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Green Chemistry Techniques for Enhancing Pharmaceutical Waste Management

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Abstract: *The pharmaceutical industry is a significant contributor to chemical waste, posing severe challenges to environmental sustainability. Green chemistry offers innovative techniques to minimize waste generation and enhance the management of pharmaceutical residues. This study explores the application of green chemistry principles—such as the use of renewable feedstocks, greener solvents, and atom-economical reactions—in reducing the environmental footprint of pharmaceutical processes. Particular emphasis is placed on advanced waste management strategies, including bioremediation, catalysis-driven degradation of harmful residues, and recycling of active pharmaceutical ingredients (APIs). Furthermore, the integration of life-cycle assessment in pharmaceutical production enables a comprehensive understanding of environmental impacts, guiding the adoption of eco-friendly practices. By implementing these techniques, the pharmaceutical sector can transition toward more sustainable operations, contributing to global efforts in achieving environmental harmony. This research underscores the pivotal role of green chemistry in revolutionizing waste management practices and fostering sustainable innovation in pharmaceuticals*

Keywords: Green chemistry, green synthesis, clean chemistry, environmental sustainability

I. INTRODUCTION

"Green chemistry" (GC) or "sustainable chemistry" (SC) refers to a process of synthesising chemical compounds that reduces or eliminates the production of hazardous chemicals. These days, GC or SC refers to the chemistry that maximizes profits while minimizing harmful consequences. The three environmentally friendly elements of a "green" reaction are the solvent, reagent/catalyst, and energy used. One innovative area of chemistry that has made ecological strides is avoiding the use of hazardous intermediates and products and reducing or eliminating the usage of hazardous substances in synthesis. To lower risk and prevent contamination, the GC tackles the basic hazards connected to chemicals. For example, since benzene is carcinogenic, it should not be used as a solvent. Reactions should always be conducted in the aqueous phase when possible. According to Adam et al. (2020), de Marco et al. (2019), and O'Brien et al. (2009), the design of synthesis techniques should guarantee that the maximum quantity of reactants are transformed into end products and that no hazardous wastes or byproducts are created.

The GC's twelve guiding principles may be used to produce reactions, products, and processes that are safer for the environment and for humans. The GC was developed in every area of chemistry, including organic, biological, inorganic, physical, toxicological, polymeric, environmental, and so on. Chemists take an oath to preserve the environment and natural resources while scrutinizing the materials and processes used in research and development. If no hazardous materials are used or produced, there is no risk and no need to be concerned about eliminating hazardous materials from the environment. Additionally, according to Cerminara et al. (2020), de Marco et al. (2019), Singh & Wakode (2018), Kim et al. (2015)3-6, and others, GC wants to reduce energy, waste, risks, raw materials, expenditures, and environmental impact.

Sustainability and environmental issues are swiftly rising to the top of the priority list for manufacturers and product developers (Sezen & Çankaya 2013). The GC executions are one of the measures that might be used to improve the quality of the environment. The industrial and chemical industries need more advanced, well-organized technology to address the upcoming resource, economic, environmental, and sustainability challenges. These challenges have been

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overcome by GC by offering a variety of chances to maximize the target molecules and minimize by-products, such as machinery used in the synthesis of naturally occurring, ecologically benign substances (Sharma et al., 2011). Reducing or eliminating the use of the production of hazardous materials for the environment and human health has been the aim of GC-related research. The GC also aims to substitute renewable raw materials with non-renewable ones in order to reduce the risks that might negatively impact the environment and human health (Saini & Singh 2002).

Basic Principles of Green Chemistry

The elimination of toxic chemicals from the synthesis is one of the main goals of green chemistry (GC). As a result, the use of chemicals that are harmful to the environment and human health is decreased or stopped. Although it is impractical to gather the requirements of every method principle at once when designing a GC process, efforts should be made to apply different principles as promising at different stages of synthesis (Singh & Wakode 2018; Ivankovic & Talic 2017; Escobedo et al., 2016; Manmohan et al., 2012; Valavanidis et al., 2009).

• Creating safer chemical designs

• Degradation design; • Waste or byproduct prevention

• Making use of biotechnology substitutes.

• Minimal energy required for any kind of synthesis

• Toxic substance reduction or prevention.

• Avoid using group protection whenever you can.

It is best to avoid unnecessary derivatization wherever possible.

• Choosing the best catalysts, reagents, and solvents.

• Employing cutting-edge strategies to distinguish industrial processes.

• The majority of reactants and reagents being incorporated into the finished products.

• When designing chemical compounds, the goal should be to minimize toxicity without sacrificing usefulness.

• The negative effects of energy requirements on the environment and the economy should be acknowledged and mitigated.

• Whenever possible, raw materials should be renewable rather than finite, both financially and scientifically.

• Since chemical substances decompose into innocuous degradation chemicals and do not linger in the environment, they need to be developed.

• Design manufacturing facilities to reduce the possibility of mishaps during processes escalation of analytical practices to control hazardous compounds. • Analytical procedures need to be established to enable real-time, procedure examining and control prior to the production of toxic compounds.

• Materials used in chemical processes should be selected to reduce the risk of chemical mishaps, explosions, and fires. Synthetic techniques should, wherever possible, be designed to utilize and generate a compound that does little or no damage to human health and the environment.

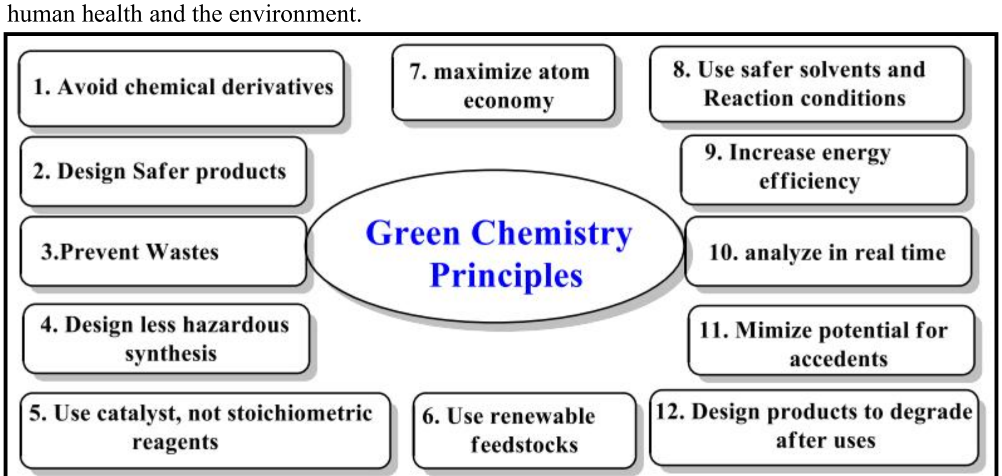

Fig. 1: Principles of Green Chemistry

Pharmaceutical Green Chemistry

The most active sector of the chemical manufacturing industry is pharmaceutical businesses. It is at the forefront of significant changes toward "greener" feedstock, cleaner solvents, alternative techniques, and innovative concepts. All of these changes will help pharmaceutical companies become more environmentally friendly while also reducing expenses and materials for their production processes, which is a positive step toward sustainability (Cichosz & Masek 2020; Lasker et al., 2019; Fanelli et al., 2017; Tucker 2006).

It is possible to see the use of GC principles in the pharmaceutical industry as both a duty and a significant opportunity to enhance our positive influence on the world's population.

Fig. 2: Green chemistry in a pharmaceutical company

Chemists support the pharmaceutical firm in its ongoing attempts to create medications and pharmaceuticals with fewer dangerous side effects by using methods that generate less hazardous waste or byproducts. The process of finding marketable medications using chemistry differs greatly from traditional production. To further medication research, some firms collaborate with environmental experts, medicinal chemists, and chemical engineers. For many years, the pharmaceutical company's "green" methods and practices gained acceptance. A number of pharmaceutical corporations' research departments have produced several advancements in the areas of innovative methodologies, enhanced bio-catalysis reactions, reduced solvent use, and waste production. Pharmaceutical businesses have had to translate green ideas into significant goals for environmental research, development, and manufacturing over the course of many years. In order to safeguard their employees and meet environmental standards for their goods, pharmaceutical firms implemented precise safety and health systems. The four pillars of modification are safety, efficacy, economy, and consistency. The metrics used to assess their support are competitive advantage, enhanced environmental credentials, and economical profit.

Green Synthesis

The phrase "green synthesis" (GS) is often used to refer to the process of creating goods that doesn't negatively impact the environment at any stage of the synthetic process. It has been shown that the GS is a crucial concept for lowering emissions and industrial waste. Avoided waste may provide affordable benefits and competitive outcomes. GS seeks to facilitate the effective use of money and enhance ecological activities. Green technology, which tries to mitigate the negative effects of human concern, is also known as the application of one or more of the disciplines of environmental, GC, environmental examination, and electronic devices to test, model, and safeguard the natural environment and resources. There are two ways to look at green synthesis. In the narrow sense, GS is concerned with creating green products that are utilized in renewable energy systems and clean technology. In the broad sense, on the other hand, GS refers to greening synthesis by reducing waste and conserving resources. The policy environment, company awareness,

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and stakeholder act are examples of external variables that may have an impact on the application of GS practices in the synthesis process.

Economic, social, and ecological impacts are also important when it comes to a company's implementation of GS. Reducing the usage of raw materials, recycling solid waste, and redesigning substances are examples of environmental synthesis methods that may help make something more environmentally sustainable. With the development of products or systems that use less substance and energy, replacing input materials (non-toxic to toxic, renewable to non-renewable), reducing needless production, and changing output to input or recycling, the term "green synthesis" refers to a study that reflects a new synthesis pattern that uses various green techniques to be more ecologically capable (Deif 2011).

The product life cycle may be shortened by the GS, which lowers manufacturing costs. Owing to ecological responsibilities, the firm strives to reduce the adverse effects on the environment by reusing, replicating, and recycling discarded items, especially those made by manufacturers of electric consumer goods. As a result, the reverse synthesis issue is crucial for the computer and electrical industries at all levels as it directly affects every step of product development. In order to determine the value of relevant policy aspects and determine the control of cost goods in semi-green supply chains, the best inventory system available was built (Lee et al., 2021).

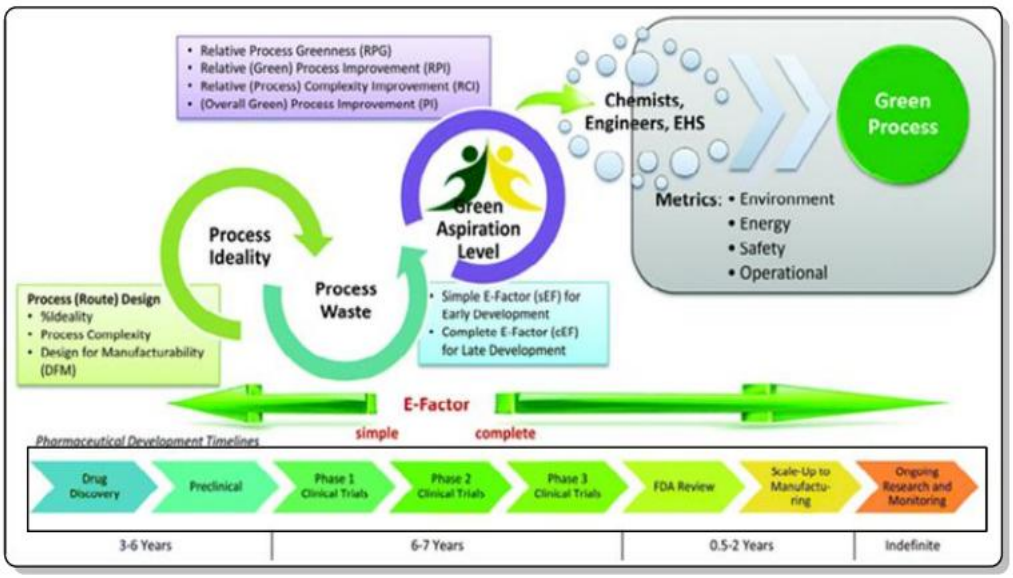

Fig. 3: Pharmaceutical company: the green aspiration level conceptGreen Chemistry and Environmental Sustainability

Green chemistry (GC), which focuses on the synthesis of compounds as well as methods and stages of reactions, is one tactic to address environmental challenges. This approach's cornerstone is lowering the amount of dangerous chemicals produced and used throughout procedures (Crawford et al., 2017). The domain of chemical risks associated with the GC concept encompasses several threats to the environment and public health, in addition to physical hazards, toxicity, resource depletion, and climate change (Kharissova et al., 2019). In order to reduce the use of potentially harmful compounds and protect the environment, the GC aims to study how various chemical principles are used in the design or synthesis of chemicals (Schulte et al., 2013). A comprehensive plan to safeguard the environment and public health must include the GC. The GC is associated with the following practices: minimizing waste at the source, using safe reagents and catalysts, boosting economic efficiency, using recyclable and safe solvents, and utilizing renewable resources (Shanghi 2003). Improving worker health and the industry's environmental circumstances is the GC's main objective (Ubuoh 2016).

Resource depletion, worries about chemical pollution, and catastrophic environmental events all contributed to the development of the notion of sustainability. Sustainability is based on the triple-bottom-line strategy, which takes the social, economic, and environmental domains into account. This theory holds that progress cannot proceed without guaranteeing the addition and balance of the economy, society, and environment (Anastas & Warner 1998). The process of creating industrial and human systems such that the use of natural resources and the human cycle does not reduce the value of life or exacerbate environmental injustice is known as sustainability, according to Ragazzi and Ghidini (2017). Examples of environmental sustainability include lowering emissions, decreasing the amount of solid and liquid waste produced, using less hazardous products and resources, reducing the frequency of environmental accidents, and improving human health. It was determined that growth that meets current needs without compromising the capacity to meet those of future generations would constitute sustainable development. The two major ideas are the idea of "needs"—the necessity for human survival—and the idea of limits—the outcome of social and technical restrictions on the environment's ability to meet both the needs of the present and the needs of the future (Geyer & Jackson 2004).

The use of GS has a noteworthy beneficial impact on the environment; GC offers exceptional environmental benefits. Reduced waste, pollution, and resource and energy usage might result from GS adoption. It's critical to assess GS goods and processes and to find any possible sources of contamination or pollution. These pollutants endanger the ecology and our future. They include toxic emissions from medication production, waste disposal, and greenhouse impacts (Nukman et al., 2017). In the chemical industry, design for sustainability encompasses more than just process reform, process escalation, and continual improvement of green chemical procedures. It also involves significant research and development projects at all chemistry levels. Sustainability is generally acknowledged to be the primary objective of ecological strategy (de Marco et al., 2019).

Pharmaceutical Applications

By using the knowledge related to green chemistry (GC), pharmaceutical businesses may achieve improved environmental performance. The GC is engaged in developing novel drug release methods which are less poisonous and more useful, proficient and could help millions of patients (Santi et al., 2021; Al-Hakkani et al., 2021; Banik et al., 2021; Arora et al., 2021; Draye et al., 2020; Gao et al., 2020; Patel et al., 2020; Dwivedi et al., 2019; Castilla et al., 2018; Jahangirian et al., 2018; Jahangirian et al., 2017; Jaiswal et al., 2017; Sindhu et al., 2017; Shah et al., 2015; Smita & Falfuni. 2012; Wolfson et al., 2007; Ingrid et al., 2006; Yogesh et al., 2001; Anastas et al., 2000), Examples:- 1. Phosphoramidite; a solid phase which is a mix of antisense oligonucleotides has been changed to entrain the ideas of GC by removal the usage and generation of hazardous materials and recycling the main substances like protect

2. The good yield of 2,2'-bis[diphenylphosphino]-1,1'-binaphthyl ligand in the chiral metal catalyst used to synthesise naproxen.

3. Green solvents, such as water, are very effective in a variety of organic processes, such as the synthesis of benzothiazoles and benzothiazoline, among others. They may also replace a number of hazardous solvents. However, glycerol has been identified as a significant green solvent. Glycerol's low toxicity, affordability, wide accessibility, and renewability may combine the advantages of water. Glycerol's strong polarity makes it possible to reduce a variety of carbonyl compounds using sodium borohydride.

4. Because of its use in chemical extraction, low toxicity, and little environmental effect, supercritical carbon dioxide (ScCO2) is a major commercial and industrial solvent. When CO2 is held at or above its critical temperature (31.10 0C) and critical pressure (72.9 atm), it becomes ScCO2, a fluid state of CO2 that fills its container like a gas but has the density of a liquid. With the benefit of water, the ScCO2 functions similarly with other difficult compounds without having any harmful consequences. ScCO2 may be used as a reaction medium for a variety of processes, including polymerization, ring-closing metathesis, hydrogenation, epoxidation, radical reactions, and palladium-mediated C-C bond formation. ScCO2 is used to create micro- and nanoscale particles for application in medicine.

5. Stoichiometric amounts of reagents are used in traditional organic synthesis, which results in large amounts of waste or byproducts. The use of the appropriate catalyst technology raises product value while decreasing waste streams and speeding up cycle durations. Catalysis has advanced recently, opening the door to several valuable applications, most notably the synthesis of intermediates and active pharmaceutical ingredients (APIs). 6. In the production of anthraquinone for the dyestuffs firm, aluminum chloride (AlCl3) is the essential catalyst in the first step, acylation of benzene. There are two kinds of catalysts: biocatalysis and chemo-catalysis. It's a Friedel-Craft kind of reaction where wastes and the catalyst are both worthless. For the next batch of reactants, new catalyst is needed. Large volumes of

corrosive waste are produced as a consequence of the AlCl3 complexes' strong binding with the products, which form [AlCl-] and cannot be recycled at a reasonable cost. Currently being tested is a novel catalyst with excellent ecological characteristics. Dysprosium (iii), a very acidic compound, is one example of a compound that gives the opportunity to separate from the sacrificial catalyst by allowing the catalyst to be recycled.

7. A pharmaceutical business finds and manufactures substances to be used as medications. Nowadays, the chemical company's pharmaceutical division is considered to be its most active division. Each year, a significant volume of analgesic and anti-inflammatory medications are generated. Ibuprofen, acetaminophen (Paracetamol), and aspirin (acetylsalicylic acid) are a few essential medications.

Phenol was converted into paracetamol in three stages. The solvent from step two was retained in the synthesis process, which helped lower atom economy. In order to create 4-nitrophenol, the initial step included electrophilic aromatic substitution on phenol using nitric acid. P-aminophenol was created in the second stage by hydrogenation using an iron (catalyst). Ultimately, the aminophenol was acylated to create paracetamol. This approach reduced chemical waste while including the green step. NSAIDs, or non-steroidal and anti-inflammatory medications, include ibuprofen. There are six steps in this synthesis process, and 60% of the waste or byproducts are undesirable and need to be controlled or disposed of. Many of the wastes are produced and end up as undesirable byproducts rather than the intended Ibuprofen.

•Paclitaxel, also used in chemotherapy, is another medication that produces less waste (Taxol). It was first created by removing compounds from the bark of yew trees, a process that killed the tree and required a lot of solvent. Tree cells are now grown in a fermentation vat to make the medication.

•There are two phases in the GC process used to manufacture an important atorvastatin intermediate: • The first stage involves the bio-catalytic reduction of ethyl-4-chloro-3-oxobutanoate using a combination of glucose and keto-reductase to regenerate the beneficial chemical that is essential for the enzyme's activity and make a high-yield product called ethyl-4-chloro-3-hydroxybutyrate.

The next stage involves using a halohydrinde halogenase to speed up the process of replacing the chloro group with a cyano group. This reaction occurs in the presence of a catalyst at room temperature and neutral pH.

developed efficient, rapid, and inexpensive processes for synthesizing amines containing a significant amount of medicinal molecules. Businesses used expensive, two-step processes to make amines, which produced a large number of byproducts. However, GC principles do not produce any waste products, and when a catalyst is present, the reaction proceeds quickly in a single step. Microwave aspirin synthesis steps have been created using catalysts such as H_2SO_4, $MgBr_3.O(C_2H_5)_2$, $CaCO_3$, NaOAc, Et_3N, $AlCl_3$, and solvent-free techniques.

Future Perspectives of Green Chemistry

Green chemistry's (GC) prospects will be examined in more detail and with greater criticality across a range of scientific domains. The environment and manufactured commodities should be taken into consideration jointly, keeping in mind that the world need a natural equilibrium. Any effort to disturb this balance will result in more dire consequences. We thus need more eco-friendly tactics and concepts. Future Trends in GC include the use of safe substances to remove toxic materials like heavy metals from the environment, develop noncovalent derivatization, develop biometric multifunctional reagents, and continue supramolecular chemistry to create solid-state reactions that can continue without the need for solvents. Combinatorial GC is the chemistry of being able to produce various chemical compounds rapidly on a small scale using reaction matrices, and increase the number of solventless reactions to help isolate, separate, and refine products with the least amount of solvent and with the greatest possible benefits.

- Green nanochemistry;
- combinatorial green chemistry;
- supramolecular chemistry;
- biometric multifunctional reagents;
- oxidation reagents and catalysts;
- non-covalent derivatization techniques

GC is a trend in the pharmaceutical business to create safer methods and substances. It lessened the harmful effects of chemicals on the environment and human health and helps the CS become sustainable. The goal of chemists to create affordable and practical goods increased the use of GC.

- Reduction of sources
- Photovoltaic cells
- Preventing waste;
- using base metal catalysis;
- creating money from waste;
- reducing the amount of hazardous items;
- including sustainability early in the design process.
- Creating ecologically friendly materials and chemicals;
- Using solvent systems that are safe for the environment.
- To create industrial processes that avoid risk issues
- Examining how biomass processing affects the environment and ecotoxicology.

II. DISCUSSION

The literature review indicates that green synthesis (GS) and green chemistry (GC) contribute to improving environmental quality. Utilizing fewer hazardous chemicals that have an impact on the environment and human health is the aim of both green GC and GS. It is essential to use GS and GC in order to provide both environmental and economic advantages. It is possible to assess some of the financial gains that come from using GC in industrial operations, such as lower expenses for waste treatment and storage and payments for environmental harm. Without continuous progress, accomplishment, improvement, and achievement are worthless. GC is meant to be used with safer materials and processes. It reduces the damaging impacts of chemicals on the environment and aids in the sustainability of chemical production. The usage of GC developed as chemists sought to make items that were both practical and inexpensive. GC techniques have the potential to promote social and economic objectives in addition to environmental advantages. Preferring to the total of these three profits, the "triple bottom line" offers strong support for the creation of more environmentally friendly goods and procedures. The General Catchment (GC) is a basic approach to pollution prevention, not a magic bullet for all ecological problems, even if it is better to avoid trash than to clean it up after it is produced. The efficient and selective GS processes are often associated with the sonochemical and microwave activation methods.

The replacement of dangerous solvents with safer ones, such supercritical liquids, ionic liquids, and water, is another major issue. Additionally, solvent-free and solid-phase synthesis are growing in popularity. The creation and use of green catalysts presents additional difficulties. Further data regarding enantioselective methods, the production of chemicals from biomass and waste materials, the extraction of natural compounds, green biotechnology, green analytical methods, and sustainability concerns associated with environmentally friendly chemistry are obtained.

An excellent example of GC principles is the alternative ibuprofen synthesis procedure, which may influence more effective synthetic methods from an economic and scientific/technical perspective. According to research, GC will transform the pharmaceutical industry and pharmaceutical manufacture in the future. The company is keen to put most of GC's recommendations into practice since they can benefit the economy and the environment. Even if the scientific community has accepted the general consensus (GC) theory, money and education are still necessary for technological GC progress to get the proper attention.

III. CONCLUSION

Pharmaceuticals have been used by chemistry to create a lot of beneficial items, but chemistry also creates dangerous and unwanted waste in addition to the needed result. The industries struggle to provide non-toxic products. Green chemistry (GC) offers an excellent foundation for the fight against these harmful substances. It provides a broad and adaptable research window for the development of more efficient reaction procedures that reduce waste and raise the yield of highly sought products. GC, however, is unable to mitigate these consequences by itself. GC principles pave the path for a future that is more ecologically sustainable. Great efforts are still being made to develop an excellent technique that doesn't use solvents for separation, purification, or storage, employs pure raw materials, and produces no byproducts. Human life expectancy and quality of life have increased dramatically thanks to the pharmaceutical sector, but these gains must be made without putting the environment in peril.

The pharmaceutical business was helped by the GC to meet its environmental goal. Designing and implementing sustainable methods, such as reducing waste, boosting method effectiveness by utilizing fewer raw materials, recycling and reusing solvents, and developing cleaner, greener, and more energy-efficient processes, is thus the producer's duty. The reduction of environmental problems is the aim of the GS and GC. The use of GS and GC is beneficial to the environment and public health. Therefore, GS and GC must be carried out by various organizations in order for them to conduct their trade activities. We have restricted some of the main successes in transitioning to more environmentally friendly pharmaceutical enterprises in this evaluation in an effort to improve performance. Even yet, there are still many challenges and excellent prospects.

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