PROSPECTS
IN PHARMACEUTICAL SCIENCES

Prospects in Pharmaceutical Sciences, 23(4), 159-174
https://prospects.wum.edu.pl/

Original Article

FUTURE DIRECTIONS FOR GREEN CHEMISTRY IN INDIAN PHARMACEUTICALS: A SURVEY-BASED ANALYSIS

Venkateswara Raju K, Badugu Priyanka, Lakshmi Prasanthi Nori*

[1] *Department of Regulatory Affairs, Shri Vishnu College of Pharmacy, Bhimavaram, West Godavari (Dt), Andhra Pradesh, India.*

* Correspondence, e-mail: lakshmi.n@svcp.edu.in

Received: 13.02.2025 / Revised: 09.04.2025 / Accepted: 05.05.2025 / Published online: 06.08.2025 / Published in final version: 27.12.2025

ABSTRACT

Green chemistry, focused on the sustainable design and production of chemicals, aligns with global efforts to mitigate environmental harm and promote resource efficiency. Regulatory considerations are crucial in advancing green chemistry practices and minimizing environmental impact. Key regulatory frameworks such as the Toxic Substances Control Act (TSCA) in the United States and the Registration, Evaluation, Authorisation, and Restriction of Chemicals Act (REACH) in Europe mandate assessment and management of chemical risks. These regulations drive innovation by encouraging the substitution of hazardous substances with safer alternatives and promoting sustainable processes. Compliance with regulatory standards not only ensures environmental protection, but also fosters industry competitiveness and supports public health goals. This research article underscores the implementation of green chemistry in Indian pharmaceutical companies through a survey conducted through a questionnaire filled by employees of various pharma industries across India on issues related environmental/sustainability goals and targets, use of green chemistry, barriers to greater adoption of GC by Indian pharmaceutical companies, external GC collaborations, use of GC resources by Indian pharmaceutical companies, use of green chemistry metrics by Indian pharmaceutical companies, and the reported stage in the waste management hierarchy. From the analysis we found it satisfactory, and also that this requires further in-depth investigation.

KEYWORDS: green chemistry, environmental, renewable resources, sustainable.

1. Introduction

"Green chemistry" purpose is the development of chemical products and processes that focus on minimizing or eliminating hazardous substances. Introduced in the early 1990s, the concept of green chemistry has since gained global approval, resulting in the creation of numerous programs and governmental initiatives worldwide, with pioneering projects initially emerging in the United States, the United Kingdom and Italy. Those initial efforts have contributed a crucial role in advancing green design practices. Prominent initial efforts include establishing the U.S. Presidential Green Chemistry Challenge Awards in 1995, the founding of the Green Chemistry Institute in 1997, and the launch of the Green Chemistry journal by the Royal Society of Chemistry in 1999.

The essence of green chemistry lies in its design principles, which emphasize intentionality rather than chance. Effective design necessitates thorough planning, innovation, and organized thinking [1]. The Twelve Principles of Green Chemistry function as "design guidelines" to steer chemists toward more sustainable methods. By meticulously planning chemical synthesis and molecular design, green chemistry aims to achieve synergies rather than mere trade-offs, with a focus on molecular-level sustainability.

This approach has led to its adoption across various industries, including automotive, cosmetics, electronics, power, domestic goods, pharmaceuticals and agriculture. The broad impact of green chemistry extends beyond research labs to industry, education, and public life, demonstrating its ability to produce profitable, environmentally friendly, and health-promoting products and processes. Over the past 20 years, increased interest in green chemistry has led to expanded teaching programs, government investment, and the creation of Green Chemistry Research Centres. Green engineering and chemistry have become prominent subjects at numerous institutions, and government investment has significantly increased.

As traditional industrial processes reveal their environmental risks, green chemistry, also known as sustainable chemistry, offers innovative solutions. By incorporating these guidelines, sectors can develop long-lasting renewable processes that reduce waste, energy consumption, and the use of hazardous substances [2]. Although they are not exactly the same, green chemistry and sustainable chemistry are closely connected. Sustainable chemistry includes green chemistry, but sustainability encompasses more than just environmental issues.

2. Renewable materials

Natural gas and petroleum feedstocks are believed to be the primary sources for most of our manufactured goods. The depletion of these resources will significantly affect various aspects of our consumer lives and the economy. As a result, moving towards renewable feedstocks for energy and materials is becoming more vital [3]. Biomass, originating from living organisms, serves as the Earth's primary renewable resource for materials and power. It includes nutrition, wood, crops, and agricultural residue. Renewable materials consist of components like cellulose, lignin, and suberin from wood; polyhydroxy alkanoates, Lactic acid, chitosan, carbohydrates, glycerin and oils [4]. For example, lignin – a significant byproduct in the pulp and paper manufacturing sector – has traditionally been used for energy production by burning. Recently, its uses have expanded to encompass applications as dispersing agents, preservatives, and as primary materials for creating elements such as humic acid, dimethyl sulfoxide (DMSO), and vanillin. Chitin, a natural polymer located in the exoskeletons of arthropods like crustaceans, is an important byproduct of the aquaculture industry. Chitin can undergo deacetylation to produce natural polysaccharides, which have been implemented in various fields, including water purification and biomedical applications. Recycling waste from bio-industries can provide substantial amounts of natural resources to serve as alternatives to current petroleum resources [5].

3. Implementation

Conventional chemical methods usually produce significant amounts of residue. Sustainable chemistry aims to minimize residue through techniques including solvent reuse and enzyme-mediated reactions. The Green Chemistry Institute reports that applying these methods has caused up to a 70% decrease in waste material in some industrial sectors. The pharmaceutical industry, for example, has adopted green chemistry principles by redesigning synthesis methods to use fewer toxic chemicals and produce less residue [6]. One remarkable case is the greener synthesis of the drug atomoxetine, which improved sustainability by reducing the number of process stages, using less solvent, and increasing overall yield. Green chemistry is also crucial for developing renewable energy systems, such as enhancing the efficiency of organic photovoltaic materials using non-toxic and readily available substances. Moreover, green chemistry has spurred innovation in cleaning agents and other consumer products by replacing harmful ingredients with environmentally friendly alternatives, resulting in better indoor air quality, reduced health risks, and diminished environmental impact as illustrated in Fig. 1 [7].

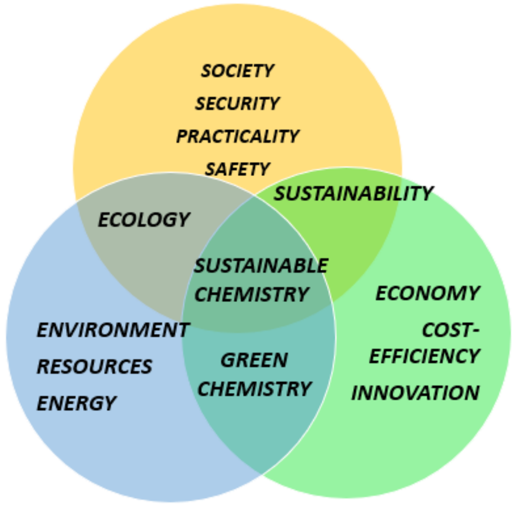

Fig. 1. Implementation of green chemistry.

4. Green chemistry reduces

This article highlights current trends in how sustainable chemistry is minimizing the environmental impact of chemical interactions and technologies as illustrated in Fig. 2. These advancements in scientific and technological development throughout the mid-to late twentieth century have driven substantial economic growth and improved quality of life. However, this economic progress has also led to severe environmental damage, as evidenced by intensified environmental change, the depletion of ozone, as well as the proliferation of persistent organic toxins throughout the biosphere [8].

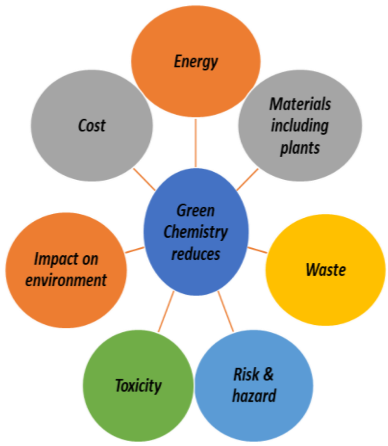

Fig. 2. Aspects reduced by using green chemistry.

5. The twelve principles

Paul Anastas and John Warner in 1998 described the 12 principles of Green Chemistry (12 PGCs) as shown in Fig. 3, which serve as guidelines for facilitating green chemistry through responsible practices. The 12 PGCs dovetail with global sustainability standards, like ISO 14001, which targets environmental management systems. To demonstrate their dedication to sustainability, the development of environmentally friendly products, and secure manufacturing processes, organizations have to adhere to ISO 14001 standards [9].

Fig. 3. 12 Principles of Green Chemistry.

5.1. Prevention

Preventing waste is the primary principle of green chemistry, emphasizing that it's better to avoid creating waste at the outset rather than dealing with it afterward. Waste can refer to any material produced without realized value or unused energy. It can assume various shapes and affect the environment in various ways, depending on factors like its harmfulness, essence, quantity and method of release. It is more effective to minimize waste at the source rather than handling it after it has been created [10].

5.2. Atom Economy

In 1990, Barry Trost developed the concept of synthetic efficiency which is called “atom economy” (AE) or atom efficiency. This concept emphasizes optimizing the utilization of resources by ensuring that the end product incorporates as many of the reactant atoms as possible. Ideally, a reaction would transform all the atoms from the reactants into the final product. Atom economy is determined by assessing the proportion of the molecular weight of the target product to the total molecular weights of all the reagents employed in the reaction [11].

5.3. Less Hazardous Chemical Syntheses

Whenever feasible, synthesis methods should be designed to utilize and produce compounds that have minimal or no harmful effects on public health and environmental conditions. Environmental and health risks should be minimized by creating synthetic methods that use and produce substances with minimal or no toxicity. Although some toxic substances may be necessary in certain cases, alternative approaches should be sought that achieve the same outcomes without harmful effects [12].

5.4. Designing Safer Chemicals

Chemical compounds should be designed to achieve their intended functions while reducing their adverse effects. Achieving this balance between function and safety is one of the biggest challenges in developing safer products and techniques, requiring knowledge of both chemistry and fundamentals of toxicology and environmental studies. The objective is to create compounds that are non-carcinogenic, non-genotoxic, and non-neurotoxic, ensuring that their performance is optimal while keeping toxicity and risk to the lowest feasible level. In essence, harmful substances are required to be eliminated and substituted with safer alternatives whenever possible, while still considering their effectiveness.

5.5. Safer Solvents and Auxiliaries

Auxiliary substances (e.g.: solvents, separation agents, etc.) should be considered unnecessary whenever possible and kept harmless when utilized [13].

5.6. Design for Energy Efficiency

The energy demands should be recognized for their effect on both environmental and economic factors and reduced as much as feasible; synthesis processes must be performed under standard thermal conditions and pressure [14].

5.7. Use of Renewable Feedstock

A core concept of sustainable chemistry is to utilize renewable resources when it’s both economically and technically feasible. For instance, using renewable raw materials in place of various plastics and effectively managing waste is encouraged. This approach has led to a current trend toward developing biodegradable plastics, with biodegradable packaging expected to have a promising future in the food industry [15].

5.8. Reduce Derivatives

Nonessential chemical derivation steps, including using masking groups, temporarily modifying physicochemical methods and protection/deprotection procedures, have to be reduced or avoided when possible. These steps require additional reagents and contribute to the generation of waste.

5.9. Catalysis

Catalytic reagents are more advantageous than stoichiometric reagents because the creation of waste is often associated with the traditional approach of using stoichiometric amounts of reagents. To promote environmental protection, the principle of catalysis supports the implementation of renewable catalysts, which results in reduced energy consumption, eliminates the need for organochlorine compounds, and lowers the production of wastewater and overall energy use.

5.10. Design for Degradation

Chemical products should be designed to decompose into harmless degradation products that pose no threat to the environment. The objective is to develop degradable chemicals and products that, once their intended use is complete, break down into non-toxic substances. This approach aims to prevent the generation of harmful substances and maximize the recovery and recycling of waste materials [16].

5.11. Real-time Analysis for Pollution Prevention

Analytical techniques must be developed to allow real-time observation and control during the process, before any harmful substances are produced [17].

5.12. Inherently Safer Chemistry for Accident Prevention

The 1990 Amendments to the Chemical Accident Prevention and Clean Air Act emphasize that accident prevention starts with the identification of hazards. It is crucial to address all types of hazards such as toxicity, physical dangers like explosivity or flammability, and global hazards when designing chemicals and processes to avoid incidents similar to the Love Canal and Bhopal disasters. These events should remind the scientific field that numerous chemicals substances still pose severe risks and need to be replaced with less hazardous alternatives to reduce the likelihood of accidents.

Example: Synthesis of ibuprofen.

6. Role of Green Chemistry in Sustainable Development

In 2015, the United Nations approved the Sustainable Development Goals (SDGs), which are 17 interrelated goals to ensure poverty eradication and the planet's better protection by 2030. These goals can be implemented in any setting and call for the joint application of resources like technology, skills, innovation, and funds [17]. Of the 17 Sustainable Development Goals (SDGs), 11 are directly addressable by using the 12 Principles of Green Chemistry (PGCs). Detailed descriptions of how each of the 11 SDGs can be influenced by using the principles, along with emphasis on practicing green chemistry are listed below.

a. **Good Health and Well-being:** Green chemistry can help to advance good health and well-being by reducing death and disease from toxic chemicals and pollutants. It can also assist in vaccine, medicine and treatment research and development using safer, less toxic materials [18].

b. **Quality Education:** The quality of primary education is central to enhancing awareness and knowledge among experts, prompting them to integrate green chemistry into processes and projects. A good background in education will ensure that individuals have the technical as well as professional expertise required for promoting sustainable development across industries. With a thorough knowledge base coupled with a quest for alternatives, education can keep the environment free from harm as well as develop more sustainable options [19].

c. **Clean Water and Sanitation:** There are different chemical processes that can be utilized to treat water before and after use, as well as recycle it. Green chemistry enables chemists and chemical engineers to improve water quality, increase collection efficiency, and increase supply while also encouraging the sustainable use of water resources [20].

d. **Clean and Affordable Energy:** Diversifying the energy mix, promoting renewable energy sources, investing in clean energy technologies, and upgrading services are measures to increase energy efficiency. Such upgrades will have a positive effect on the environment and bring long-term economic advantages. Although it might cost a lot in the beginning, the medium- and long-term sustainability issues like depletion of resources, climate change, and energy crises can outweigh these initial expenses [21].

e. **Decent Work and Economic Growth:** Research investment is important for promoting decent work and economic growth through productive activity, quality employment generation, entrepreneurship promotion, and creativity and innovation development. It also contributes to decreasing the population of youth not working, studying or receiving training. Scientific activities can induce technological diversification and innovation in various fields. Green chemistry will help save natural resources through their increased efficiency. The use of chemicals during reactions and processes in a safe and proper manner also increases the safety of workers linking the economic growth to social and environmental development [22].

f. **Industry, Innovation, and Infrastructure:** Studies, projects, and procedures for green chemistry contribute significantly to pushing research, innovation, and technology forward. They enable the updating of visions in terms of creating greener infrastructures and industrial processes [23].

g. **Sustainable Cities and Communities:** The 12 Principles of Green Chemistry (PGCs) are designed to avoid pollution at all stages of a process: pre-, during, and post-. This is helpful in improving sustainable urbanization and lowering environmental footprints at different levels, aiding the growth of smart cities [24].

h. Responsible Consumption and Production: Using environmentally friendly raw materials is a good method for saving natural resources and reducing waste. This can be achieved by prevention, reduction, recycling, and reuse. Intelligent and effective management of resources leads to more sustainable consumption and production and minimizes adverse effects on human health and the environment. It also encourages a culture of pollution control at all phases of production and product life cycles [25].

i. Climate Action: Green chemistry has an indirect effect on the health of the climate by contributing to environmental well-being. Encouraging research focusing on the 12 PGCs can reduce the climate footprint through processes being made less environmentally degrading. Methods like prevention, less environmentally hazardous chemical syntheses, safer auxiliaries and solvents, derivative minimization, and design for degradation, among others, can all result in beneficial effects on the environment.

j. Life below Water: Life below water can be safeguarded through the development of biodegradable compounds within the short term or through reactions that degrade pollutants before release, thus not causing damage to marine organisms. Efficient municipal wastewater treatment contributes to the maintenance of life below water. Green chemistry may also be utilized to respond to ocean acidity and decontamination, contributing to maintaining marine ecosystem health [26-28].

k. Life on Land: All the Principles of Green Chemistry (PGCs) play a role in enhancing the quality of life on Earth. Key factors include the selection of raw materials, the management of waste and byproducts, and the degradation of products throughout their entire life cycle. These elements can impact the environment, biodiversity, and even human life. When applied effectively, the 12 PGCs can help eliminate or, at the very least, reduce these impacts [29-31].

7. Survey

As part of the effort to understand SDGs and GC awareness and implementation across the Indian pharmaceutical industry, we conducted a survey of 81 managers across various pharmaceutical companies on issues related to environmental/sustainability goals and targets, use of green chemistry, barriers to greater adoption of GC by Indian pharmaceutical companies, external GC collaborations, use of GC resources by Indian pharmaceutical companies, use of green chemistry metrics by Indian pharmaceutical companies, and the reported stage of the waste management hierarchy.

We collected the data through a set of questionnaires and tabulated and analysed the data in the form of Excel tables and charts. We gained new insights and conclusions from the survey, which we present below.

7.1. Environmental/sustainability goals and targets

a. For environmental/sustainability goals and targets, water use optimization was most common goal (93%), followed by wastewater reduction (91%) and toxic solvent reduction (81%).

b. Other targets, i.e. alternate energy sources, greenhouse gas emissions reduction, bio-renewables, and waste valorisation, were reported with relatively lower frequency.

c. "Other" environmental sustainability goals are the least reported at 8%.

In conclusion, the overall progress demonstrates a strong commitment to environmental sustainability, with substantial strides in water and solvent management, energy efficiency, and renewable energy. However, there is still room for growth in areas like waste valorization, bio-renewables, and greenhouse gas emissions reduction. More focused efforts, technological innovation, and investments will be needed to achieve these sustainability targets in the long term as shown in Fig. 4.

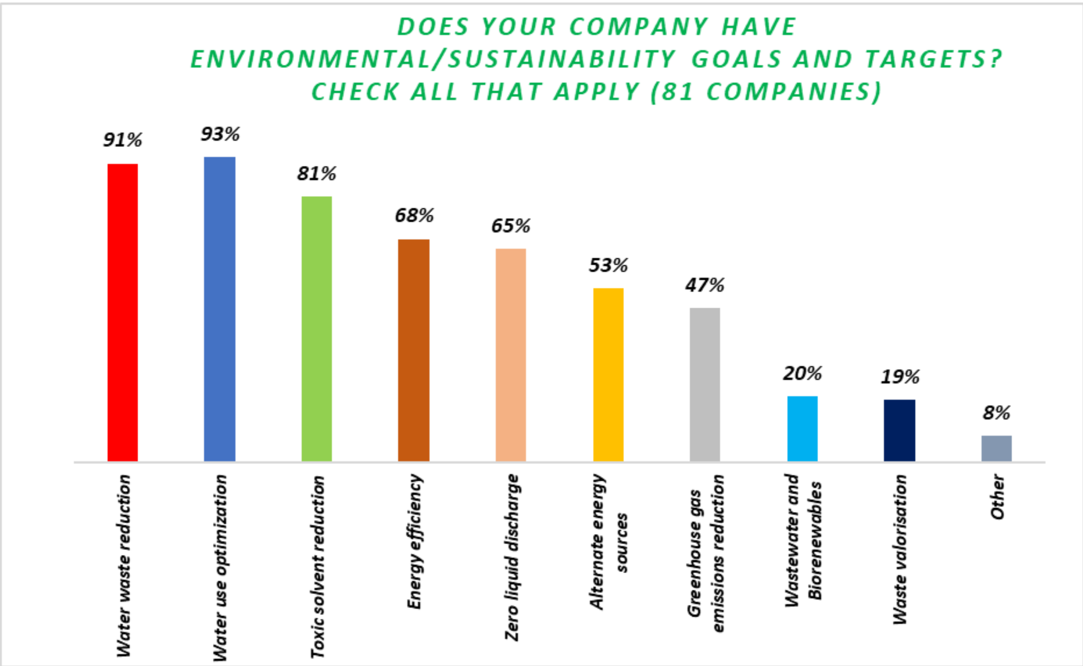

Fig. 4. Environmental/sustainability goals and targets.

7.2. Reported stage of the waste management hierarchy

a. **Highest-Focus Areas:** Treatment and disposal of wastewater (62%) and recycling of water (58%) are the most significant focuses in this data. These reflect efforts to manage and reuse resources in a more sustainable way.

b. **Moderate Focus:** Prevention and reduction at the source (52%) also play a considerable role, aligning with sustainability goals.

c. **Lower Focus:** Recovery of chemicals for resale (17%) and energy recovery (3%) have relatively less attention, which may be due to the challenges involved in these processes (e.g., market demand, technology costs, or infrastructure).

Overall, as shown in Fig. 5., this data indicates that while there is an emphasis on reducing and reusing resources (particularly water), the recovery of chemicals and energy from waste is not yet prioritized.

7.3. Reported stage of the waste management hierarchy - generics vs. Active Pharmaceutical Ingredients (API) manufacturers

For API manufacturers, treatment and disposal of wastewater were highest (66%), followed by recycling of water from wastewater (52%) and prevention by reduction at source (43%).

For generic pharma, prevention by reduction at source was first (73%), followed by treatment and disposal of wastewater and recycling of water from wastewater (both 56%).

From Fig. 6 we conclude that both manufacturers have relatively less recovery of chemicals and energy.

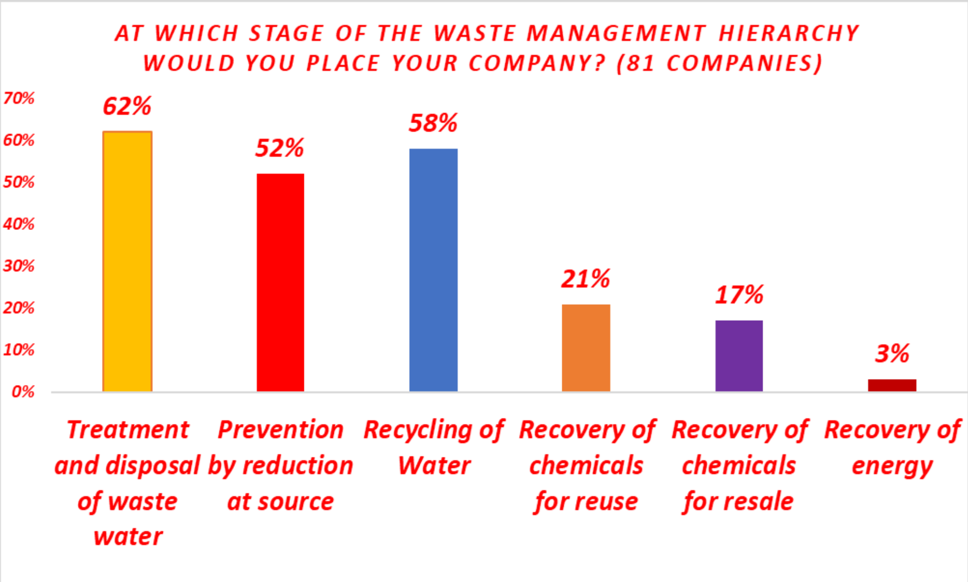

Fig. 5. Reported stage of the waste management hierarchy.

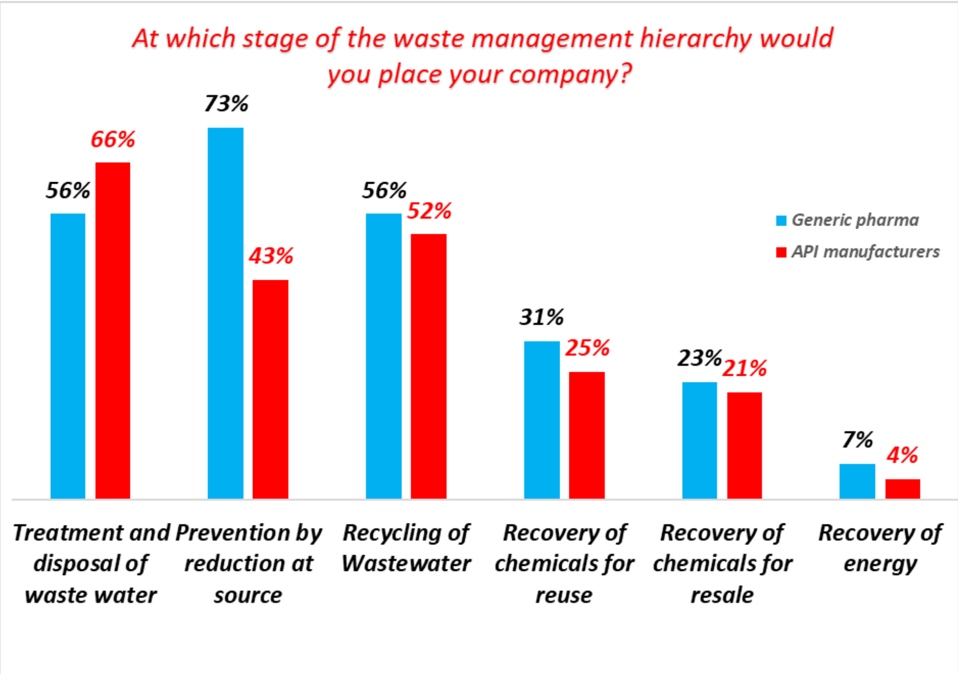

Fig. 6. Reported stage of the waste management hierarchy - generics vs. API manufacturers.

7.3.1. General Insights

Generic manufacturers tend to prioritize prevention and chemical recovery more, reflecting a potentially more sustainable approach where reducing waste generation and recovering chemicals for reuse are the main goals. API manufacturers, however, seem to emphasize treatment and disposal of wastewater more heavily, potentially due to system needs, technology, or external factors such as industry-specific requirements.

7.3.2. Possible Reasons for the Differences

Regulatory Environment: The API system might operate in an area with stricter regulations or requirements for wastewater treatment, leading to a greater focus on disposal and treatment, while generic manufacturers may have more flexibility in prevention-focused measures.

Technological Capabilities: Generic manufacturers could have access to more advanced systems for waste prevention, recycling, and energy recovery, whereas API producers might focus more on addressing immediate waste disposal issues.

Sector-Specific Needs: The generic system might apply to industries or regions with greater focus on sustainability and circular-economy principles, whereas API sector could be oriented toward more industrial or treatment-heavy applications where recycling and reuse are not as prioritized.

7.4. Use of green chemistry metrics by Indian pharmaceutical companies

7.4.1. Key Insights and Analysis

E-factor (54%):

The E-factor is one of the most widely used green chemistry metrics. It measures the amount of waste produced per unit of product, with lower values indicating more efficient processes. With 54% adoption, it seems that more than half of the pharmaceutical companies in India are focused on reducing waste, which is a positive sign of sustainability efforts within the sector as shown in Fig. 7.

Atom Economy (41%):

Atom Economy refers to the efficiency with which atoms from the raw materials are incorporated into the final product, with higher values being more sustainable. A 41% adoption indicates that many companies are considering this metric, though not as many as for the E-factor. This suggests growing awareness of the importance of resource efficiency in chemical reactions.

Steps per Product (33%):

This metric measures the number of steps involved in the synthesis of a product. Fewer steps usually indicate a more efficient process with less waste. A 33% adoption shows that companies are starting to consider process optimization, although it is less commonly used than the E-factor or atom economy.

PMI (Process Mass Intensity) (27%):

PMI measures the total mass of raw materials used (including solvents and reagents) per unit mass of the final product. The 27% adoption suggests that this metric is still not as commonly used as others, though it is an important indicator of overall material efficiency.

Carbon Footprint (23%):

The carbon footprint measures the greenhouse gas emissions associated with the production process. A 23% adoption indicates that some pharmaceutical companies are considering the environmental impact of their processes in terms of climate change. This is a crucial metric for companies seeking to reduce their overall environmental impact.

GHG Emissions (23%):

Similar to the carbon footprint, this metric focuses specifically on the greenhouse gas emissions from the production process. A 23% adoption aligns with the carbon footprint, indicating that there's an awareness of GHG emissions, but still a relatively low level of adoption.

Life Cycle Analysis (16%):

Life Cycle Analysis (LCA) evaluates the total environmental impact of a product from raw material extraction to end-of-life disposal. A 16% adoption shows that this comprehensive metric is still not widely used in the pharmaceutical industry in India, possibly due to its complexity or cost.

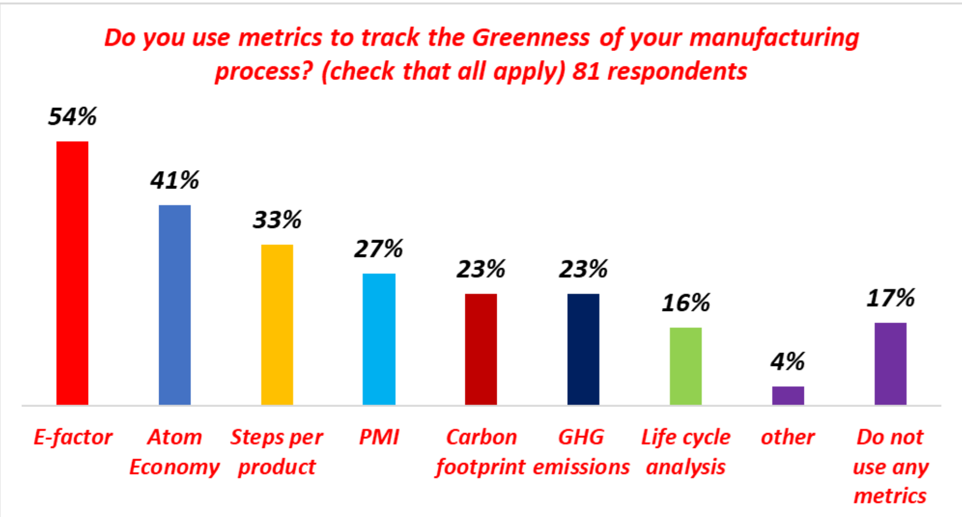

Fig. 7. Use of green chemistry metrics by Indian pharmaceutical companies.

Other Metrics (4%):

A very small portion (4%) of companies use other green chemistry metrics, which suggests that while there may be alternative metrics in use, they are not widely adopted across the industry.

No Metrics (17%):

17% of pharmaceutical companies do not use any green chemistry metrics. This highlights a gap in the adoption of sustainability practices, suggesting that a significant part of the industry may not yet be fully committed to environmental responsibility or may be unaware of the available metrics.

7.4.2. Key Takeaways

Most Commonly Used Metrics: The E-factor (54%) and Atom Economy (41%) are the most commonly used metrics, indicating that Indian pharmaceutical companies are focusing on waste reduction and resource efficiency, which are critical aspects of green chemistry.

a. Relatively Low Adoption: Other metrics like Life Cycle Analysis (16%), GHG Emissions (23%), and Carbon Footprint (23%) have relatively lower adoption, suggesting that while companies are aware of the importance of environmental impact, comprehensive sustainability practices might not yet be fully integrated into many companies' operations.

b. Room for Improvement: With 17% of companies not using any green chemistry metrics, there's room for growth in terms of integrating sustainability and environmental assessments into the decision-making process.

7.4.3. Recommendations

Increase Awareness and Training: Encourage pharmaceutical companies to adopt more comprehensive green chemistry metrics, especially Life Cycle Analysis and GHG Emissions, to gain a better understanding of their environmental impact across the entire product life cycle.

a. Promote Industry-Wide Standards: To streamline green chemistry practices, industry-wide standards or frameworks could be developed to encourage the use of multiple metrics.

b. Encourage Policy Support: Government regulations or incentives can help push more companies toward using these metrics, particularly for those that currently do not use any metrics.

7.5. Use of GC metrics by generic pharma and API manufacturers

•Generic pharma uses the E-factor (71%) and Atom Economy (53%) more than API manufacturers.

•API manufacturers have high usage of GHG emissions (34%) compared to generic pharma (7%).

•Both groups show a relative % of not using any metrics (generic pharma 8%, API manufacturers 28%) as shown in Fig. 8.

7.5.1. Key Takeaways

Generic manufacturers are more focused on waste reduction (E-factor) and resource efficiency (Atom Economy) compared to API manufacturers. This could reflect a broader industry trend where generic producers, who often produce large volumes of medicines, are more motivated to improve efficiency due to the nature of the products and their global market presence.

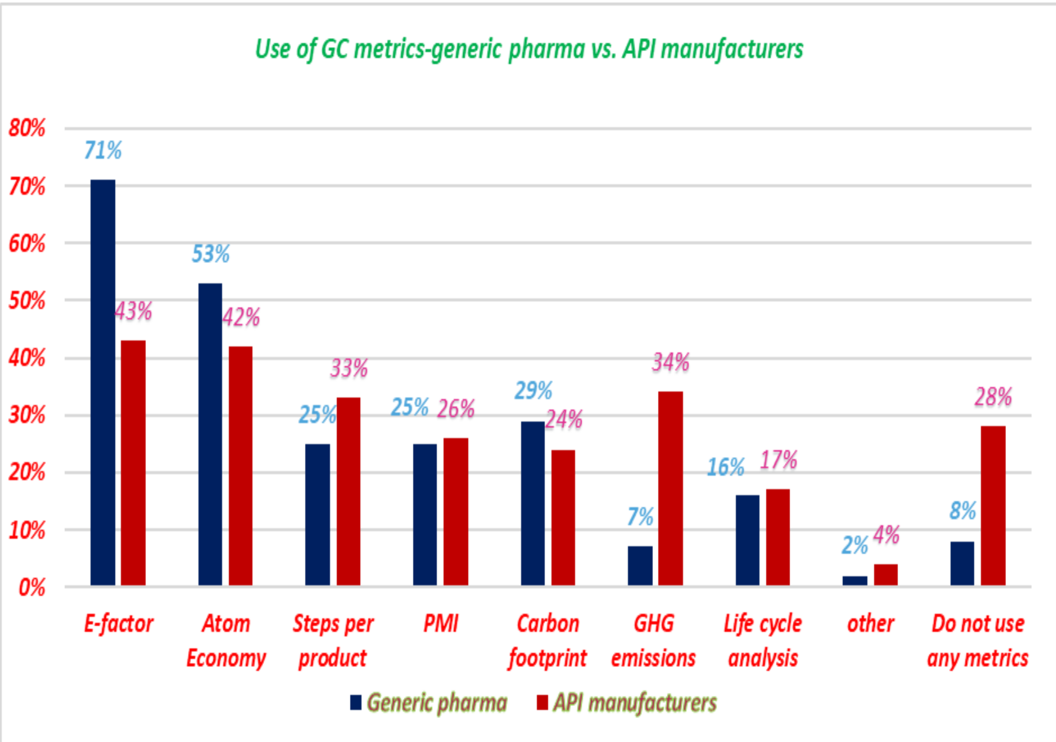

Fig. 8. Use of GC metrics by generic pharma and API manufacturers.

API manufacturers focus more on GHG emissions, with a higher percentage of companies considering the environmental impact of their greenhouse gases. This could be because API production is more energy-intensive, and there may be a stronger push in the API sector to mitigate carbon emissions.

Both groups show a relatively low adoption of Life Cycle Analysis and other metrics, suggesting that both sectors have room to improve when it comes to fully understanding and addressing the total environmental impact of their products.

API manufacturers have a significantly higher percentage of companies not using any green chemistry metrics (28%), which suggests that there is less emphasis on sustainable practices in the API sector, or that the metrics are not as integrated into their processes compared to generic manufacturers.

7.5.2. Recommendations

Encourage broader adoption of green chemistry metrics in the API sector, especially regarding Life Cycle Analysis and GHG emissions, to improve sustainability practices.

Promote education and training on the importance of green chemistry in both sectors, focusing on metrics such as E-factor, Atom Economy, and PMI to improve resource efficiency and reduce waste.

Support regulatory frameworks that encourage the adoption of green chemistry metrics across the entire pharmaceutical industry.

7.6. Use of GC resources by Indian pharmaceutical companies.

•Solvent selection guides (66%) and E-factor (65%) were the most used GC resources.

•PMI (26%), Reagent guides (27%), LCA tools (12%), and other resources (8%) were less used as shown in Fig. 9.

7.6.1. Key Takeaways

High Adoption of Solvent Selection Guide and E-factor:

66% of companies use the Solvent Selection Guide, and 65% use the E-factor. This reflects a strong focus on waste reduction and solvent sustainability, two key aspects of green chemistry in the pharmaceutical industry. These tools are foundational for improving sustainability and reducing the environmental impact of chemical processes.

Moderate Adoption of Process Mass Intensity and Reagent Guides:

26% of companies use PMI, and 27% use Reagent Guides, indicating that there is a moderate level of awareness regarding resource efficiency and reagent sustainability. However, these tools are not as widely adopted as the more basic E-factor and Solvent Selection Guide, suggesting that companies may prioritize waste and solvent management over other aspects of resource efficiency.

Limited Use of Life Cycle Analysis (LCA) Tools:

With only 12% of companies using LCA tools, comprehensive sustainability assessments throughout the life cycle of products are not yet a common practice. LCA tools require more resources, expertise, and data, which may explain the lower adoption rate.

Opportunities for Further Adoption:

The relatively low usage of LCA tools (12%) and other resources (8%) suggests that there is significant room for growth in the adoption of more advanced and holistic green chemistry tools in the pharmaceutical industry.

LCA tools, in particular, can provide valuable insights into the full environmental impact of a product, from cradle to grave, and could help pharmaceutical companies make more informed sustainability decisions.

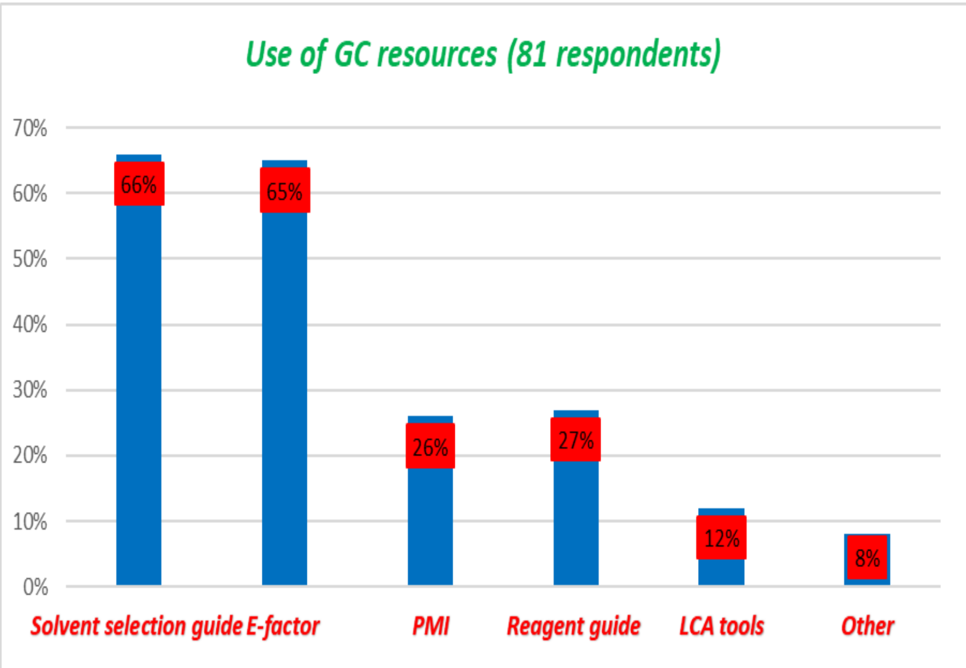

Fig. 9. Use of GC resources by Indian pharmaceutical companies.

7.6.2. Recommendations

Increase awareness and training on the benefits and usage of more advanced green chemistry tools like LCA to help companies assess their products' environmental impact throughout their entire life cycle.

Encourage wider adoption of green chemistry resources, particularly PMI and Reagent Guides, which focus on improving material and reagent efficiency.

Promote government incentives or industry collaborations to support the use of sustainable solvents and waste reduction tools across the pharmaceutical sector, with a focus on both generic and innovative drug manufacturers.

7.7. External GC collaborations - generic pharma vs. API manufacturers

•Generic pharma engages more in research projects (61%) and collaboration with solution providers (23%).

•API manufacturers collaborate more with international collaborators (37%) and research institutes (52%) as shown in Fig. 10.

7.7.1. Key Takeaways

Generic Manufacturers' Focus on Research:

Generic companies are much more focused on research projects and collaborations with research institutes. This indicates that generic manufacturers may have a larger commitment to developing novel green chemistry techniques and advancing the science behind sustainable manufacturing processes.

API Manufacturers' Preference for Solution Providers and Consultancies:

API manufacturers seem more inclined to collaborate with solution providers and independent consultancies. This suggests that API manufacturers are more focused on implementing existing, proven solutions to improve their processes, rather than conducting in-depth research themselves.

International Collaboration is More Common for Generic manufacturers:

Generic manufacturers are more likely to engage in international collaborations compared to API manufacturers. This reflects the global nature of the generic industry and the demand for meeting international sustainability and regulatory standards.

Higher Use of Consultancies by API Manufacturers:

The 37% collaboration with independent consultancies by API manufacturers highlights a strategic reliance on external expertise. This may be due to the complexity and specificity of the API manufacturing processes, which may require specialized knowledge for optimizing sustainability practices.

7.7.2. Recommendations

Generic manufacturers should continue to foster relationships with research institutes and research projects to further develop innovative green chemistry solutions. Expanding international collaborations could also help them stay ahead in terms of meeting global sustainability standards.

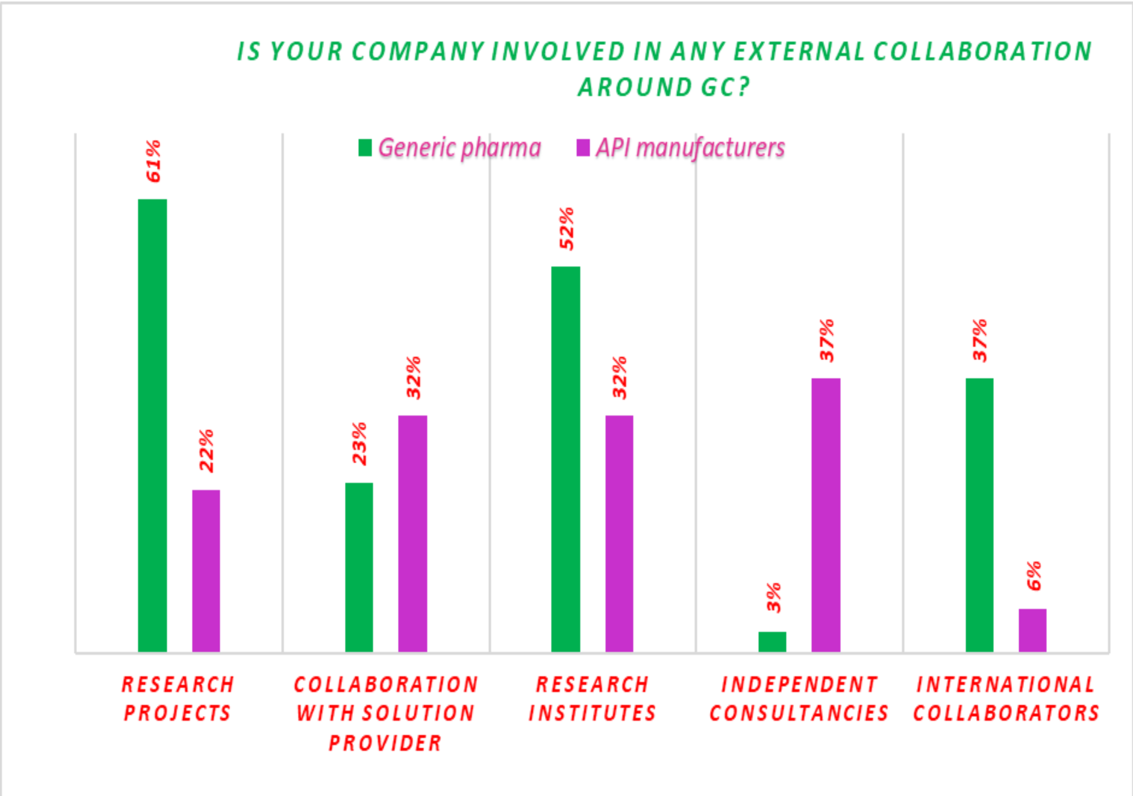

Fig. 10. External GC collaborations - generic pharma vs. API manufacturers.

API manufacturers could benefit from increasing their engagement in research projects to explore novel solutions tailored to their specific manufacturing needs, moving beyond simply relying on solution providers and consultancies.

Cross-industry collaborations between generic and API manufacturers could also be encouraged to combine strengths, with generic companies focusing on research and sustainability innovation, and API companies bringing in the practical experience of solution implementation.

7.8. Barriers to greater adoption of GC by Indian pharmaceutical companies

Fig. 11 shows that regulatory risk was the most significant barrier (66%), followed by time pressures (35%) and the upfront cost of implementing GC (21%).

•Lack of expertise (25%), awareness (24%), and proven technology (23%) were also observed barriers as shown in Fig. 11.

7.8.1 Key Takeaways

Regulatory Risk is the Most Significant Barrier:

Regulatory risk (66%) is the top challenge, making it crucial for companies to stay up to date with changing regulations and ensure that their green chemistry initiatives align with compliance requirements.

Time and Expertise Constraints:

Time pressures (35%) and a lack of expertise in GC (25%) are significant barriers, suggesting that companies may need to allocate more resources and time for training or hiring experts in green chemistry.

Awareness and Proven Technology Gaps:

Lack of awareness (24%) and lack of proven technology at scale (23%) indicate that there is still a need for greater education and the development of scalable green chemistry technologies.

Consumer Demand and Management Support are Less of a Concern:

Consumer demand for green products (11%) and lack of management support (3%) are less significant barriers, suggesting that these areas are either not yet fully developed or are not seen as immediate concerns by most companies.

Limited Use of Life Cycle Analysis (LCA) Tools:

With only 12% of companies using LCA tools, comprehensive sustainability assessments throughout the life cycle of products are not yet a common practice. LCA tools require more resources, expertise, and data, which may explain the lower adoption rate.

Opportunities for Further Adoption:

The relatively low usage of LCA tools (12%) and other resources (8%) suggests that there is significant room for growth in the adoption of more advanced and holistic green chemistry tools in the pharmaceutical industry.

LCA tools, in particular, can provide valuable insights into the full environmental impact of a product, from cradle to grave, and could help pharmaceutical companies make more informed sustainability decisions.

7.8.2. Recommendations

Invest in Regulatory Knowledge:

Companies should focus on understanding the regulatory landscape and prepare for potential changes to minimize the risk of non-compliance. Engaging with regulatory bodies and stakeholders may help them stay ahead of changes.

Allocate Resources for Expertise and Training:

Training programs or hiring green chemistry experts could help alleviate knowledge gaps and accelerate the adoption of sustainable practices across the company.

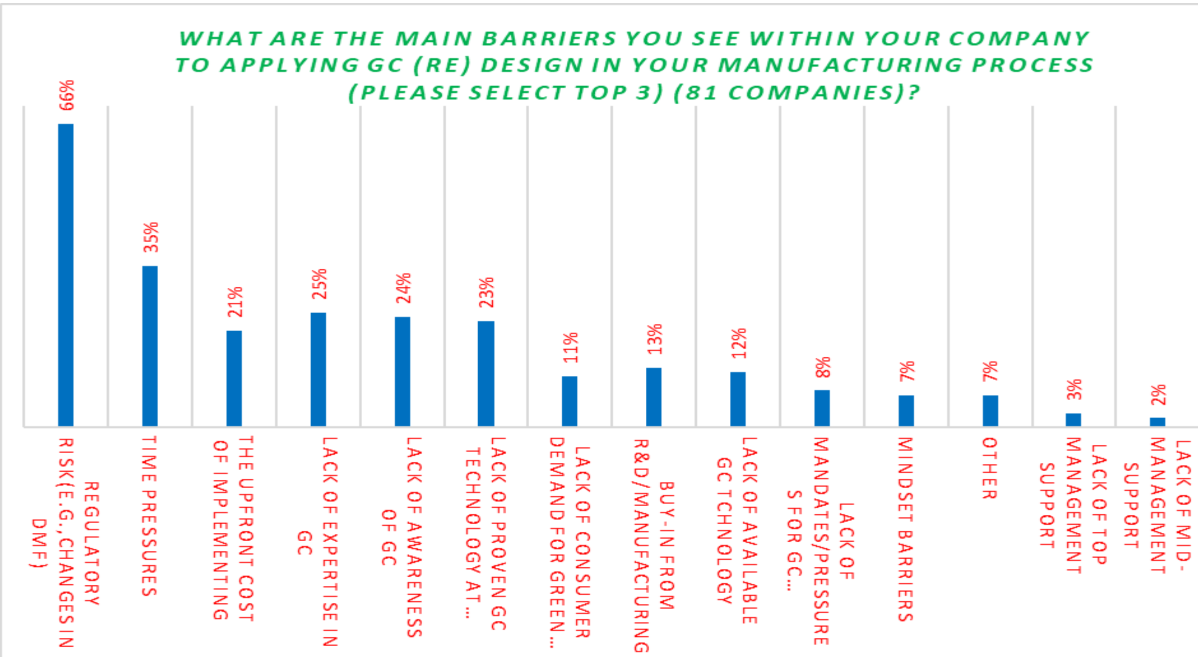

Fig. 11. Barriers to greater adoption of GC by Indian pharmaceutical companies.

Build Consumer Demand:

Companies should invest in educating consumers about the benefits of green products and explore ways to incorporate sustainable features into their products to meet evolving market demand.

Pilot and Scale Green Technologies:

Engage in pilot projects to test and prove the scalability of green chemistry technologies, which can then be expanded to larger production scales.

7.9. Barriers to greater adoption of GC - generic pharma vs. API manufacturers

•Regulatory risk was a major barrier for both, but higher for API manufacturers (72%) than generic pharma (66%).

•Generic pharma faces more challenges with time pressures (51%) compared to API manufacturers (26%).

•API manufacturers struggle more with lack of awareness (33%) and expertise (28%) in GC as shown in Fig. 12.

7.9.1. Key Takeaways

Regulatory and Time Pressures: Both generic and API manufacturers are significantly impacted by regulatory risks and time pressures, which can delay the adoption of green chemistry. These challenges are particularly pronounced in API companies.

Lack of Expertise and Awareness in API Companies: API manufacturers face a notable challenge with the lack of expertise and awareness of green chemistry. Generic companies seem to have a stronger foundation in these areas.

Cost and Technology Scaling: Generic companies are more concerned with upfront costs, while both generic and API manufacturers struggle with scaling green chemistry technologies effectively.

Mindset and Management Support: Mindset barriers and lack of management support are more of an issue for API companies, which may indicate resistance to change within the industry.

7.9.2. Recommendations for Overcoming Barriers

Training and Awareness: For API companies, investing in training and raising awareness about the benefits of green chemistry could be a priority. This can help overcome knowledge gaps and build expertise.

Support from Leadership: Both generic and API manufacturers should ensure that top management is fully committed to green chemistry, providing necessary resources and aligning business goals with sustainability.

Pilot Projects and Cost-Benefit Analysis: To mitigate concerns around cost and scaling, both types of companies could invest in pilot projects and conduct detailed cost-benefit analyses to demonstrate the financial advantages of green chemistry.

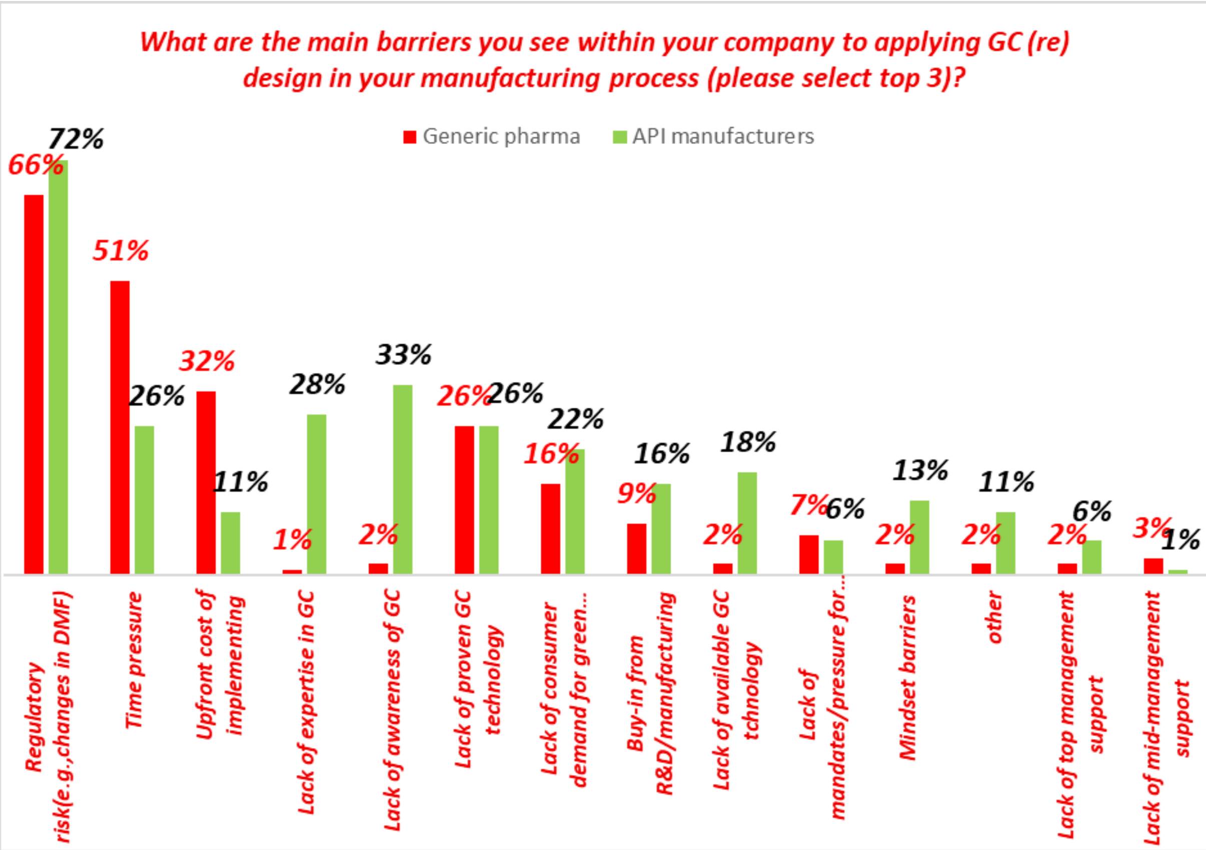

Fig. 12. Barriers to greater adoption of GC-generic pharma vs. API manufacturers.

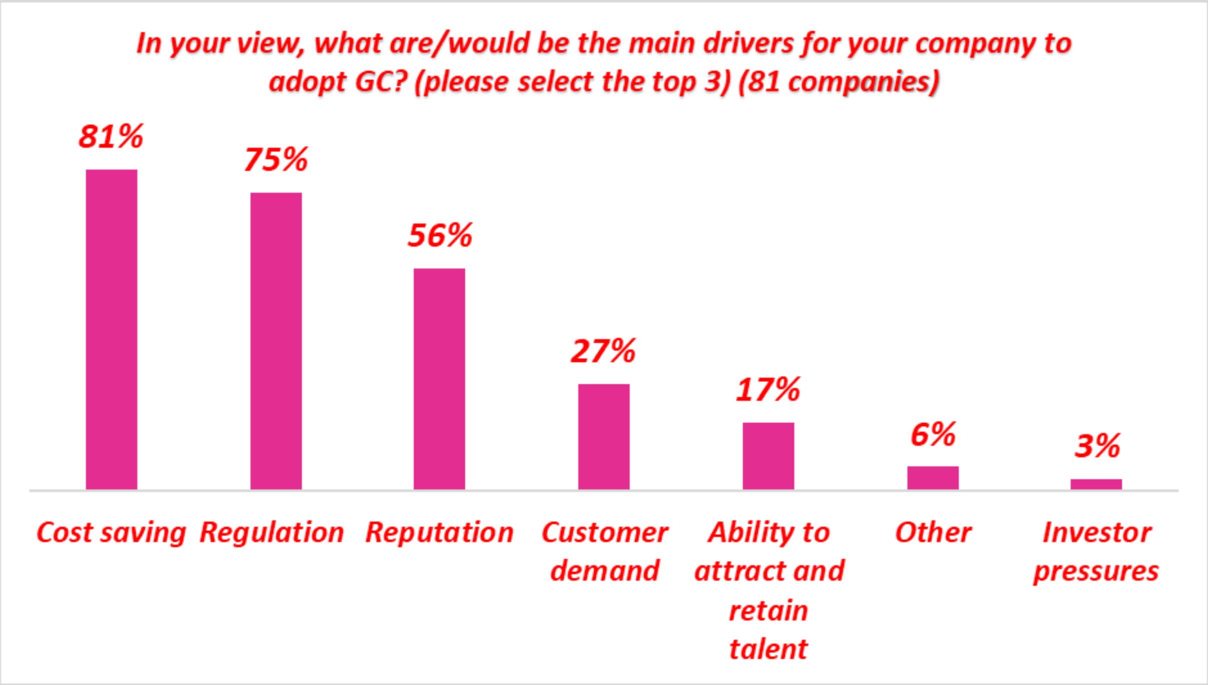

Fig. 13. Main drivers for adopting GC by Indian pharmaceutical companies.

7.10. Main drivers/reasons responsible for GC adoption by Indian pharmaceutical companies

- Figure 13 indicates that cost-saving was the primary driver (81%), followed by regulation (75%) and reputation (56%).
- Customer demand (27%), ability to attract and retain talent (17%), other factors (6%), and investor pressures (3%) were less significant as shown in Fig. 13.

7.10.1. Key Takeaways

Cost savings and regulation are the two most powerful drivers for adopting green chemistry, suggesting that companies are primarily motivated by economic factors and the need to comply with environmental regulations.

Reputation is also an important factor, indicating that companies recognize the value of demonstrating sustainability efforts to build a positive public image.

Customer demand and investor pressures are relatively less influential, but these factors could grow in importance as sustainability becomes a larger focus across industries.

Attracting talent is also a secondary concern but still noteworthy, especially as the workforce places more value on working for environmentally responsible companies.

7.10.2. Conclusion

To successfully adopt green chemistry and overcome the challenges associated with it, companies should focus on cost efficiency, regulatory compliance, and enhancing their reputation. Additionally, as consumer demand and investor expectations evolve, these factors are likely to become more central drivers in the future.

7.11. Main drivers for adopting GC - generic pharma vs. API manufacturers in India

- Cost saving is the top driver for both, but more so in API manufacturers (93%) than in generic pharma (81%).
- Regulation was also a strong target for API manufacturers (81%) than generic pharma (66%) as shown in Fig. 14.

7.11.1. Key Takeaways

Cost saving is the primary driver for API companies, which are more likely to adopt green chemistry for its direct impact on manufacturing costs. Generic companies also benefit from cost saving, but are slightly more focused on regulatory and reputational factors.

Regulation remains a strong driver for both groups, with generic companies being slightly more regulatory-focused. Ensuring compliance with environmental regulations is crucial for both types of manufacturers.

Reputation is a more significant concern for generic companies, suggesting that they are more actively marketing their sustainability efforts. In contrast, API companies might need to put more emphasis on improving their green credentials.

Customer demand for sustainable products is somewhat more pronounced in API companies, but it is still a secondary driver compared to cost and regulation.

Attracting and retaining talent is a higher priority for API companies, indicating that sustainability and green chemistry could be key factors in appealing to the next generation of professionals in this sector.

Investor pressures are a minor factor for both groups, but may increase as sustainable investing grows in importance.

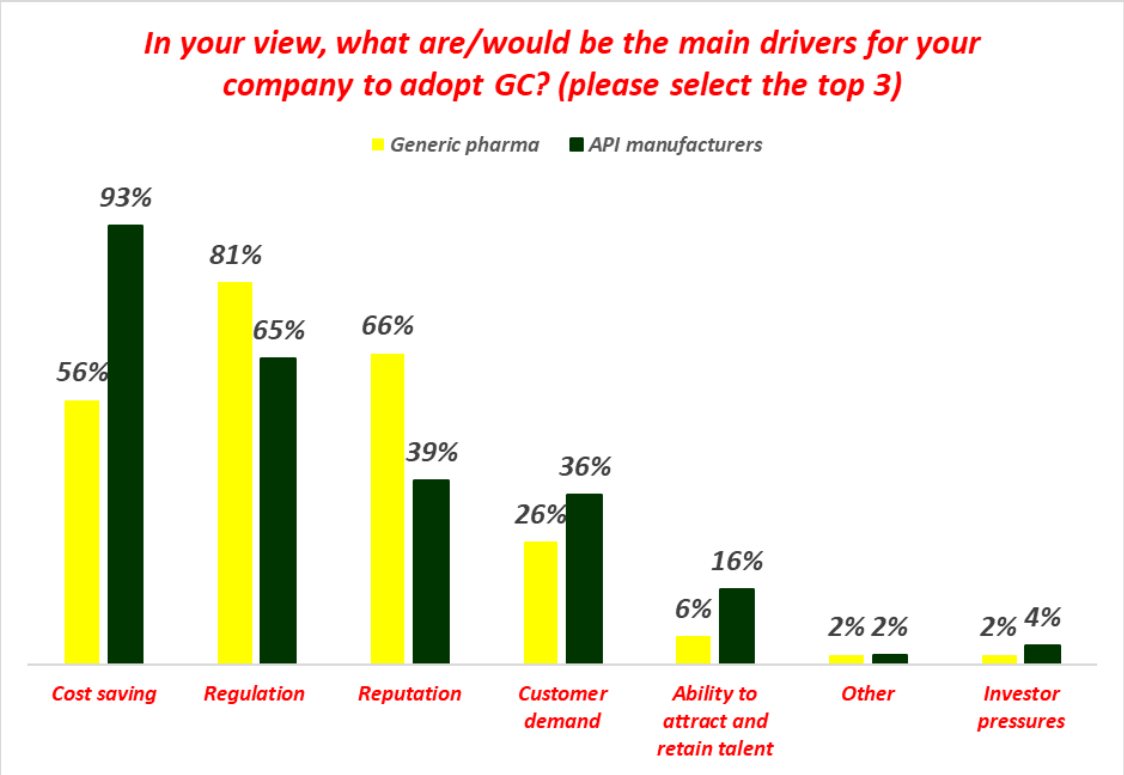

Fig. 14. Main drivers for adopting GC - generic pharma vs. API manufacturers in India.

7.11.2. Conclusion

For both generic and API companies, the key drivers for adopting green chemistry are cost saving and regulation compliance. Generic companies should focus more on reputation and market demand, while API companies should prioritize cost-saving initiatives and talent attraction. Both groups will benefit from keeping a close eye on evolving regulatory standards and market trends in sustainability.

8. Challenges and Future Opportunities

Sustainable chemistry, despite its vast potential, faces challenges in achieving widespread adoption. Shifting from traditional practices demands substantial investment in research, education, and infrastructure. Additionally, transforming entire sectors requires addressing resistance to change and incorporating expertise from multiple disciplines. However, sustainable chemistry is set to play a crucial role in meeting global sustainability goals. Trost and Crawley (2003) state that its principles can stimulate innovation, result in new inventions and open up opportunities for green product development. Through ongoing improvements in its techniques and broadening its implementations, sustainable chemistry presents an encouraging path toward a more renewable and ecologically aware future. This critical review of literature emphasizes green chemistry's multifaceted impact on sustainability, including reducing environmental impact, minimizing waste, and utilizing renewable feedstocks, showing its significant potential in contributing to global sustainability efforts. Despite ongoing challenges, green chemistry's transformative potential is clear, establishing it as a key element of sustainable development.

9. Applications of Green Chemistry

➢ Green chemistry has been used extensively in many laboratories and chemical production industries, including the polymer, fabric, paint, paper and pharmaceutical industries.

➢ It can function as a biodegradable reagent in chemical processes.

➢ It can serve as an environmentally friendly chemical product in the synthesis of alternative hydrides.

➢ Green chemistry can be applied to develop improved drugs for treating serious diseases.

➢ Green chemistry exhibits a broad range of applications in farming activities, including the use of biological pest management agents.

➢ It can lead to contributions to atom economy and homogeneous catalysis.

➢ Green chemistry can facilitate the synthesis of aromatic halides without using traditional halides.

➢ New methods have been developed by chemists to create polymers from renewable sources like biological waste.

➢ The manufacturing of electronic chips requires substantial amounts of chemicals, water, and energy, with the amount of toxic substances and energy resources used being 630 times the weight of the chip itself [32].

10. Conclusion

The goal of sustainable chemistry centres around twelve essential principles designed to minimize the use of hazardous substances in the manufacturing and implementation of chemical substances. Although it is challenging to meet all twelve principles simultaneously when developing a green chemistry approach, efforts are made to incorporate as many principles as feasible at different stages of production. Sustainable chemistry aims to protect the environment while achieving economic benefits through various approaches. For example, it emphasizes the development of chemical products that degrade into harmless substances after use, rather than persisting in the environment. Additionally, green chemistry seeks to fulfill public needs without depleting or damaging Earth's organic resources, focusing on creating products that can be fully reclaimed or reused. By altering production and consumption patterns, green chemistry aims to reduce pollution and waste. It is essential to create alternative technologies to mitigate additional damage to human well-being and the ecosystem. In summary, while green chemistry alone cannot resolve all environmental issues, applying its twelve principles can contribute significantly to creating a more sustainable world.

Author Contributions: Dr. K. VENKATESWARA RAJU : Conceptualization, Formal analysis, Methodology, Investigation, Data Curation, Writing – Original Draft. Ms. BADUGU PRIYANKA : Investigation, Data curation, Writing – Review & editing. Dr. LAKSHMI PRASANTHI NORI: Investigation, Methodology, Data curation, Writing – Original Draft. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgement: We thank the management of Shri Vishnu College of Pharmacy, Bhimavaram, for providing the necessary facilities.

Conflicts of Interest: The authors declare no conflict of interest.

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