



Role of Green chemistry in sustainable development

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Abstract

Green chemistry emphasizes the design of chemical products and processes that minimize hazardous substances, reduce energy consumption, and rely on renewable resources. This proactive approach not only mitigates environmental degradation but also enhances safety, efficiency, and economic viability across industries. Sustainable development seeks to meet present needs without compromising the ability of future generations to meet their demands, integrating environmental protection, social equity and economic prosperity as a unified framework to combat climate change. Green chemistry and sustainable development use environmentally responsible activities and resource-efficient growth to reduce greenhouse gas emissions and protect ecosystems. The green chemistry promotes growth, and innovation reducing pollution, Carbon emissions and resource waste that aligns directly with the goals of sustainable development and climate action.

This review article focuses on the scientific basis for this transition, including designing safer chemicals, cleaner reaction mechanism and energy-efficient processes, Through the development of catalysts, renewable feed-stocks, low-energy synthetic routes, benign solvents and materials for renewable energy technologies, resulting circular economic practices such as recycling, reuse and design for degradation, thereby reducing the carbon footprint of industry and supporting responsible production and consumption. Carbon Capture and Utilization (CCU), is done by investigating the chemical synthesis pathways that transform atmospheric CO₂ into value-added products like synthetic fuels and polymers.

Keywords: Carbon Capture and Utilization (CCU), Hydrogen fuel cells, Carbon emissions, Greenhouse gas emissions

Introduction

“Green Chemistry” refers to the use of chemicals in such a way to maximize their incorporation in a chemical process while reducing its innocuous effect on the surrounding environment and the organisms in that ambience. It eliminates the use of hazardous and toxic chemicals and their synthesis during a chemical reaction. The term Green Chemistry was coined by Paul T. Anastas^[1]. Green Chemistry first came into existence in 1991 by the US Pollution Prevention Act under the United States Environmental Protection Agency (USEPA). Green Chemistry aims not only to reduce the use or generation of toxic chemicals but to maximize the energy utilization, economy efficiency, reducing derivatives and promoting a greener healthier environment which is an aspect of Sustainable development. The concepts of green chemistry involves a set of basic twelve principles. It is an interdisciplinary approach that is widely adopted by pharmaceuticals and textile industry making it possible for the advent of green chemicals. It is a dedicated endeavor of scientists, industrialists and pharmacists. It is a method to minimize polluting effects of toxic chemicals on the environment and reduction of risk in handling of such chemicals which causes a reduction in the chemical accidents. Green Chemistry has led to the alternative pathways in a chemical reaction reducing derivatives and minimizing the steps in a reaction. It has led to the formulation of chemicals that are not harmful to the environment reducing traditional harmful chemical usage. Green Chemistry has led to the emergence of techniques like Microwave irradiation, sonochemical and

ultrasound approach and Nanosciences^[1]. Green Chemistry utilizes raw materials that are easily degradable. It is an innovative and effective scientific approach that perfectly fits the aim of Sustainable Development and its goals. It has developed certain analytical approaches that allows beforehand effect of chemicals and its innocuous effect on the environment. It inherent to the use of safer chemicals. It has led to the development of bio polymers and certain bio catalysts. It involves the usage of safer solvents like super critical CO₂ instead of traditional toxic solvents. Green Chemistry aims to focus greener and healthier environment for all living beings. Its essence is an economy friendly chemical production whose products are accessible and easily degradable. It is product specific which reduces time of production and overall implications of result is analyzed. It is a dynamic approach of Sustainable Development.

The role of government in green chemistry promotion:

The BioE3 Policy: Launched to drive sustainable bio-manufacturing, this policy actively funds the shift toward biomass-based materials, agricultural residues, and industrial waste to create bio-based specialty chemicals, enzymes, and bio polymers.

National Chemical Policy & PLI Schemes: The Production Linked Incentive (PLI) schemes and updated chemical frameworks provide financial support to industries that integrate green engineering, such as flow chemistry and micro-reactors, which reduce chemical waste and energy footprints.

Setting Up Green Infrastructure & Industrial Clusters:

Rather than forcing individual chemical plants to reinvent the wheel, the government is building shared, modern infrastructure to enforce a circular economy.

Centres of Excellence (CoE): The Department of Chemicals and Petrochemicals has established specialized research hubs at premier institutes like IIT Guwahati and CSIR-National Chemical Laboratory (NCL). These centers focus purely on developing biodegradable polymers and eco-friendly chemical processing techniques.

The Plastic Parks Scheme: This cluster development model focuses on moving the plastics industry from a linear "use and dispose" structure to a circular system, providing advanced, eco-friendly recycling technologies and equipment to processing hubs.

PCPIRs (Petroleum, Chemical and Petrochemical Investment Regions): Mega-clusters (such as Dahej and Vizag) are receiving massive investments to upgrade into low-environmental-impact chemical hubs.

Clean Energy and Raw Material Feed-stocks: Green chemistry relies as much on clean energy inputs as it does on safe molecular formulas [2,3].

National Green Hydrogen Mission: With a target of achieving 5 MMT (Million Metric Tons) of green hydrogen capacity per year by 2030, the government is laying the groundwork for decarbonizing chemical synthesis, particularly in heavy fertilizer and petrochemical industries.

The Policy Pivot: Moving to Bio-Based Manufacturing [4]

The cornerstone of India's current strategy is transitioning away from traditional, petroleum-dependent chemical manufacturing to renewable alternatives.

Literature review

1. Principles of green chemistry [1]

There are 12 core principles of Green Chemistry which were enunciated by Paul in 1994 [6] making the objectives of green chemistry more elaborated and specified.

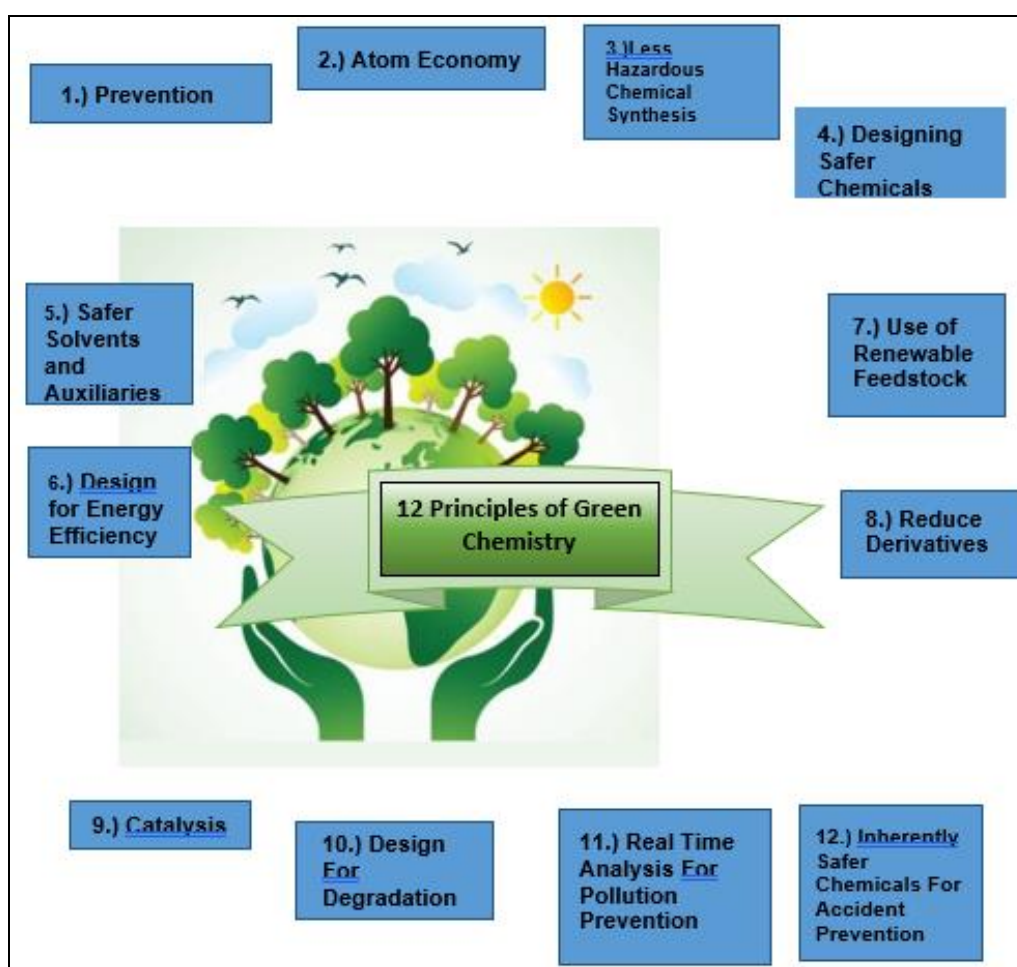


Fig 1: Principles of green chemistry

- 1. Prevention:** preventing harmful chemical synthesis initially so that it would not harm the environment.
- 2. Atom Economy:** refers to the maximization in utilization of reactants in product formation.
- 3. Less Hazardous Chemical Synthesis:** to promote safer, non-toxic environment.
- 4. Designing Safer Chemicals:** for toxicity prevention.
- 5. Safer Solvent and Auxiliaries:** must be innocuous when used.
- 6. Designing for Energy Efficiency:** energy requirements of that process must be analyzed. It should be conducted at ambient temperature and pressure.
- 7. Use of Renewable Feed-stocks:** raw materials used must be renewable rather than new after every process.

8. **Reduce Derivatives:** unnecessary derivations should be minimized.
9. **Catalysis:** catalysis are important because of better efficiency and product specificity.
10. **Design for Degradation:** chemicals must be biodegradable.
11. **Real Time Analysis for Pollution Prevention:** beforehand analytical conduct for monitoring impact on environment that is helpful for pollution prevention.
12. **Inherently Safer Chemistry for Accident Prevention:** only safer chemical use to prevent chemical accidents like fires, explosions, etc.



Fig 2: Representation of 12 principles of green chemistry.

Goals of green chemistry ^[1]

The goals of green chemistry perspective include:

- To reduce adverse environmental impacts of toxic chemicals by innovative choice of materials and their chemical transformations.
- To develop processes based on renewable raw materials.
- To achieve atom economy that is, to minimize byproducts in chemical transformations.
- To develop products that are less toxic and degrade more rapidly.
- To reduce the requirements for hazardous or environmentally persistent solvents and extractants.
- To explore reliable methods with minimum waste generation and to improve energy efficiency.

Attributes of an ideal chemical reaction ^[1]

- Safety
- Selectivity
- Energy efficiency
- Absence of toxic byproducts.
- Simplicity
- High yield
- Use of renewable raw materials

Green chemicals ^[1]

There are certain chemicals that minimize the toxic impacts of them on the environment and have efficiency in rate of product formation. Such chemicals are known as Green Chemicals.

The green chemicals can be categorized into 3 following parts namely:

1. Green Reagents
2. Green Catalyst
3. Green Solvents

1. Green Reagents

These are those chemicals which are used for transformation of selected feedstock into targeted product molecules eliminating by-product formation.

Primarily used green reagents are:

- DMC (Di-Methyl Carbonate)
- Polymer Support Reagents

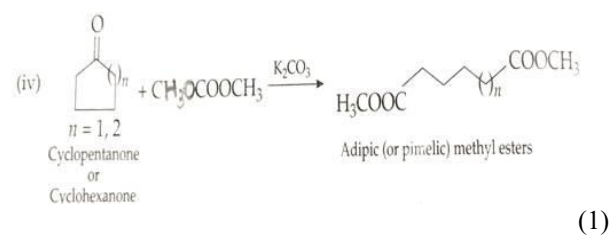
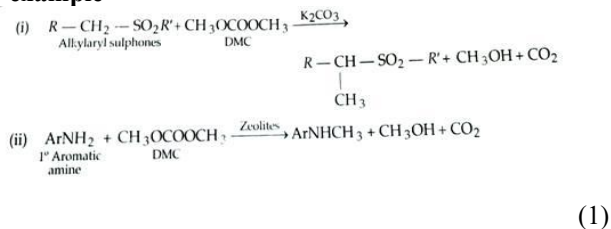
DMC (Di-Methyl Carbonate)

First reported use of DMC was by Fundo at University of Venice for methylation of sulphones, primary amine, acryl nitriles, methyl acrylate (important for synthesis of anti-depressant drugs).

Reasons for use of DMC

- Safe
- Non-toxic
- Green alternative for methylation of primary amines, sulphones, etc in place of Di Methyl Sulphate (DMS), phosgene as toxic intermediate in carbonylation process.

For example

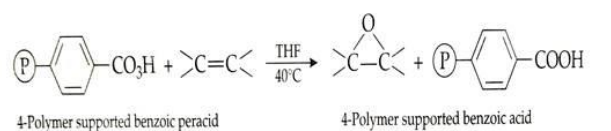


Polymer Support Reagents ^[1]

Polymer supported per-acids are used in epoxidation of alkene.

For example

- Polymer supported benzoic per acid
- Polymer supported chromic acid
- Poly N Bromo Succinamide, etc



2. Green Catalyst ^[1]

Catalysts play a major role in a chemical reaction by altering the rate of reaction reducing the time of product formation utilizing energy efficiency and atom economy.

Various types of catalysts used are as follows:

2.1 Photocatalyst

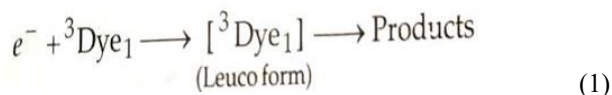
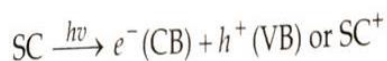
Uses the phenomenon of photo catalysis for product formation.

It utilizes light radiation of certain characteristic energy and frequency for creating electron and hole pair in semiconductors.

This phenomenon is useful in treatment of waste-water, organic and inorganic contaminants, dyes, surfactants, pesticides, m, industrial and bacterial pollutants from drinking water.

For example

1. Photo-catalytic bleaching of various dyes using ZnO semiconductor (over toxic Rhodamine-B)
2. Use of TiO₂ as photo catalyst over toxic metal ions from waste-water.

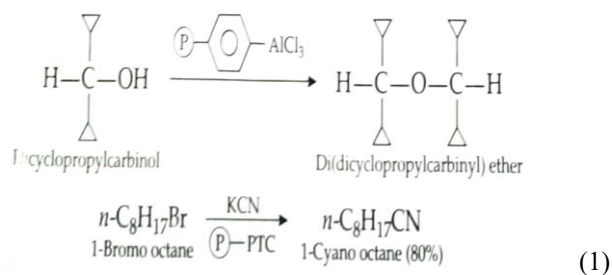


2.2 Polymer Supported Catalyst

Catalyst + polymer backbone (in homogeneous phase) = Polymer Supported Catalyst

For example

- Polymer supported AlCl₃ for formation of ether from alcohols.
- Use of Polymer supported PTC



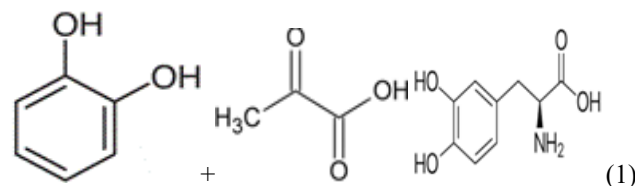
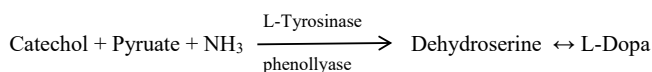
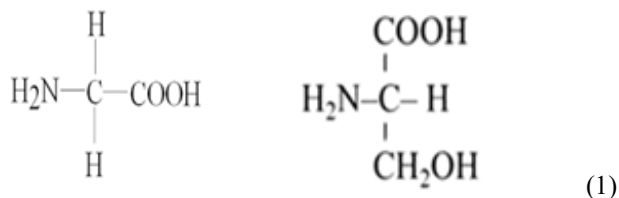
2.3 Biocatalysts

These are enzymes in biological system that catalysis a chemical reaction improving its efficiency and rate of reaction.

Enzyme + Microbes → biocatalysts that facilitates oxidation, reduction, acylation, halogenation, hydrolysis, etc.

These are highly stereo-specific, regio-selective and chemo-selective.

For example



L-Dopa is used in treatment of Parkinson's disease.

3. Green Solvents ^[1]

- **Classical solvents:** THF, ether, acetone, benzene (lesser efficiency, more reaction time, less product specific follows by-product formation).
- **Green Solvents:** Ionic Liquids, Super Critical CO₂, Aqueous Solvent System.

3.1 Super Critical CO₂ (SC CO₂)

- It is a low cost, innocuous green solvent.
- It is non-toxic, non-inflammable, inexpensive.
- Super Critical CO₂ ^[10] is used in decaffeinating coffee beans from green coffee beans.
- SC CO₂ + green coffee beans + water = caffeine → passed on activated charcoal Super Critical CO₂ adsorbed on activated charcoal and caffeine filtered as aqueous solution.
- Super Critical CO₂ is extracted for further use again.

3.2 Aqueous Solvent System

- Utilizes water as solvent for chemical reaction
- It is a safer, non toxic, inexpensive alternative over conventional solvents.
- It is used at high temperature say 100°C.

For example

- Baeyer Villiger Oxidation
- Dipolar Cycloaddition
- Claisen condensation
- Pericyclic Reaction all these enlisted reaction uses water as a solvent.
- Water increases the rate of reaction by packing hydrophobic surfaces in transition phase, thereby facilitating polar interactions.

3.3 Ionic Liquids

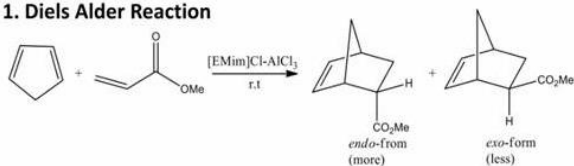
- These are highly ionic with melting point ≤100°C.
- They are non inflammable
- Have low vapour pressure.
- Are easy to use and recyclable.
- They are considered as photo-initiators which absorbs HCl or any other byproduct which is undesirable.
- They are non-toxic and non volatile.
- They are ions: organic cations and inorganic or organic anions.

For example

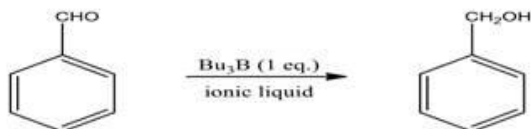
- Ethyl ammonium nitrate [(C₂H₅NH₃)NO₃] is considered as the first ionic liquid discovered by Walden.
- Bronsted acidic ionic liquid: 1 methyl imidazolium tetrafluoroborate (green catalyst) [H_{mim}]⁺BF₄⁻.

Role of Ionic Liquids in Green Chemistry

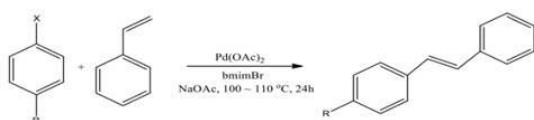
1. Diels Alder Reaction



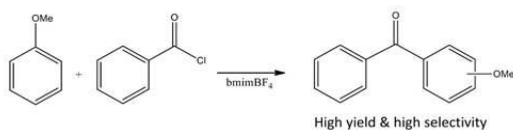
5. Reduction



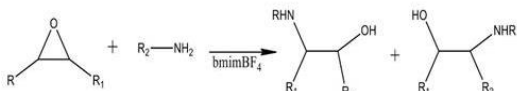
2. Heck reaction



4. Friedal Craft acylation



8. Ring opening reaction



Emerging green techniques

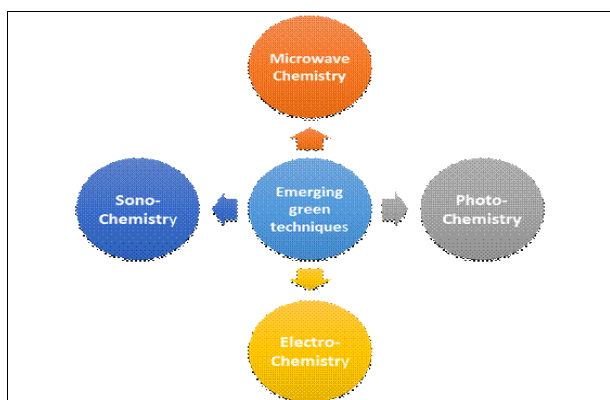


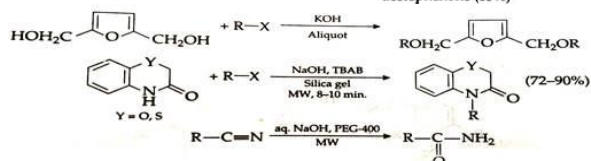
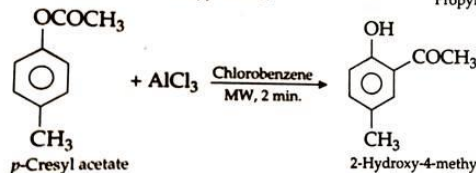
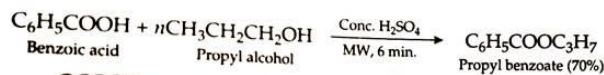
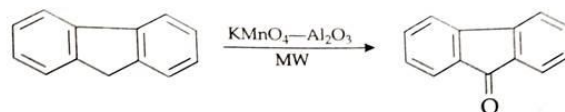
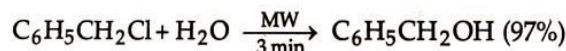
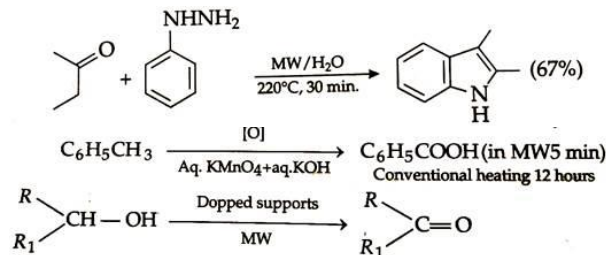
Fig 3: Emerging green chemistry techniques

1. Microwave Chemistry [1]

- It utilizes the microwave radiations of wavelength of 1 cm to 1m.
- The frequency of such waves is 300 Hz to 30 GHz.
- Features of Microwaves:
 - High rate of reaction
 - Improved yield of product

- Reduction of side product
- Limited need of solvents
- Stereo-selective and regio-selective

For example



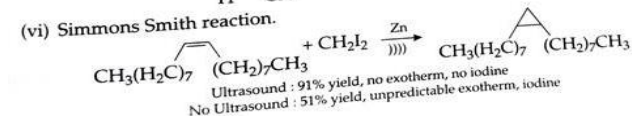
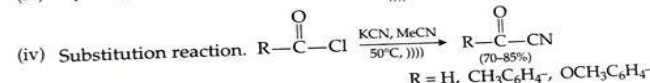
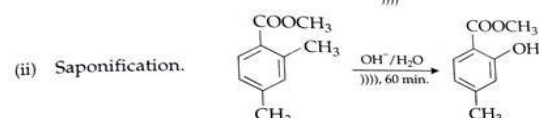
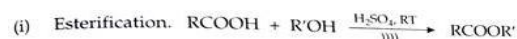
2. Photo Chemistry

It utilizes light radiation which leads to the formation of product by inter conversion from singlet to triplet state and then the formation of product without any side product formation.

3. Sono Chemistry

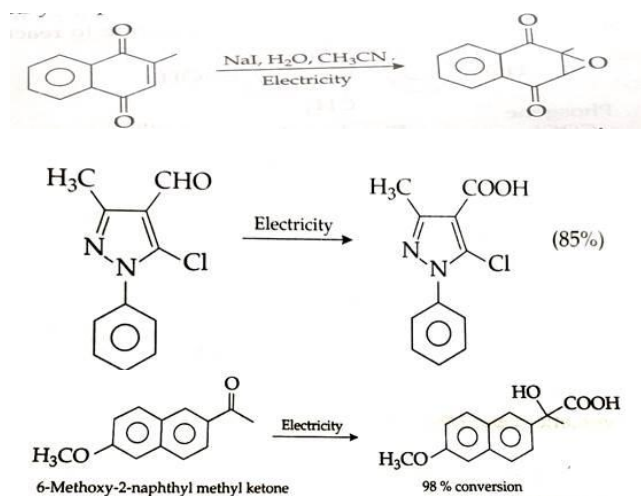
It refers to the use of sound waves that are inaudible to human i.e., sound of frequency more than 20,000 Hz to create a chemical reaction.

This method is more efficient than conventional used methods.



4. Electro Chemistry

It uses electricity to initiate a chemical reaction which is very fast, stereo-selective and efficient than the conventional methods.



Applications of green chemistry

1. Solution to Turbid Water Clear

Using the principles of green chemistry and through research for longer time duration it was found that tamarind kernel powder can turn turbid water into clean water. This was earlier done using Potash Alum ($K_2SO_4 \cdot Al_2(SO_4)_3 \cdot 24H_2O$) which was found to cause Alzheimer's disease.

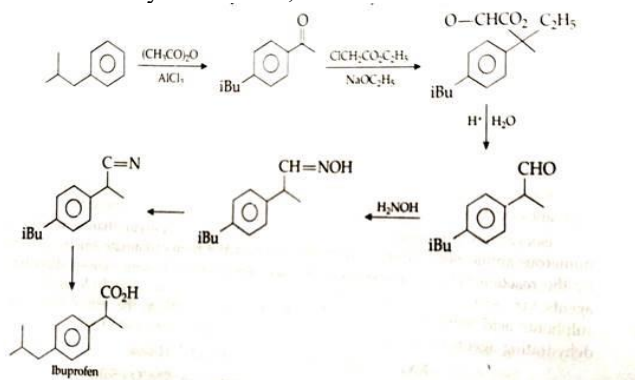
Kernel powder is non toxic, inexpensive and perishable.

2. Eco Friendly Dry Cleaning of clothes

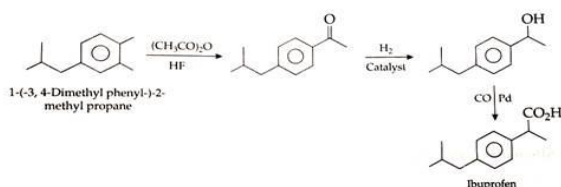
Traditional methods of dry cleaning uses PERC-Per Chloro Ethylene which was cancerous and water polluting. Now-a-days this is replaced by Super Critical CO_2 for cleaning clothes acting as surfactants.

3. In Medicinal Chemistry

In pharmaceuticals industry green chemistry principles is utilized. For Example: Ibuprofen a painkiller was traditionally prepared using many steps with by products and lesser yield. But now using the green chemistry principles ibuprofen is prepared in three step synthesis only. Conventional synthesis [1] [6],

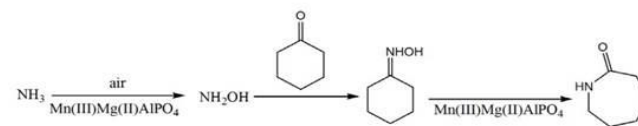


Green synthesis of Ibuprofen



4. Next generation catalysis design

Use of catalyst like nanoporous aluminophosphate catalyst with acidic and redox sites for synthesis of Nylon 6,6 precursor caprolactam. The one step synthesis is solvent free and eliminates waste byproducts [2, 3, 4],



5. Green Bleaching Agents

Conventionally Sodium hydroxide and sodium sulphide was used along with chlorine for manufacturing of good quality white paper from lignin in wood. The chlorine used in this process generated toxic intermediates. These compounds were known to cause health problems and were considered as carcinogenic.

Terrence Collins of Carnegie Mellon University developed green bleaching which uses hydrogen peroxide as bleaching agent. This technique reduces water usage at shorter time and lower temperature lignin was bleached [14, 15]

6. Computer Chips

Researchers have developed prototype computer circuit boards using chicken feathers [16] [18], offering a sustainable, biodegradable alternative to traditional fiberglass and epoxy components. The technology uses keratin from feathers to create strong, lightweight composites that can increase signal speeds. It is a promising "green" initiative for electronics, though not yet in widespread commercial use.

1 A comparison on synthesis of Nylon 6:

Features	Traditional Route	Green Route
Oxidant	Hydroxylamine sulphate	H_2O_2
Byproduct	High quantity of Ammonium Sulphate	Water
Catalyst	Liquid acids (H_2SO_4 , Oleum)	Solid - zeolites
Energy	High pressure and high temperature	Mild conditions
Sustainability	Low	High

A comparison on synthesis of Ibuprofen

Features	Traditional Route	Green Route
Number of steps	6	3
Atom Economy	~40%	~77%
Reagents and catalyst	Toxic $AlCl_3$, corrosive HCl	Recyclable like Raney Ni
Waste and Byproduct	Toxic inorganic salts of $AlCl_3$ hydrate	Minimal and useful if produced

Future scope of green chemistry

Green chemistry, was once a considered as a academic pursuit, which has now transitioned into a global industrial mandate. Often defined as the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances, its future scope is far more broad and diverse and shifting toward regenerative design, where chemistry actively restores ecosystems and fuels a circular economy.

1. Integration of Artificial Intelligence and Machine Learning [18]

The most immediate frontier for green chemistry lies in the digital realm. Traditional chemical discovery is often a

process of trial and error, leading to significant waste. The integration of Artificial Intelligence (AI) and Machine Learning (ML) allows scientists to predict the toxicity, reactivity, and environmental persistence of a molecule before it is ever synthesized in a lab. In the coming decade, "In silico" design will minimize physical experimentation, drastically reducing solvent waste and energy consumption.

- 2. The Rise of Bio-Based Feedstocks** ^[19]: The future of the chemical industry depends on decoupling itself from fossil fuels. We are moving toward a "bio-refinery" model where agricultural waste, algae, and CO₂ itself serve as the primary carbon sources.
- 3. Lignocellulosic Biomass:** Utilizing non-food plant materials to create plastics and fuels ensures that chemical production does not compete with global food security ^[19].
- 4. Carbon Capture and Utilization (CCU):** Future chemical plants will likely treat CO₂ emissions as a raw material, converting greenhouse gases into high-value polymers and synthetic fuels ^[20].
- 5. Solvent Innovation and "Solvent-Free" Chemistry** ^[21, 22]

Volatile Organic Compounds (VOCs) are a primary source of industrial pollution. The future scope of green chemistry emphasizes the development of Switchable Solvents, which can change their properties (like polarity) with the application of a small trigger (e.g., CO₂ or heat). Furthermore, Mechanochemistry—using mechanical force rather than heat or solvents to drive reactions—is poised to revolutionize manufacturing by making "dry" chemical synthesis a standard industrial practice.

6. Electrification and Photocatalysis

To reach net-zero goals, the energy used to drive chemical reactions must change.

The future will see a shift from thermal heating (often powered by gas) to Electrochemical and Photochemical processes. By using renewable electricity to drive electrons directly into a reaction, or using sunlight to activate catalysts, the carbon footprint of chemical manufacturing can be virtually eliminated.

7. Circular Economy and Molecular Recycling

Green chemistry will provide the technical backbone for a truly circular economy. Current recycling methods often degrade the quality of materials (downcycling). Future "molecular recycling" techniques will allow polymers to be broken down into their original monomers with 100% efficiency, enabling an infinite loop of use. This transition ensures that materials like plastics are viewed as "borrowed" carbon rather than "disposable" waste.

Conclusion

Green chemistry plays a crucial role in advancing sustainable development by reshaping how chemicals and materials are designed, produced, and used. At its core, green chemistry focuses on minimizing environmental impact while maximizing efficiency, safety, and economic viability. This approach aligns closely with the broader goals of sustainable development, which seek to balance

environmental protection, economic growth, and social well-being.

One of the most significant contributions of green chemistry is the reduction of hazardous substances in industrial processes. Traditional chemical practices often involve toxic reagents and generate harmful by-products, leading to pollution and health risks. Green chemistry promotes the use of safer alternatives, reducing the release of dangerous chemicals into air, water, and soil. This not only protects ecosystems but also improves human health, particularly for workers and communities living near industrial areas.

Another important aspect is resource efficiency. Green chemistry encourages the use of renewable raw materials instead of depleting finite resources. For example, bio-based feedstocks derived from plants can replace petroleum-based inputs, reducing dependence on fossil fuels and lowering carbon emissions. Additionally, green chemistry emphasizes energy-efficient processes, often conducted at ambient temperature and pressure, which helps conserve energy and reduce greenhouse gas emissions.

Waste prevention is also a central principle. Rather than managing waste after it is created, green chemistry focuses on designing processes that generate little to no waste in the first place. This approach, often referred to as "atom economy," ensures that most of the raw materials are incorporated into the final product. As a result, industries can reduce disposal costs and environmental damage simultaneously.

Green chemistry also drives innovation and economic growth. By encouraging the development of new materials, cleaner technologies, and efficient production methods, it opens up opportunities for sustainable industries. Companies that adopt green chemistry practices often gain a competitive advantage through reduced costs, improved safety, and compliance with environmental regulations. This demonstrates that environmental responsibility and economic success can go hand in hand.

Furthermore, green chemistry supports global efforts to combat climate change. By reducing emissions, promoting renewable energy sources, and improving energy efficiency, it contributes to lowering the overall carbon footprint of industrial activities. This is essential for achieving long-term sustainability goals and ensuring a stable climate for future generations.

Green Chemistry is a powerful tool for achieving sustainable development. It addresses critical environmental challenges by reducing pollution, conserving resources, and promoting safer and more efficient chemical practices. At the same time, it fosters innovation and economic growth, proving that sustainability is not a limitation but an opportunity. As industries, governments, and individuals increasingly adopt green chemistry principles, the path toward a cleaner, healthier, and more sustainable world becomes clearer and more attainable.

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