction conditions, leading to higher yields and reduced by-products compared to traditional batch methods (Trojanowicz, 2020; Hughes, 2020; Ley, 2012; Baumann et al., 2021). Moreover, the implementation of biocatalysis often results in fewer hazardous by-products, as enzymes typically operate under mild conditions and can be highly selective, thus enhancing atom economy and minimizing environmental impact (Bornscheuer et al., 2012).

3.2. Advancement of Sustainable Practices in Drug Discovery

Sustainable methods are being used more often in the drug development industry with the goal of lowering environmental impact and enhancing safety. Molecules can be virtually screened using methods like computer-aided drug design (CADD), which eliminates the requirement for labour-intensive physical synthesis of potentially unfeasible molecules (Barrawaz, 2020). The transition to sustainability is also demonstrated using greener solvents and renewable materials in the synthesis of pharmaceuticals. Pharmaceutical companies are collaborating to implement green chemistry concepts, thanks to initiatives like the Pharmaceutical Roundtable that highlight the significance of sustainability in medication development (Simon & Li, 2012; Kar et al., 2021). This all-encompassing strategy improves the effectiveness and safety of the medication development process while simultaneously lowering environmental footprints.

4. Applications in Medicinal Chemistry

4.1. Case studies of successful green synthetic approaches in drug development

Improved design ABT-546 - The procedure for the manufacture of the endothelin- was previously published by (Mishra et al., 2021). An outstanding illustration is given by the antagonist ABT-546 (Neerhoof et al., 2011). A similar approach

was used to create a cost-effective and selective catalytic process technique. In most cases, this approach works well when non-linearity results from prochiral initial material (Table 1). The racemic pyrrolidine core of ABT-546 was prepared by a polymerized method, however it needed to be resolved with D-tartaric acid afterwards. Nevertheless, only 40% resolved tartrate salt was produced after multiple recrystallizations. To support several impending clinical trials, an asymmetric synthesis of the pyrrolidine core is unquestionably needed.

A catalytic, highly enantioselective conjugate addition was created after meticulous screening and analysis. This involved catalysing the addition of the b-ketoester anion 15 to the nitroolefin 16 using a 4 mol% bis(oxazoline) - Mg (OTf)2 amine complex. By achieving 88% selectivity in this addition, the chiral purity might be upgraded with less reliance on the tartrate salt. Using green solvents in the last stages of drug manufacturing has the distinct benefit of reducing concern over any residual in the API (Valavandis & Vlachogianni, 2012).

Water was intended to be used as a co-solvent in the final three phases of the synthesis of ABT-546. With potassium carbonate (K_2CO_3), the free base present in the THF layer, the tartrate salt was broken. After that, aqueous $NaHCO_3$ and bromoacetamide were added to the THF solution of the free base, and the reaction was heated until alkylation was achieved. Following separation, ethanol was used to dilute the product in the THF layer. Lastly, saponification was accomplished using aqueous NaOH. Without the requirement for extraction or solvent removal, the three-step, one-pot method produced the free base of ABT-546 in an exceptional yield (96%) (Mishra et al., 2021)

Table 1 Green solvent process in the synthesis of Sertraline Hydrochloride (Mishra et al., 2021)

SN.	Traditional (Conventional) Method	Green Method
1	Multiple Step Synthesis of Tetralone	Single Step Formation of Imine + Tetralone
2	Condensation of Tetralone with Methylamine in Presence of Titanium Chloride	Use of Selective Palladium Catalyst to Reduce Formation of Impurities
3	Reduction of Imine Double bond Lead to Rac-cis and Rac-Trans Amines	Reduction of the Imine Function
4	Resolution D-Mandelic Acid at the Endo of the Process	Formation of Chilarry Pure Sertaline
5	Recovery of Four Solvents: Methylene Chloride, Tetrahydrofuran, Toluene, Hexane	Use of Benign Solvent Ethanol for the combined process

Biocatalysts (The Medicine Paroxetine): The overall yield was nearly twice as high as the old standard procedure, resulting in a quicker, more economical, and environmentally friendly process. Applying the protease enzyme, which hydrolysed an ester group with regioselectivity (Mishra et al., 2021) was the most crucial step.

4.2. Sustainability in drug discovery and development

4.2.1. Challenges in Sustainable Synthesis

In medicinal chemistry, sustainable synthesis faces a number of difficulties, chief among them being how to maximize environmental effect while preserving efficiency. The intrinsic complexity of pharmacological compounds is a significant obstacle since they frequently call for certain synthesis processes that could entail toxic reagents or produce dangerous byproducts (Kumar et al., 2021). Furthermore, it might take a lot of time and effort to optimize green processes; in order to find viable green alternatives without sacrificing the final product's quality or effectiveness, significant research and development activities are frequently needed (Roy et al., 2000). One major obstacle in the pursuit of sustainability is continuing to strike a balance between the requirements for strong and trustworthy synthetic methodologies and the principles of green chemistry.

4.2.2. Common Barriers to Adopting Green Chemistry in the Pharmaceutical Industry

Several obstacles stand in the way of the pharmaceutical business using green chemical methods. The industry's conservative stance, which frequently favours tried-and-true procedures over cutting-edge ideas, is one major obstacle. Businesses may be reluctant to invest in novel technologies or techniques because of worries about safety, legal compliance, and possible production interruptions (González, 2021). Furthermore, businesses may be discouraged from investigating sustainable alternatives by the belief that using green chemistry results in increased manufacturing costs. It is difficult for businesses to make the switch to more sustainable operations since there are no incentives or legal frameworks that support the adoption of greener practices (Tao & Kazlauskas, 2011).

4.2.3. Technological Limitations and Cost Concerns

Another major barrier to the widespread use of green chemistry in pharmaceutical production is technological restrictions. Many green technologies, such as flow chemistry and advanced biocatalysis, call for specialized tools and knowledge that are not always available in pharmaceutical manufacturing facilities (Chigorimbo-Murefu et al., 2012). Additionally, there may be significant upfront expenditures associated with these technologies, making them unaffordable for startups or businesses with narrow profit margins. Furthermore, even while using greener practices might lessen waste and its negative effects on the environment, the initial expenses of research, development, and implementation frequently prompt questions regarding profitability and return on investment (Henkel & Rønde, 2018). Therefore, encouraging sustainable practices in the pharmaceutical industry requires overcoming these financial and technological obstacles.

5. Application of Green Chemistry Principles in the Synthesis of Drugs

5.1. Design of Drugs

The environmental impact of drug development must be given equal weight with effectiveness and safety when using the principles of green chemistry in drug design. The goals are to decrease the need for hazardous chemicals, cut waste, and enhance pharmaceutical sustainability. The following key facets of green chemistry are relevant to medication design:

5.1.1. Atom Economy

The atomic economy, which gauges a chemical reaction's efficiency by counting the percentage of atoms that make up the final product, is one of the fundamental concepts of green chemistry (Hui et al., 2023). The ratio of the total mass of atoms in the predicted product to the total mass of atoms in all reactants is indicated by the measure, which is given as a percentage. Greater atomic economies equate to reduced waste creation and higher resource efficiency. In chemical synthesis, atom economy strongly emphasises making the most use of reactants and reducing the creation of byproducts or unintended side reactions (Gou et al., 2022).

Chemical engineers can decrease material waste, preserve resources, and enhance the sustainability of chemical processes by refining reaction conditions and creating synthetic routes that give priority to atom-efficient transformations (Buskes et al., 2023). In order to evaluate the effectiveness and environmental impact of chemical reactions, atom economy is a crucial parameter that directs the creation of more environmentally friendly and sustainable chemical processes in the interest of sustainable development goals (Fan et al., 2023).

5.1.2. Renewable Feedstocks

A variety of sustainable and renewable raw materials, including plants, algae, biomass waste, and agricultural leftovers, are used in production processes. Renewable feedstocks have the benefit of constantly replenishing themselves through natural processes like photosynthesis, in contrast to fossil-based feedstocks, which are limited and non-renewable (Haydari & Kiyani, 2023). Vegetable oils, starch, cellulose, lignin, and sugars generated from biomass are a few examples of renewable feedstocks. Through a variety of chemical and biological processes, these feedstocks can be transformed into a wide range of valuable products, such as biofuels, bioplastics, biochemicals, and medicines.

Renewable raw materials offer numerous environmental and financial benefits, including decreased greenhouse gas emissions, decreased reliance on fossil fuels, and enhanced resource sustainability (Simic et al., 2022). Renewable raw resources also aid in the growth of a bio-based economy, which fosters innovation, the creation of jobs, and the development of rural areas (Rai et al., 2024). In order to prevent climate change, preserve natural resources, and promote a sustainable future as the world transitions to a more sustainable and circular economy, it is imperative that renewable feedstocks be used. The utilization of renewable raw materials aligns with the principles of green chemistry, which highlight the need for using renewable resources, cutting waste production, and encouraging ecologically friendly methods in the chemical industry (Rai et al., 2024).

5.1.3. Biocatalysis

Utilizing the catalytic potential of entire cells or enzymes, biocatalysis is a green chemistry strategy that promotes environmentally benign and sustainable chemical transformations. According to (García-Fernández et al., 2023), enzymes are biological catalysts that are created by living things like fungus, plants, and bacteria. They have a high selectivity and efficiency in catalysing certain chemical reactions. These organic catalysts are used in biocatalysis to carry out a variety of moderate chemical reactions, such as synthesis, transformation, and degradation reactions. In

contrast to conventional chemical catalysts, which frequently necessitate severe reaction conditions and produce hazardous byproducts, biocatalysts function in mild pH and temperature environments, minimizing their negative effects on the environment and consuming less energy (Moermond et al., 2022).

Several benefits of biocatalysis include compatibility with aquatic settings, high substrate specificity, and regio- and stereoselectivity. According to (Rai et al., 2024), this technique holds great value in the fine chemical, pharmaceutical, and agrochemical industries as it facilitates the synthesis of complicated compounds with exceptional efficiency and purity. Furthermore, the development of a sustainable bioeconomy is aided by biocatalysis's ability to harness renewable feedstocks and produce bio-based products and chemicals. Biocatalysis, which aligns with the concepts of green chemistry and promotes environmentally conscious practices in the chemical industry, offers a sustainable and green approach to chemical synthesis by utilizing the power of nature's catalysts (Malik et al., 2022).

5.1.4. Microwave and Ultrasonic-Assisted Synthesis

Chemical synthesis can benefit from the novel approaches of microwave and ultrasonic-assisted synthesis, which increase yields, shorten reaction durations, and speed up reactions (Rai et al., 2024). Compared to traditional approaches, these techniques use microwave or ultrasonic radiation to speed up chemical reactions and encourage molecular interactions, resulting in more sustainable and effective synthesis processes (Malik et al., 2022). By subjecting reaction mixtures to microwave radiation, which quickly warms the reactants, microwave-assisted synthesis produces higher reaction rates and faster reaction times. This method works especially well for processes that have sluggish kinetics or need high temperatures (Li et al., 2023). By using ultrasonic waves to produce cavitation bubbles in the reaction mixture, ultrasonic-assisted synthesis, on the other hand, promotes faster and more uniform reactions by improving mass transfer and facilitating mixing.

Reduced energy usage, less solvent quantities, and increased product yields are just a few benefits of both microwave and ultrasonic aided synthesis (Rai et al., 2024). With increased efficiency and selectivity, a variety of organic and inorganic molecules can be synthesized thanks to these approaches. Furthermore, because microwave and ultrasonic aided synthesis usually calls for lower reaction temperatures, shorter reaction times, and less solvent consumption, which minimizes waste production and environmental impact, they are also consistent with the concepts of green chemistry (Rai et al., 2024).

Researchers and industry practitioners can further green chemistry and sustainable practices in the chemical industry by developing more environmentally friendly and sustainable synthesis methods using microwave and ultrasonic radiation. The first image explains the fundamentals of green chemistry (Malik et al., 2023)

5.1.5. Safer Solvents and Reagents

Safer reagents and solvents are needed for green chemistry, which aims to lessen the risks chemical processes have to the environment and public health. In comparison to their conventional counterparts, these solvents and reagents are chosen for their enhanced biodegradability, decreased volatility, and decreased toxicity (Singh et al., 2024). Safer solvents are defined as those that can dissolve materials efficiently with the least amount of harm to the environment and public health. These substitutes have benefits including low toxicity, nonflammability, and recyclable nature. Ionic liquids, supercritical carbon dioxide, and water are a few examples (Castiello et al., 2023).

In a similar vein, safer reagents are made to promote chemical reactions with the least amount of waste or dangerous byproducts. In order to decrease the use of hazardous chemicals and lessen the environmental impact of chemical processes, these reagents place a high priority on efficiency, selectivity, and safety (Rai et al., 2024). By incorporating safer solvents and reagents into chemical synthesis, scientists and business experts can lower risks to public health, lessen environmental damage, and encourage sustainable practices in the chemical sector (Simic et al., 2022). The move toward safer substitutes is consistent with green chemistry concepts, which emphasize the need to develop chemical processes that prioritize sustainability, safety, and environmental protection (Win, 2023).

5.2. Environmental Impact of Traditional Synthetic Routes in Comparison to Sustainable Approaches

Due to the widespread use of dangerous chemicals and solvents, traditional synthetic approaches in medicinal chemistry frequently have a substantial negative influence on the environment. Many synthetic pathways are characterized by low atom economy, which means that only a small fraction of the starting elements is converted into the intended product, and as a result, these procedures frequently result in considerable waste creation (Sheldon, 2014). This inefficiency adds to pollution by releasing hazardous byproducts into the environment and causes significant problems with trash management. Conventional pharmaceutical synthesis techniques, for example, can yield waste

ratios more than 100:1, requiring strict waste management procedures that increase environmental concerns (Gadipelly et al., 2014).

Sustainable methods, on the other hand, emphasize waste reduction and the use of safer chemicals and solvents. By increasing yield and reducing potentially harmful byproducts, methods like flow chemistry and biocatalysis improve efficiency (Bornscheuer et al., 2012). These techniques frequently work in milder environments, which further reduces energy use and environmental impact. By implementing sustainable techniques, pharmaceutical production can have a smaller overall environmental impact, resulting in cleaner processes that adhere to the principles of green chemistry and promote ecological health over the long run (Eissen et al., 2021).

6. Sustainability in Drug Discovery and Development

The need for sustainability in drug research and discovery is becoming more widely acknowledged as a means of reducing the negative environmental effects of pharmaceutical production without sacrificing the efficacy and safety of novel medications. This strategy includes several tactics meant to cut down on waste, preserve resources, and improve the overall effectiveness of the drug development process. Integrating sustainable practices has become a priority as the pharmaceutical business comes under increasing scrutiny for its environmental impact. Using green chemistry concepts in synthetic processes is one of the keystones of sustainable drug discovery. Traditional (conventional) synthetic techniques produce large amounts of waste and frequently use dangerous substances. Green chemistry, on the other hand, places more emphasis on the utilization of efficient synthetic routes and safer, renewable resources (Sheldon, 2014). Researchers can considerably lessen the environmental impact of drug synthesis by using techniques including solvent-free reactions, the use of non-toxic solvents, and catalysis (Proctor et al., 2010; Becker et al., 2022). A prime example of the promise for sustainable approaches in pharmaceutical development is the synthesis of the antiviral medication Remdesivir, which was done using greener methods that reduced waste and environmental pollution (Spinner et al., 2020).

Technological developments, in addition to green chemistry, are essential for improving sustainability in drug discovery. The identification of possible therapeutic candidates has been transformed by high-throughput screening and computer-aided drug design (CADD), which enable scientists to quickly assess large libraries of chemicals (Ou-Yang et al., 2012; Sang et al., 2018). By avoiding the requirement for laborious physical synthesis of potentially unviable molecules, these methods preserve resources and cut down on waste. Additionally, the identification and optimization of drug candidates can be streamlined by using artificial intelligence and machine learning in drug discovery procedures, which will reduce the amount of time and money needed for development (Hasslegren & Oprea, 2024).

Fostering sustainability in drug research and development also requires cooperation between academic institutions and pharmaceutical businesses. The adoption of sustainable practices and green chemistry principles is facilitated by initiatives like the Pharmaceutical Roundtable, which encourages industry stakeholders to share best practices and research findings (Simon & Li, 2012; Kar et al., 2021). These kinds of partnerships have the potential to provide more environmentally friendly procedures as well as standards and guidelines that promote the inclusion of sustainability in every facet of drug discovery. Furthermore, regulatory frameworks are realizing more and more how crucial sustainability is to the advancement of pharmaceuticals. Environmental factors are starting to be included in the evaluation procedures of organizations like the European Medicines Agency (EMA) and the U.S. Food and Drug Administration (FDA) (Asad & Popesko, 2022). These regulatory organizations can stimulate innovation and enhance the pharmaceutical industry's overall environmental performance by pushing businesses to implement sustainable practices.

The full implementation of sustainable approaches in drug discovery and development still faces obstacles, notwithstanding significant achievements. It may be difficult for green chemistry and sustainable practices to become widely used due to obstacles like financial worries, technology constraints, and the pharmaceutical industry's conservative mindset (González, 2021). To overcome these challenges, the pharmaceutical business needs to foster a culture of sustainability, and this will involve a coordinated effort from all stakeholders, including investors, regulators, and researchers.

Therefore, maintaining the safety and effectiveness of new medications while lowering the environmental effect of pharmaceutical manufacturing depends on sustainability in drug discovery and development. The pharmaceutical business can lead the way towards a more sustainable future by adopting green chemistry principles, utilizing technology breakthroughs, promoting collaboration, and campaigning for supporting regulatory frameworks. Achieving these objectives and guaranteeing that the industry benefits from sustainable practices will depend on resolving the outstanding issues.

7. Conclusion

It is imperative that sustainable techniques be implemented in medication discovery and development to address the environmental issues associated with conventional pharmaceutical production processes. Putting a focus on green chemistry principles improves medication synthesis efficiency overall and helps reduce hazardous waste. The pharmaceutical sector may greatly minimize its ecological footprint and meet global sustainability goals by emphasizing waste minimization and atom economy. Effective outcomes can be achieved with ecologically friendly approaches, as demonstrated by the production of antiviral medications such as Remdesivir, which is an example of the successful application of green chemistry in pharmaceutical synthesis. However, achieving a completely sustainable pharmaceutical sector necessitates removing current obstacles, such as the requirement for improved stakeholder participation and the creation of supportive regulatory frameworks. Sustained investment in research and innovation will be necessary to advance sustainable techniques, such biocatalysis and safer solvents, as the demand for greener options in drug development increases. In summary, including sustainability into drug research not only guarantees the development of successful treatments but also protects the environment and public health, opening the door for a more conscientious pharmaceutical sector.

Compliance with ethical standards

Disclosure of Conflict of interest

All the authors have no conflicts of interest to declare. Any financial and personal relationships with other people or organizations that could inappropriately influence (bias) our work are completely transparent and disclosed.

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