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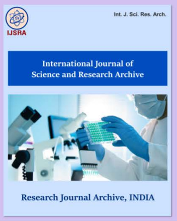

(Review Article)

A review of the progress and developments of green chemistry

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Abstract

The purpose of this review is to present the progress and development of a fundamental field that aims to design chemical processes with as little adverse effect on the environment as possible. The paper discusses the relevance of changes in industries considering the impact of the conventional chemical industry on the environment, people, and resources, with pollution, toxicity, and depletion of the resources being alarming effects. Waste minimization as one of the ten principles of green chemistry, atom economy and safer solvents and auxiliaries, is also described in detail. In the best practice examples drawn from key industries such as Unilever and BASF, a positive approach toward integrating biodegradable materials and renewable resources is evident. Furthermore, new developments in the catalysis and biocatalysts techniques as well as innovative methods of carbon dioxide conversion are also explored to demonstrate that sustainability is a core direction of chemical transformations. Nevertheless, prospects are evident albeit constrained in economic, regulatory, and technical sectors. Overcoming these barriers is crucial to the complete realization of green chemistry in the industry and the scale-back of environmental harm. It is for this reason that the present review offers a final reflection on how both green chemistry and a circular economy can change various sectors and offer more sustainable solutions.

Keywords: Green Chemistry; Waste Reduction; Safer Solvents; Biodegradable Material, Sustainable Practices; Co2 Utilization

1. Introduction

Green chemistry is required to be driven by growing concern for the environment and human health that are connected with conventional processes. Conventional methods often use hazardous substances, generate toxic waste, and deplete non-renewable resources, contributing to pollution and climate change. The evaluation of green chemistry was triggered by the devastating environmental consequences of traditional chemical practices such as chemical pollution, industrial waste, toxicity and resource depletion. Many conventional chemicals are toxic to human health and ecosystem. The wide use of hazardous chemicals and pesticides such as DDT leads to significant environmental degradation and health. Similarly, the reliance on non-renewable resources such as fossil fuels has raised and contaminated air water and soil further harming the ecosystem.**[1]**Recognizing these issues, industries and governments aim to minimize environmental impacts by adopting safer, more sustainable practices. This awareness resulted in many approaches that focus on developing environmentally friendly methods for synthesizing chemicals to reduce waste generation and conserve resources.

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1.1. Definition

Green chemistry is the design of chemical products and processes aimed at reducing or eliminating the use and generation of hazardous substances. It encompasses the entire lifecycle of a chemical product, from design and manufacture to use and disposal, promoting safer alternatives and minimizing environmental impact.[2]

1.2. History

The history of green chemistry involves the collaborative support of chemists, researchers and policymakers to shift towards more sustainable environmentally conscious practices.

The Act of Pollution Prevention passed in 1990 is an important piece of legislation in the United States of America, that provided for the elimination of pollution at its source rather than recycling or disposing of it. The Pollution Prevention Act of 1990, signed under George H.W. Bush, came at a time when the environment and economy were a big issue in America. E. The Act brought out the fact that a great deal of pollution was taking place in the United States and the cost of abating this pollution was going to be in the tens of billions of dollars per year.[3][4]

The US Congress thus recognized the need for announcing a pollution prevention policy owing to environmental as well as economic issues at hand. This paved the way for the 1990 Pollution Prevention Act, which requires the EPA to develop source reduction activities and engage with states and industries. This is a joint interest between the government and the chemical industry in promoting such environmental as well as economic objectives that aver that pollution should be prevented rather than controlled once it has occurred. This cooperative approach, therefore, is in harmony with the general trends of evolution in the US environmental policy[3][5].

Paul Anastas and John Warner who are practically oriented in Green Chemistry have closely worked with the EPA to encourage sustainable approaches for any chemical practice. They have been very active in advocating the incorporation of Green Chemistry concepts into industrial practices and in research projects aimed at the reduction of pollution and minimization of chemical risks to the environment. Anastas and Warner in their work concerning Green Chemistry contributed to the formulation of EPA strategies and approaches on pollution prevention, minimization of wastes and utilization of safer chemicals. Such efforts have supported this country in influencing the direction of environmental regulations and ongoing initiatives towards the protection of human health as well as the environment through enhancing sustainable and innovative approaches to methods of chemical processes and manufacturing. He and a colleague formulated the 12 principles of green chemistry that focused on such areas as waste avoidance, safer chemicals and materials, and renewable carbon sources. They help direct industries on how to reduce their negative impacts on the environment and improve chemical processes' sustainability.

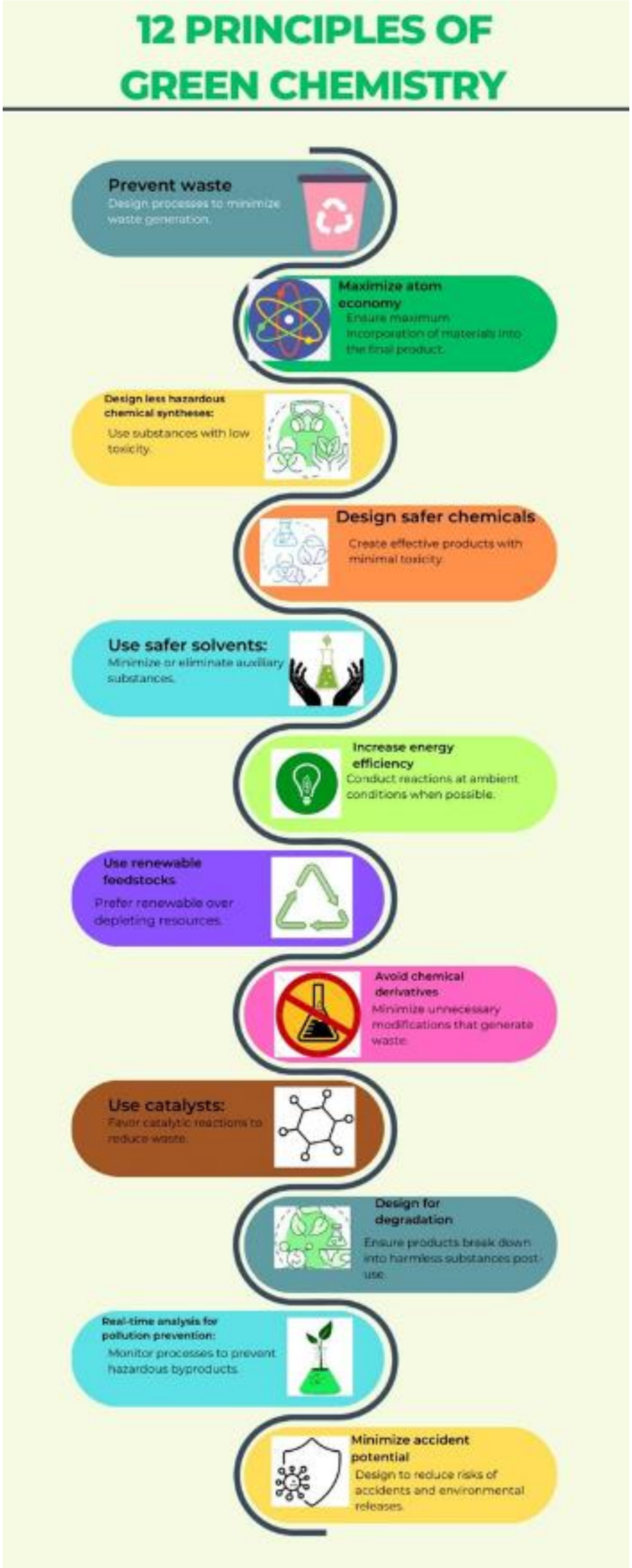

Figure 1 Principles of Green Chemistry

The prevention of waste through green chemistry is a multifaceted approach that emphasizes reducing hazardous materials and enhancing sustainability in chemical processes. By integrating innovative techniques and principles, green chemistry aims to minimize waste generation while promoting environmental safety.

1.3. Waste Prevention Strategies

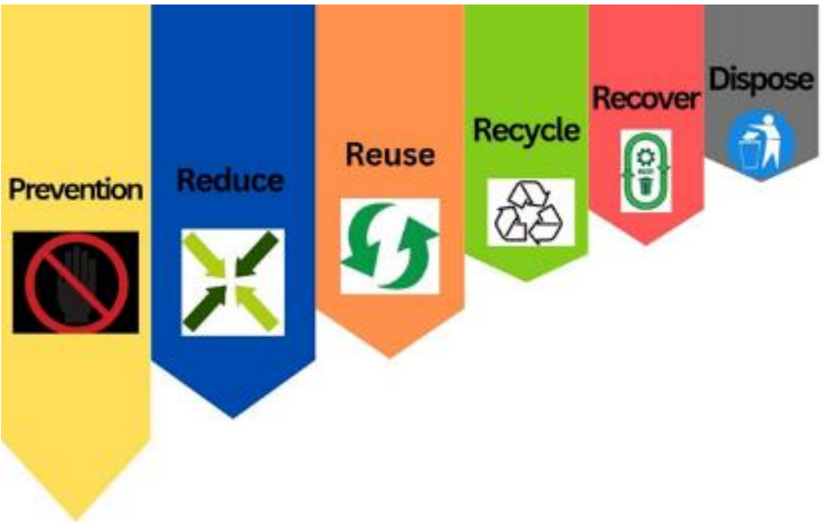

Figure 2 Waste Management Strategies

1.4. Prevention of waste

Waste prevention also known as waste reduction is a crucial aspect of waste management that focuses on minimising waste generation in the first place. Waste prevention is more effective than waste treatment. A Green Chemistry approach is economically attractive and environmentally beneficial.[**9]**. Here are some key strategies that are involved in preventing waste.

1.4.1. Source Reduction

Source reduction targets the reduction of the waste at its source often during the designing, manufacturing or use phase of products and materials. This can involve

-Products designing

Designing products with longer life spans, using fewer materials.

-Material Substitution

Replacing virgin with recycled or renewable alternatives.

-Packing

Using minimal and sustainable packing materials.[9][10]

1.5. Recycling and Reusing

Recycling and reusing are vital components of waste prevention that significantly contribute to environmental sustainability. Recycling involves processing used materials into new products, which conserves natural resources, saves energy, and reduces pollution. For instance, recycling paper reduces the need for deforestation and energy-intensive manufacturing processes. On the other hand, reusing means the ideas that bring the use of some goods for new value without major changes in its form, which is also characterized by minimum waste and consumption. The two practices reduce landfill waste disposal practices in addition to contributing to efficient and enhanced resource utilization and cost benefits for anybody and the populous. Recycling or reusing therefore goes along way in instilling a culture of sustainability with a positive impact on the physical environment.[10]

1.6. Biological treatment

It is important in waste prevention strategies because it deals mainly with biological waste which concentrates on the management and processing of biodegradable waste. Some are aerobic methods like composting and anaerobic methods like the digging of trenches to obtain biogas. These processes minimize the volume of waste produced while at the same time recovering energy and nutrients for a circular economy.An integrated process of using biological treatment technologies in combination with others helps overcome problems like high energy usage and high volumes of sludge production. Concisely, the application of biological treatment remains very significant in environmental pollution management and resource recycling in waste management systems generally.[10][11]

1.6.1. Atom economy

Atom economy is an essential principle of green chemistry that determines the effectiveness of the chemical transformations ejecting the additional reactant atoms. It is calculated using the formula:

Atom economy= (Total mass of products)/(Total molar mass of reactants) x 100

More specifically, a high atom economy suggests that there is less waste and that resources are used more efficiently, which must benefit both the environment and the wallet. This metric differs from percentage yield, which gives the actual results of experiments rather than ideal efficiency.[12][13]

1.6.2. Less Hazardous Chemicals Synthesis

Safer chemical synthesisations concern themselves with the volatile and hazardous effects that may ensue from the chemical synthesis process. E.g

- Water-based solvents. The substitution of toxic organic solvents for water has been used to minimize emissions [14][15].
- Biocatalysis. The application of engineered enzymes in the preparation of medicines also reduces pollution and intrinsic toxification more than using conventional processes[14].
- Metathesis reactions: It involves a process with low energy consumption and it also leads to minimal waste production which makes it an environmentally friendly way of synthesizing chemicals[14]
- Biodegradable plastics: Thus, creating products like Ecovio® from renewable raw materials contributes to the reduction of environmental persistence[14].

These approaches are in line with green chemistry regarding safety and sustainability.

1.6.3. Use of Safer Solvents

It is often argued that in green chemistry, solvents constitute one of the most important components since they may have a decisive effect on the environmental impact and the degree of sustainability of chemical processes. Most conventional solvents have the disadvantage of presenting risks regarding toxicity, pollution, and wastage. However, the choice of low-toxic solvents is one of the most important tenets of green chemistry. These solvents are supposed to have a low impact on human health and the environment. For example, using water as a solvent is an advantage for the process because it is environmentally friendly, easily available and cheap. Further, concerning environmental concerns, the use of bio-based solvents from renewable feedstock free from petroleum origin can be encouraged. Solvent-free reactions or the ones conducted with supercritical fluids like supercritical carbon dioxide are effective methods to increase the efficiency with least waste production and are another example of best practices**. .[16][17]**

Table 1 Greener Solvent Vs Traditional Solvent

Characteristics	**Green Solvent**	**Traditional Solvent**
Definition	Derived from renewable resources, Biodegradable	Petroleum based, Synthetic
Example	Ethanol, Glycerol, Limonene	Benzene, Toluene, Xylenes, Chloroform
Environmental impact	Low toxicity, Biodegradable, Minimal waste	Toxic, Non-Biodegradable, Harmful to ecosystem
Health effects	Non Carcinogenics,Low VOCs	Carcinogenic,High VOCs

Cost	Variable often high	Generally lower
Performance	Comparable or better	Established, widely used
Renewability	Renewable resources	Non renewable resources
Recyclability	Easily recyclable	Difficult to recycle
Applications	Pharmaceuticals, Cosmetics, Cleaning agents	Industrial, Manufacturing ,Coatings, Adhesives

1.6.4. Catalysis

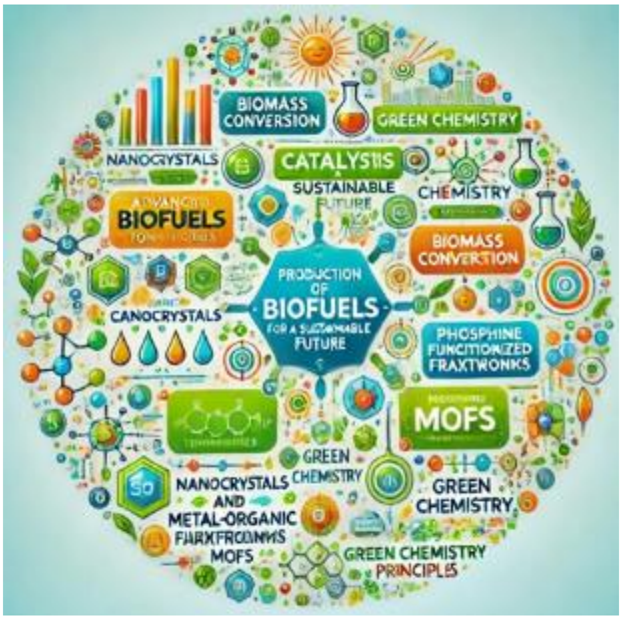

Figure 3 Catalysis

Another key application of catalysis in sustainable chemical synthesis and processes for the production of biofuels, chemicals and organic compounds is through green chemistry. Implementation of advanced catalytic systems and methodological approaches is associated with essential improvements and the minimization of adverse effects on the environment.

1.7. Production of Biofuels for Sustainable Future

Biomass conversion to biofuels and biochemicals requires catalysis in techniques such as catalytic pyrolysis and Fischer-Tropsch synthesis.These methods do not only increase yield but also correlate to life-cycle evaluation stressing sustainable production.[**19**]

1.8. Advanced Catalytic Techniques

Catalytic processes advanced The following advancement of more elaborate catalytic techniques could be expounded;

The improvement in selectivity and catalytic efficiency has been achieved in recent years through modern materials like nanocrystals and metal-organic frameworks (MOFs) for reactions like hydrogenation and oxidation. The functionalization of MOFs offers impressive selectivity and stability while lying between homogeneous and heterogeneous catalysts. New development has presented phosphine-functionalized metal-organic frameworks (P-MOFs) as potential heterogeneous catalysts for diverse catalytic transformations due to their structural endowment. These frameworks consist of high metal content and large surface area indicators which improves their performance relative to conventional catalysts. As a result of the tunable pore size and mechanically stable framework, these materials interact effectively with the substrate, making them ideal for use in organic transformations.**[18]**

The change in the synthesis of new catalysts and organic solvents such as ionic liquids and water is another evidence of green chemistry.The concepts of green chemistry call for minimizing waste and energy use, which are now being dealt with more and more via effective catalytic systems.**[18]**

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2. Case Studies

Figure 4 Case studies In Green Chemistry

Here's a list of several fairly interesting examples of green chemistry.

2.1. BASF and Bio-Based Plastics

BASF is one of the largest chemical manufacturers in the world and has been active in the offering of bio-based plastics. These are materials produced from renewable resources in contrast to the more common fossil resources.

2.1.1. Product Range

- **Ecovio**: A biodegradable and compostable plastic made from renewable resources. It's suitable for applications like packaging, shopping bags, and agricultural films.
- ****Ecoloop****: A system that incorporates waste materials into the production of new plastics, promoting circular economy principles.

BASF aims to reduce carbon footprints and enhance sustainability in plastics. By focusing on bio-based materials, they seek to minimize reliance on fossil fuels and reduce greenhouse gas emissions.

BASF is transitioning its Ethyl Acrylate (EA) production to bio-based sources. This new bio-based EA will contain a certified 40% bio content and reduce the Product Carbon Footprint (PCF) by approximately 30% compared to fossil-based EA. The bioethanol used is sourced from sustainable, non-food feedstock primarily in Europe. BASF aims to provide a drop-in solution for various applications, particularly in the coatings and adhesives industries, while phasing out fossil-based EA entirely. Bio-based plastics are used in various sectors, including packaging, automotive parts, consumer goods, and agricultural applications. Their biodegradability makes them particularly attractive for single-use items.BASF employs innovative technologies to convert biomass into high-performance polymers. This includes fermentation processes and the use of biotechnological methods to produce monomers- Bio-based plastics can help in reducing plastic waste and decreasing environmental impact. However, their sustainability also depends on the sourcing of raw materials and the entire lifecycle management.**[21][22]**

2.2. Phramceuticals (The Merck Process)

The Merck Process integrates green chemistry principles to enhance sustainability in drug manufacturing. Merck focusses on developing innovative, environmentally friendly processes that minimise waste and reduce hazardous materials. Notable achievements include:

2.2.1. Biocatalytic Cascade Design

The application of green chemistry principles in Merck's biocatalytic cascade design significantly enhances the sustainability of pharmaceutical manufacturing. By utilising enzymes as biocatalysts, the process minimises the use of hazardous chemicals and reduces waste generation, aligning with the green chemistry goal of safer, more environmentally friendly processes. Enzymatic reactions often occur under mild conditions, such as ambient temperature and pressure, which lowers energy consumption compared to traditional chemical synthesis. Moreover, the integration of multiple enzymatic steps in a single reaction vessel minimises the need for purification and isolation, thereby reducing solvent use and waste.

Apart from leading to a higher yield, this cascade design also enhances atom economy, another aspect of green chemistry. Finally, Merck has directed its investment in green chemistry for the synthesis of biocatalytic cascades that serve sustainable purposes for regulating authorities and consumer preferences for green and sustainable pharmaceutical industries.**[23]**

2.2.2. SMART PMI Tool

SMART-PMI, the in silico MSD aspirational tool, sustains pharmaceutical manufacturing more efficiently by evaluating the process mass intensity (PMI). This metric embodies the simple ratio of the amount of raw material used to develop one kilogramme of active pharmaceutical ingredients (APIs). Through the structural profiling of molecular targets, SMART-PMI sets challenging PMI goals based on the hierarchy of "Success," "World Class," and "Aspirational" to inspire chemists to embrace creative synthetic methods. This approach is consistent with Merck's strategy in green chemistry and resource efficiency for drug designing in an industry where the company has made substantive influence in the enhancement of sustainability standards.**[24][25]**

2.3. Green chemistry in agrochemicals

Green chemistry is revolutionizing conventional agrochemicals through green approaches aimed at reducing the impact of toxins on the environment. Key applications include:

2.3.1. Biopesticides

The employment of native elements in pest control with less dependence on chemical extenders.

Renewable Resources : Utilisation of biomass for the manufacture of agrochemicals, which boosts soil health and also at the same time reduces pollution.

Process Innovation: Innovating more environmentally friendly ways to produce goods and product manufacturing that will lead to less waste.

These strategies are intended to improve the safety of foods, lower levels of pesticide residues, and consider environmental health in addition to meeting the world's increasing population's increasing demands for food sustainably. [25] [26]

2.4. Unilever sustainable surfactant:

Some of the finest green chemistry examples currently in practice by Unilever are in the surfactant production processes where innovative approaches are being implemented. In June 2022, it became the first company to use NextLab linear alkylbenzene (LAB), a biodegradable surfactant produced from renewable biomass, in place of a fossil fuel. By ensuring the ongoing availability of linear alkylbenzene sulfonate (LAS), the world's most widely used synthetic surfactant, the company advanced the sustainability of cleaning products. Components of this commitment are sourcing 100% of the carbon used in its formulations from renewable or recycled sources as a way of easing the firm's carbon footprint. With the help of Cepsa Química, the company underlines its shift towards circular chemistry even more.[27]

3. Challenges In Implementation Of Green Chemistry

3.1. Economic barriers

Economic challenges are also major hurdles for growing green chemistry due to restricted capital and the inclusion of efficient, environment-friendly technologies in the market. Stakeholders also argue that it might take a lot of money to initially incorporate green functions and processes in their production lines, a factor that could be a major stumbling block for firms- particularly small and medium firms. Moreover, they are reluctant often time to put up with cost savings and subsidies on sustainable practices, which obstruct innovation. This is because existing chemical practices are difficult to change, and some of these have been fine-tuned to operate specifically for the cheapest methods of production, not necessarily the greenest, making it a challenge to replace them with green chemistry innovations in a competitive market situation. Such economics furthermore further acts as a brake to the use of more sustainable solutions while at the same time encouraging the continued use of environmentally, unhealthy and detrimental materials and methods.[28][29]

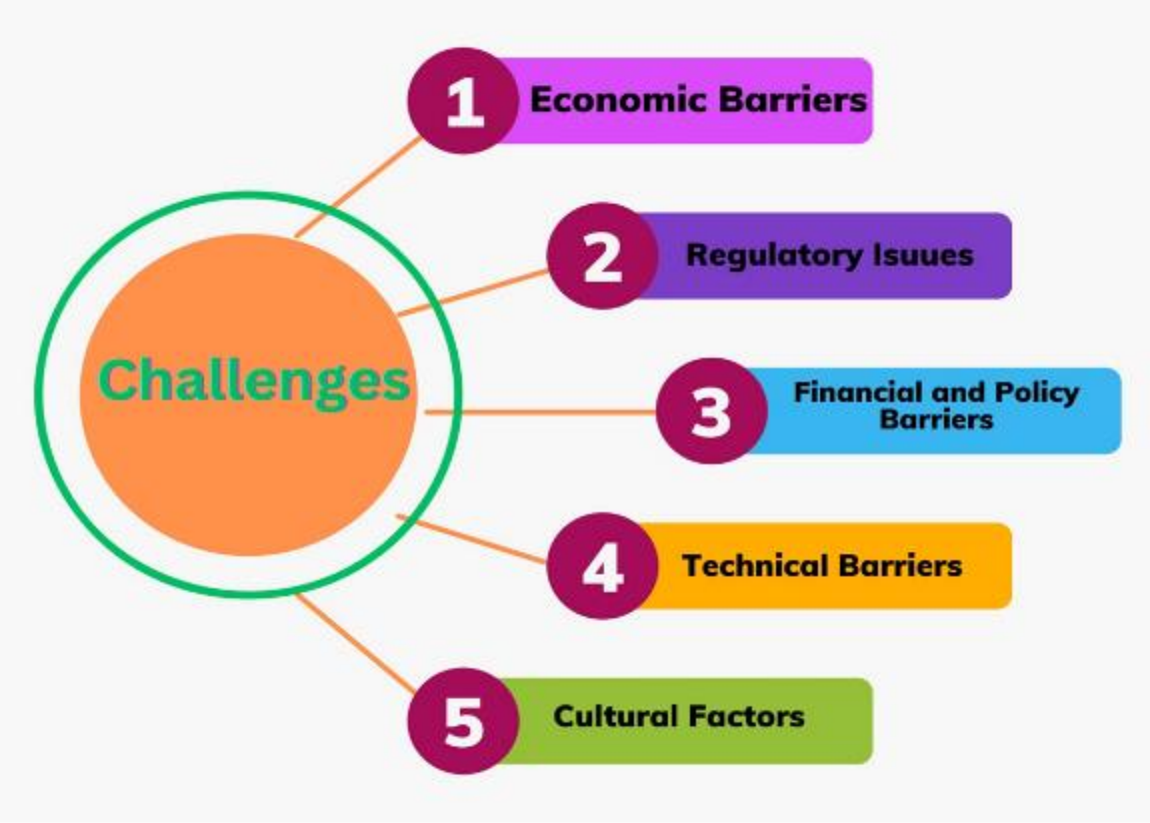

Figure 5 Challenges in Implementation OF Green Chemistry

3.2. Regulatory Issue

This problem explains that regulatory constraints present major challenges to green chemistry by erecting walls to the practice of sustainable chemistry. Current legislation is usually only developed according to conventional chemical processes and does not have enough versatility to adapt to different green chemicals. Prolonged approval procedures for the new chemicals weaken the introduction of improved, ecofriendly materials while prevailing toxicity testing fails to assess the safety of materials in many cases. On the same note, a lack of coherent policies and in some areas regional disparities in policy implementation can hinder market access to green technology. These challenges make it necessary to increase interdisciplinary cooperatiojn between scientists, companies, and policymakers in the development of principles for green chemistry.[30][31][32]

3.3. Financial and Policy Constraints

Tremendous yet striking financial and policy problems hamper the progress of green chemistry. Many a time due to financial constraints, research, and development is kept to a minimum, and innovative ideas on a sustainable solution are never ventured. Further, it may be seen that current legislation lacks the required provisions to encourage green chemistry and therefore the use of conventional methodologies continues. Policymakers thus may be inclined to provide short-term economic incentives to businesses at the expense of long-term environmental gains as well as inhibiting innovation in sustainable technologies. It will be crucial to abolish these barriers for the overall funding, regulation and participation of green chemistry and adoption of its technology aiming at decreasing environmental degradation.[31][32]

3.4. Technical Limitations

The influence of technical factors on green chemistry is evident in the following ways. First, reaction efficiency bears issues with low yields and selectivity that contribute to slow reaction rates and produce unwanted by-products that reduce sustainability. Furthermore, some of these reaction conditions may require high temperatures and pressures that make energy consumption high, and not favorable to green chemistry. Catalytic limitations, which include among others the availability and costs of renewable feedstocks will always present impediments to sustainable processes. This also leads to the challenges of forming endothermic and efficient, non-toxic, and recyclable catalysts. In addition, conventional separation and purification processes are often expensive and energy-consuming, and high purity standards mandate extra steps that produce more waste. Integration of processes into other industries can be challenging because of compatibility barriers, and as a result of poor information flow across disciplines, there may be limited change. Altogether, these technical issues have to be solved if green chemistry is to perform further and follow through on its promise of development sustainability.[31][32]

3.5. Cultural Factors

Genres and attitudes granted impact the realization of green chemistry by shaping perceptions, priorities and practices regarding sustainability. The population of some areas may not want to adopt improved practices due to culture and tradition, or due to the absence of belief in new environmentally friendly practices. Moreover, cultural factors explain the reluctance of communities to transform into an economy based more on preserving the environment and aspiring to switch to more environmentally friendly products. This is made worse by the educational imbalances because a lack of adequate knowledge of the principles of green chemistry slows down the innovation and implementation process. To overcome these barriers, specific key message(s) for public sensitization need to be culturally appropriate and tailored to encompass the collaborative aspects of sustainability.[31][32]

4. Potential Advancements In Green Chemistry

These recent developments in green chemistry are in line with sustainability and decreased effect on the environment. These include:

4.1. Innovative catalysis

Green catalysis in environmental science and green chemistry applications is decisive in the generation of catalytic processes with less pollution. This is because the novel catalysts—biocatalysts, nanocatalysts, and photocatalysts, among others—allow reactions to be sustained under mild conditions, thereby curtailing energy spending and emissions. For instance, enzyme catalysis encompasses a remarkable selectivity in organic transformations, which occurs mostly in water, avoiding toxic solvents. Also, the usage of renewable materials, too, for example, biomass importance in the catalytic processes and turning waste into products, supports the concept of circular economy. Research into sustainable catalytic materials, including those derived from earth-abundant elements, further underscores the commitment to reducing reliance on toxic substances and non-renewable resources. Overall, innovative catalysts not only improve the economic viability of chemical processes but also align with the principles of green chemistry, promoting a more sustainable future. [34] [35]

4.2. Biocatalysis and enzyme engineering

Biocatalysis and enzyme engineering are two of the most important sub-disciplinary areas of green chemistry that emphasize the green synthesis of chemicals, drugs, and fuels. Biocatalysis therefore denotes those procedures in which living catalysts, including enzymes or whole microorganisms, perform the feat of speeding up chemical reactions. Such processes work to minimize the use of extreme reagents, elevated temperatures, and poisonous solvents, so these are less damaging to the natural world. They are selective, meaning that they reduce the formation of byproducts and waste, so their separation and purification are easier and cheaper. In addition, biocatalysis reduces the demand for materials that are scarce because enzymes are made from renewable materials. Enzyme engineering builds on these natural catalysts by increasing or modifying their stability, activity, or selectivity for the industry and therefore increases green chemistry efficacy. Isolation, manipulation, and controlling procedures such as directed evolution and rational design are used to enhance enzyme reactions for enhanced efficiency for use in industrial processes. It applies to the process of synthesis of toxic reagents in industries, such as the pharmaceutical industry, using enzymatic methods instead of toxic chemical reagents in the synthesis of biofuels, where enzymes degrade biomass into renewable energy sources. They are also employed in farming to form environment-friendly insecticides, and fertilizers are also applied in water treatment to break down pollutants. However, some issues are still open, for instance, the increasing of enzyme stability within the operative conditions of industrial production and the decrease of enzyme cost. Nevertheless, there are barriers to these processes that have been somewhat mitigated by improvements in enzyme engineering to make them more of a viable option for large-scale green chemistry initiatives.[34][36]

4.3. The integration of circular economy

Therefore, two important principles of circular economy integration for green chemistry solutions are aimed at reducing waste and optimizing the use of materials and energy resources. In a cyclic system of production, products are created to be manually recycled at the consumer's end rather than being disposed of. Green chemistry corresponds to these principles in the sense that the field offers sustainable ways to perform chemical synthesis without the employment of hazardous chemicals and little energy input. When nations practice a circular economy for green chemistry, they can develop good, softer chemicals and products and minimize harm to the surrounding environment. For instance, materials that end up as waste in one process may well become feeds for another process, thereby giving a circular economic system. This approach fosters the usage of biodegradable materials, energy consumption in reactions is low, and the feedstocks used are renewable, aiming at achieving pollution control and resource management in a closed cycle.[37]

4.4. Energy-efficient synthesis

Green chemistry in the synthesis of energy-efficient processes seeks to minimize harm to the environment in chemical processes with equal efficiency gains. Catalysts, rotated field synthesis, mechanosynthesis, microwave-assisted reactions, and solvent-free methods are the ways to achieve this. Photosynthesis is carried out without using organic solvents and unnecessary energy such as heating or cooling through the mechanical breakdown of reactants. Microwave-assisted reactions involve the application of microwave energy to heat reactions and yield faster reaction rates and lower energy consumption compared with conventional methods. Solvent-minimized techniques have zero or low content of solvents, hence minimizing or eradicating dangerous waste such as solvents and energy used in solvent recovery. These and other principles of green chemistry, like atom economy, where all materials are incorporated into the final product, meaning that reactions under normal conditions do not need high heat for reactions or high pressure to force a reaction. Such methods as the low-energy synthesis of carbon quantum dots show the possibility of obtaining unique materials with less harm to the environment. [38][39]

4.5. Carbon dioxide utilization

CO2 utilization in green chemistry is a crucial strategy for reducing greenhouse gas emissions and fostering sustainable materials and processes. One key approach is Carbon Capture and Utilisation (CCU), where CO_2 is transformed into valuable chemicals, such as carboxylic acids, through innovative biocatalytic processes that operate under mild, energy-efficient conditions. This method not only repurposes waste products but also enhances sustainability. Additionally, the utilization of waste plastics integrates CO_2 capture with recycling efforts, promoting a circular economy by reusing existing materials to capture and convert CO_2, thus reducing landfill waste and creating new products. Emerging technologies are also making significant strides, with advancements in catalyst design that lower the energy requirements for CO_2 conversion processes. This progress is vital for making CO_2 utilization commercially viable and environmentally sustainable on a large scale, ultimately reducing dependence on fossil fuels and minimizing the environmental impact of industrial activities. [40] [41]

5. Conclusion

Green chemistry is an important departure to make the chemical industry more sustainable and environmentally friendly. Using cases and industry examples, he described case studies where new principles of green chemistry (waste reduction, atom economy, safer solvents) were already 'home-made' for piping companies such as BASF or Unilever. This is achieved not only by reducing environmental complications but also by paving the way for biodegradable and alternative materials.

However, the move to green chemistry is not so straightforward. There can be economic challenges, such as the cost of implementing new technology in the first place and regulatory overhead that can hinder growth, especially for small to medium-sized enterprises. Moreover, much new progress must be made in developing new catalytic processes and sustainable synthesis methods if the promises of green chemistry are not to be empty.

In a broader sense, all stakeholders i.e. policy makers, industries and researchers need to be on the same page and work together to develop a platform through which green chemistry can grow rapidly. We cannot solve all the economic, regulatory and technical challenges, but by promoting the further integration of green chemistry with circular economy principles we hope to create processes that benefit society as a whole and create a cleaner environment. Together can help create an even wider impact. Finally, the sustainable development of green chemistry is paramount to reducing environmental impacts, supporting global public health, and achieving the Sustainable Development Goals for future generations.

Compliance with ethical standards

No conflict of interest to be disclosed.

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