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Review Article

Introduction to Green Chemistry and Catalysis

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ABSTRACT

Green chemistry is an innovative approach to chemical science that emphasizes designing products and processes that minimize or eliminate the use and generation of hazardous substances. It promotes sustainability through the development of safe, efficient, and environmentally friendly chemical reactions. Catalysis plays a central role in green chemistry, offering pathways to achieve higher selectivity, energy efficiency, and waste reduction. This paper explores the fundamental principles and concepts of green chemistry and catalysis, emphasizing their applications in the pharmaceutical and chemical industries. This work provides an overview on applicability of 12 principles of green chemistry. Green chemistry is a term that indicates the creation of chemical products and procedures that reduces the use and production of harmful materials. The goals of green chemistry for protecting the environment can be achieved via several main directions. Some of them are bio-catalysis, use of alternative repeatable raw materials (biomass), alternative reaction solution (such as ionic liquids, supercritical fluids, water), alternative reaction circumstances (microwave activation) as well as to new photocatalytic reactions. Moreover, keep natural resources on earth without using harmful materials is the main objective of green chemistry.

INTRODUCTION

The global chemical industry is undergoing a paradigm shift toward sustainability due to concerns about environmental pollution, resource depletion, and human health risks. Green chemistry, introduced by Paul Anastas and John Warner in the 1990s, provides a scientific framework to design chemical processes that reduce or eliminate toxic substances. Catalysis,

being a cornerstone of modern chemistry, complements this approach by enhancing reaction rates, improving selectivity, and reducing energy demands. The development of green chemistry is traced from the introduction of the concepts of atom economy (atom utilisation) and E factors in the early 1990s. The important role of catalysis in reducing or eliminating waste is emphasised and illustrated with examples from heterogeneous catalytic oxidations with hydrogen peroxide,

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homogeneous catalytic oxidations and carbonylations and organocatalytic oxidations with stable N-oxy radicals. Catalytic reactions in non-conventional media, e.g. aqueous biphasic, supercritical carbon dioxide and ionic liquids, are presented. Biotransformations involving non-natural reactions of enzymes, e.g. ester ammoniolysis, and the rational design of semi-synthetic enzymes, such as vanadatephytase, are discussed. The optimisation of enzyme properties using in vitro evolution and improvement of their operational stability by immobilisation as cross-linked enzyme aggregates (CLEA®) are presented. The ultimate in green chemistry is the integration of catalytic steps into a one-pot, catalytic cascade process. An example of a chemoenzymatic synthesis of an enantiomerically pure amino acid in water and a trienzymatic cascade process using a triple-decker oxynitrilase/nitrilase/amidase CLEA are discussed. Finally, catalytic conversions of renewable raw materials are examined and the biocatalytic aerobic oxidation of starch to carboxy starch is presented as an example of green chemistry in optima forma i.e. a biocompatible product from a renewable raw material using a biocatalytic air oxidation.

PRINCIPLES OF GREEN CHEMISTRY:

1. Prevention of waste rather than treatment.
2. Atom economy – maximizing incorporation of reactants into products.
3. Less hazardous chemical synthesis.
4. Designing safer chemicals.
5. Safer solvents and auxiliaries.
6. Energy efficiency – prefer ambient temperature and pressure.

7. Use of renewable feedstocks.
8. Reduction of derivatives.
9. Catalysis – use of catalytic reagents over stoichiometric reagents.
10. Design for degradation – products should break down into innocuous substances.
11. Real-time analysis for pollution prevention
12. Inherently safer chemistry for accident prevention

The twelve principles:

The twelve principles of green chemistry were introduced by Paul Anastas and John Warner in 1998. They are a guiding framework for the design of new chemical products and processes, applying to all aspects of the process life-cycle from the raw materials used to the efficiency and safety of the transformation, the toxicity and biodegradability of products and reagents used. They were briefed recently into the more suitable and memorable acronym, productively.

The principles of green chemistry including:

1. Prevention of waste rather than treatment:

This is the most fundamental principle. It states that it is better to prevent the formation of waste than to deal with its disposal after the reaction.

Traditional chemical processes often produce large quantities of waste that must be treated or discarded, which is expensive and harmful to the environment. Green chemistry encourages chemists to design synthetic routes that produce little or no waste. This includes optimizing reaction conditions, using precise stoichiometric amounts, and designing processes that inherently minimize by-products.



Example:

Using catalytic reactions instead of stoichiometric reagents reduces waste production. Bulk pharmaceuticals often aim for “zero-waste synthesis.”

2. Atom economy:

This principle emphasizes designing reactions where the maximum portion of the reactants ends up in the final product.

Atom economy measures the efficiency of a chemical reaction. Many traditional reactions (e.g., substitution, elimination) create significant by-products. High atom economy reactions reduce raw material consumption and minimize waste.

. Example:

- Addition reactions have high atom economy.
- The Diels–Alder reaction is a classic example where almost all atoms from the reactants appear in the product.

3. Less hazardous chemical synthesis:

Chemical processes should be designed to use and generate substances with minimal toxicity.

This principle ensures that reaction pathways minimize toxic materials. Hazardous reagents, explosive intermediates, carcinogenic solvents, and corrosive chemicals should be replaced with safer alternatives whenever possible. This improves worker safety, reduces accidental risks, and minimizes environmental contamination.

Example:

Using hydrogen peroxide (H₂O₂) instead of toxic chromates for oxidation reactions.

4. Designing safer chemicals:

Chemical products should be designed to function effectively while reducing toxicity and harmful side effects.

This principle focuses on molecular design. Chemists should study structure–activity relationships (SAR) to modify molecules in a way that maintains performance but reduces environmental persistence or toxicity. This is important for pharmaceuticals, pesticides, and consumer chemicals.

Example:

Designing biodegradable plastics that decompose naturally without producing microplastic pollution.

5. Safer solvents and auxiliaries:

Solvents, separation agents, and other auxiliary substances should be minimized or replaced with safer options.

Solvents often contribute the most environmental impact in chemical industries.

Many traditional solvents (benzene, toluene, chloroform) are toxic, volatile, and flammable. Green chemistry encourages replacing them with safer alternatives like water, supercritical CO₂, ionic liquids, or bio-derived solvents.

Example:

Using water as a reaction solvent in Suzuki coupling or using supercritical CO₂ in extraction processes (e.g., caffeine extraction from coffee).

6. Energy efficiency – prefer ambient temperature and pressure:

Processes should be conducted at ambient temperature and pressure whenever possible.

Heating, cooling, and pressurizing reactions consume large amounts of energy and increase carbon footprint. Energy-efficient reactions reduce operational costs and environmental impact.

Techniques used:

- Microwave-assisted organic synthesis
- Ultrasound-assisted reactions
- Photochemical reactions using visible light
- Room-temperature catalysis

Example:

Using enzymes (biocatalysts) allows reactions to occur under mild conditions.

7. Use of renewable feedstocks:

Raw materials should come from renewable resources instead of depleting fossil fuels.

Renewable feedstocks include biomass, plant-based chemicals, agricultural waste, and other sources that regenerate naturally. The goal is to reduce dependence on petroleum-based chemicals and promote circular economy.

Example:

- Producing bio-ethanol from sugarcane
- Using vegetable oils to make biodiesel
- Polylactic acid (PLA) from corn starch for biodegradable plastics

8. Reduction of derivatives:

Minimize or avoid protection, de-protection, and temporary modification steps. Each derivatization step requires additional reagents and produces waste. Also it consumes time and increases energy needs. Green chemistry favors direct functionalization or one-pot synthesis to avoid these inefficient pathways.

Example:

Avoiding the protection of an amino group when another functional group can be selectively reacted.

9. Catalysis – use of catalytic reagents over stoichiometric reagents:

Use catalytic reagents instead of large quantities of stoichiometric chemicals.

Catalysts (enzymes, metal catalysts, organocatalysts) enhance reaction rates and selectivity. They can be reused, are needed in smaller quantities, and often enable milder reaction conditions. Catalysts also improve atom economy and reduce waste.

Example:

- Palladium catalysts in cross-coupling reactions
- Enzymes for stereoselective synthesis
- Acid catalysts instead of large amounts of acidic reagents

10. Design for degradation – products should break down into innocuous substances:

Chemical products should break down into harmless substances after use.

Non-degradable chemicals accumulate in the environment, causing long-term pollution (e.g., plastics, pesticides). Green chemistry focuses on



designing products that degrade naturally through sunlight, microbes, or oxidation into non-toxic components.

Example:

Biodegradable polymers used in packaging and medical implants.

11. Real-time analysis for pollution prevention:

Develop methods that allow continuous monitoring during reactions.

Real-time analytical techniques help detect hazardous by-products as they are formed, allowing immediate corrective actions. This increases safety, reduces waste, and optimizes reaction conditions.

Methods used:

- In-line spectroscopy (IR, RAMAN)
- Gas sensors
- Chromatography monitoring

Example:

Monitoring exothermic reactions in pharmaceutical manufacturing to avoid runaway reactions.

12. Inherently safer chemistry for accident prevention:

Design chemicals and processes to minimize explosion, fire, and toxicity risks. This principle deals with process safety engineering. Chemical industries should avoid using volatile, explosive, or reactive reagents. Equipment, reaction conditions, and storage should be optimized to reduce hazards.

Example:

- Avoiding cyanide-based plating chemicals
- Using aqueous hydrogen peroxide instead of anhydrous peroxides
- Avoiding highly pressurized systems when possible

CONCEPT OF CATALYSIS:

Catalysis is the process of increasing the rate of a chemical reaction by using a catalyst, a substance that is not consumed during the reaction. Catalysts work by lowering the activation energy and providing an alternative reaction pathway. They can be classified as:

- a) Homogeneous catalysts: present in the same phase as reactants.
- b) Heterogeneous catalysts: exist in a different phase (e.g., solid catalyst in gas-phase reaction).
- c) Biocatalysts: enzymes and microorganisms used in biochemical reactions.

Catalysis is the increase in rate of a chemical reaction due to an added substance known as a catalyst. Catalysts are not consumed by the reaction and remain unchanged after the reaction. If the reaction is rapid and the catalyst is recycled quickly, a very small amount of catalyst often suffices; mixing, surface area, and temperature are important factors in reaction rate. Catalysts generally react with one or more reactants to form intermediates that subsequently give the final reaction product, in the process of regenerating the catalyst.

CATALYSIS:

1. The Role of Catalysis :



Catalysis directly supports several principles of green chemistry. It increases selectivity, reduces waste, and enhances efficiency. For instance, catalytic hydrogenation and oxidation reactions minimize by-products and energy usage. Biocatalysis, using enzymes, is especially valuable in pharmaceutical synthesis due to its mild conditions and specificity. Recent advancements include nanocatalysis, photocatalysis, and electrocatalysis, which integrate renewable energy and sustainable materials.

Catalysis plays a crucial role in green chemistry by enabling more efficient and sustainable chemical processes. It promotes green chemistry by improving reaction rates and selectivity, which leads to lower energy consumption, reduced waste, and the use of less toxic materials. Catalysts are reusable and can be filtered from the product, unlike stoichiometric reagents, making them environmentally friendly alternatives.

How catalysis supports green chemistry:

Increased efficiency and selectivity: Catalysts accelerate reactions and can guide them to produce a specific product with fewer by-products. This is more efficient than traditional methods that often produce large amounts of waste.

Reduced energy consumption: By providing an alternative pathway with lower activation catalysts allow reactions to occur at lower temperatures and pressures, reducing the need for energy input.

2. Solid Acids and Bases as Catalysts:

Solid acid and solid base catalysts offer advantages such as recyclability, reduced corrosion, and easy product separation.

Solid acids are solid materials that possess acidic properties, usually in the form of Brønsted acid sites (proton donors) or Lewis acid sites (electron-

pair acceptors) present on their surface. Because the acidic sites are immobilized on a solid surface, these catalysts behave like traditional acids but do not dissolve into the reaction mixture

Solid base catalysts are solid materials containing basic sites capable of donating electron pairs or abstracting protons. These basic sites may arise from oxide ions on the surface, hydroxyl groups, or basic metal–oxygen bonds. Typical solid base catalysts include metal oxides such as magnesium oxide (MgO), calcium oxide (CaO), barium oxide (BaO), zinc oxide (ZnO), hydrotalcites (layered double hydroxides), basic ion-exchange resins, and carbonates supported on solid surfaces.

Common Solid Acids:

- Zeolites
- Sulfated zirconia
- Heteropoly acids
- Silica-alumina

Common Solid Bases:

- MgO, CaO
- Hydrotalcites
- Alkali-modified alumina

Applications:

- Esterification and transesterification
- Alkylation and isomerization
- Petrochemical cracking
- Fine chemical synthesis

3. Catalytic Reductions:

Catalytic reductions are essential transformations utilizing metal catalysts. Catalytic reduction is an important type of catalytic process in which a catalyst accelerates the transfer of electrons or hydrogen atoms to a chemical compound, thereby reducing it. This process is widely used in organic



synthesis, pollution control, wastewater treatment, petroleum refining, and the manufacture of fine chemicals. In green chemistry, catalytic reduction is preferred because it avoids the use of harsh reducing agents, minimizes waste generation, and carries out reactions under milder and safer conditions.

Key Metal Catalysts:

- Pd/C, Pt/C
- Raney nickel
- Ruthenium and rhodium complexes
- Nitro to amine reduction
- Carbonyl reductions

Applications:

- API synthesis (e.g., antihypertensives, antihistamines)
- Aroma chemical production

4. Enzyme Technology in Biocatalytic Reduction:

Biocatalysis employs enzymes as environmentally benign catalysts.

Enzyme technology is a major branch of biocatalysis where enzymes are used as natural catalysts to carry out chemical transformations with high specificity, efficiency, and selectivity. In recent years, biocatalysis has emerged as an important tool in green chemistry because enzymes operate under mild conditions, avoid toxic reagents, and minimize waste. One of the most significant applications of enzyme technology is in biocatalytic reduction, in which enzymes catalyze the reduction of organic molecules using biological cofactors. This method provides an environmentally friendly alternative to traditional chemical reduction.

Key Enzyme Classes:

- Reductases
- Oxidoreductases
- Hydrolases

Advantages:

- High stereoselectivity
- Mild reaction conditions
- Biodegradable systems

Applications:

- Chiral alcohols and amines
- Asymmetric reduction
- Green processing in pharma industries

5. Catalytic Oxidations:

Oxidation reactions are central to producing fine chemicals and intermediates. Catalytic oxidation is an important class of catalytic reactions in which a catalyst accelerates the oxidation of chemical compounds using an oxidizing agent, often molecular oxygen or hydrogen peroxide. Oxidation processes are fundamental in the chemical industry because they convert raw materials into valuable products such as alcohols, aldehydes, ketones, acids, and epoxides. In traditional chemistry, oxidation frequently relies on strong oxidizing agents such as permanganates, dichromates, and chromates, which are hazardous, toxic, and generate large amounts of inorganic waste. Green chemistry promotes catalytic oxidation because it replaces these harmful oxidants with cleaner alternatives and utilizes catalysts to improve efficiency while minimizing environmental impact.

Catalysts Used:

- Metal oxides (MnO₂, V₂O₅)
- Noble metals (Pt, Pd)
- Biomimetic catalysts

Applications:

- Alcohol to aldehyde/ketone oxidation
- Epoxidation of alkenes
- Environmental pollutant degradation

6. Catalytic Carbon–Carbon Bond Formation:

Catalytic carbon–carbon (C–C) bond formation is one of the most fundamental transformations in organic chemistry because nearly all complex organic molecules—such as pharmaceuticals, polymers, agrochemicals, natural products, and fine chemicals—are built upon carbon–carbon frameworks. Traditionally, many C–C bond-forming reactions required strong bases, harsh reaction conditions, toxic reagents, or stoichiometric amounts of metal salts. These methods often produced large quantities of inorganic waste, low selectivity, and posed serious environmental hazards.

Major Catalytic Methods:

- Pd-catalyzed coupling (Suzuki, Heck, Sonogashira)
- Organometallic catalysis
- Enzymatic C–C coupling

Applications:

- Drug molecule synthesis
- Agrochemicals
- Material science intermediates

7. Hydrolysis:

Hydrolysis is a fundamental chemical reaction in which a molecule is broken down by the addition of water. In hydrolysis reactions, the water molecule splits into hydrogen (H^+) and hydroxide (OH^-) ions, which attack specific bonds within the substrate, leading to cleavage of chemical bonds such as ester, amide, glycosidic, or peptide bonds.

Although hydrolysis can occur spontaneously, its rate is often slow and inefficient. Catalysis significantly accelerates hydrolysis and allows it to occur under milder, environmentally friendly conditions.

Catalysts Used:

- Acid and base catalysts
- Enzymatic hydrolases (lipases, proteases)

Application:

- Biodiesel production
- Pharmaceutical intermediate hydrolysis
- Biomass degradation

8. Catalysis in Novel Reaction Media:

Catalysis in novel reaction media refers to the use of alternative, environmentally benign solvents or fluid systems that enhance catalytic efficiency and reduce pollution. Traditional organic solvents (benzene, toluene, chloroform, carbon tetrachloride) are volatile, toxic, and often flammable. To overcome these limitations, green chemistry promotes the development of new reaction media that are safe, sustainable, recyclable, and compatible with catalytic processes.

Novel reaction media not only improve reaction rates, increase selectivity, and facilitate catalyst recovery, but also minimize waste and environmental hazards. They allow catalytic reactions to proceed under mild conditions (low temperature and pressure), significantly reducing energy consumption. These media also support both homogeneous and heterogeneous catalysis, making them highly valuable in green chemical engineering.

Benefits:



- Improved solubility
- Enhanced reaction rates
- Greener processing options

Examples:

- Ionic liquid-supported metal catalysts
- Enzyme stability in DES

9. Chemicals from Renewable Raw Materials:

The production of chemicals from renewable raw materials is a major focus of green chemistry and sustainable industrial development. Renewable raw materials are naturally available, replenishable biological resources such as biomass, plant oils, starch, cellulose, sugars, agricultural residues, and natural polymers. These resources replace petroleum-based feedstocks, helping reduce environmental pollution, greenhouse gas emissions, and dependence on fossil fuels.

Catalysis plays a central role in transforming renewable raw materials into fuels, polymers, solvents, fine chemicals, and pharmaceuticals. Catalysts—such as enzymes, metal catalysts, solid acids, solid bases, and biocatalysts—enable efficient conversion of raw biomass into valuable chemicals under mild, energy-saving conditions.

Key Conversions:

- Biomass to bioethanol
- Furfural, levulinic acid derivatives
- Biodiesel via transesterification

Importance:

- Reduces dependence on fossil fuels
- Enables sustainable chemical production

10. Process Integration and Cascade Catalysis:

Modern chemical industries aim to reduce waste, energy use, and process steps. Traditional

chemical synthesis involves multiple separate stages—each with its own reactors, purifications, solvents, and catalysts. This results in high cost, large waste generation, and low atom economy.

To overcome these limitations, green chemistry introduces two interconnected concepts:

1. Process Integration
2. Cascade Catalysis (Tandem / Domino Catalysis)

Both methods make chemical processes more efficient, sustainable, and environmentally friendly by combining multiple operations into a single streamlined process.

Advantages:

- Eliminates purification steps
- Saves energy and time
- Enhances atom economy

Types:

- Chemo-enzymatic cascades
- Multi-metal catalytic sequences

Applications:

- API synthesis with multiple stereocenters
- Fine chemical multi-step transformations

1. Types of Catalysis — Homogeneous, Heterogeneous & Biocatalysis

Homogeneous Catalysis: Catalyst and reactants in the same phase (usually liquid). Offers high selectivity and mechanistic understanding. Examples include acid catalysis by H₂SO₄, organometallic complexes in polymerization.

Heterogeneous Catalysis: Catalyst is in a different phase, typically solid with gaseous or liquid

reactants. Advantages include ease of separation, catalyst recyclability, and industrial suitability. Examples: metal catalysts (Pd, Pt, Ni), solid acids like zeolites.

Biocatalysis: Enzymes used to catalyze reactions under mild conditions with exceptional enantioselectivity. Applications in pharmaceuticals, food, and environmental industries.

2. Industrial Importance of Solid Acids and Bases (More Examples Zeolites):

Widely used in fluid catalytic cracking (FCC), isomerization, and hydrocarbon rearrangement.

Sulfated Zirconia: Superacid catalyst used in alkane isomerization. **Hydrotalcites:** Used in transesterification reactions for biodiesel production.

Applications in Pharma: Protection-deprotection steps, dehydration, rearrangement.

3. Catalytic Reductions - Mechanisms & Selectivity

Heterogeneous Hydrogenation: Occurs on metal surfaces; selectivity controlled by metal type and support material.

Transfer Hydrogenation: Uses hydrogen donors like isopropanol with catalysts such as Ru- or Ir-complexes.

Asymmetric Reduction: Chiral catalysts (e.g., BINAP-Ru complexes) used for synthesizing enantiopure pharmaceuticals.

4. Biocatalytic Reductions — Cofactor Regeneration

NADH/NADPH-dependent reductases require cofactor recycling systems (glucose dehydrogenase, formate dehydrogenase).

Enzyme immobilization techniques enhance stability and recyclability.

Widely used for manufacturing chiral drugs like statins, antidepressants, and β -blockers.

5. Catalytic Oxidations — Green Oxidants & Mechanisms Green Oxidants: O₂, H₂O₂, t-BuOOH.

Metal-Catalyzed Oxidations: Ru, Fe, Cu complexes mimic natural enzymatic oxidation.

Selective Oxidations in Industry: Production of aldehydes, ketones, epoxides. **Environmental Role:** VOC removal, water purification.

6. Catalytic C–C Bond Formation — Modern Developments

Cross-Coupling Reactions: Pd-catalyzed Suzuki, Heck, Negishi reactions dominate API intermediate synthesis.

Organocatalysis: Uses small organic molecules like proline; greener alternative.

Enzymatic C–C Bond Formation: Aldolases and transketolases enable stereoselective transformations.

7. Hydrolysis — Mechanistic Insights

Acidic Hydrolysis: Protonation of electrophilic centers accelerates cleavage. **Basic Hydrolysis:** Nucleophilic attack by hydroxide ion.

Enzymatic Hydrolysis: Lipases, cellulases, proteases widely used for food, pharma, and biomass conversion.



8. Catalysis in Novel Reaction Media — More Depth

Ionic Liquids (ILs): Non-volatile, thermally stable solvents; enhance catalyst life. Deep Eutectic Solvents (DES): Biodegradable and low-cost alternatives to ILs.

Supercritical Fluids (SCFs): Supercritical CO₂ offers tunable solvent properties; widely used in green extraction and hydrogenation.

9. Chemicals from Renewable Materials — Key Pathways

Sugar Platform: Glucose → HMF → FDCA → bioplastics.

Lignocellulosic Biomass: Conversion to aromatics, bio-oils.

Fatty Acids: Catalytic transesterification yields biodiesel.

Biorefineries: Integrate catalytic processes to replace petroleum routes.

10. Process Integration & Cascade Catalysis — Case Studies

Chemo-Enzymatic Cascades: Metal catalyst forms intermediate → enzyme converts to final product.

One-Pot Multistep Reactions: Reduce cost and waste.

Pharma Examples: Synthesis of chiral amines, lactones, and steroid intermediates.

APPLICATIONS:

Green chemistry and catalysis have transformed many industrial processes Examples include:

- The synthesis of ibuprofen using a catalytic process with 99% atom economy.
- Biocatalytic production of antibiotics, vitamins, and steroids.
- Solvent-free or microwave-assisted organic synthesis reducing waste and energy usage.

These examples demonstrate how catalysis ensures eco-friendly and cost-effective manufacturing. Green chemistry's applications are diverse, aiming to reduce or eliminate the use and generation of hazardous substances in chemical products and processes. Key applications include designing safer chemicals, developing energy-efficient processes, and using renewable feedstocks across industries like pharmaceuticals, agriculture, textiles, and polymer production. For example, it is used to develop biodegradable plastics, create eco-friendly dyes for textiles, produce biodiesel, and find less toxic solvents for manufacturing.



Specific industry applications:

Pharmaceuticals: Designing more efficient and less wasteful synthetic pathways, using safer solvents like water instead of volatile organic compounds (VOCs), and developing biodegradable drug formulations.

Agriculture: Developing agrochemicals that use safer solvents and are less harmful to the environment and human health.

Textiles: Creating eco-friendly dyes, reducing water usage, and developing sustainable textile finishing processes.

Polymers: Designing biodegradable plastics and replacing hazardous substances with safer alternatives, such as using supercritical carbon dioxide as a blowing agent in polystyrene foam production.

Cleaning: Implementing "green dry cleaning" that uses liquefied carbon dioxide instead of the toxic solvent perchloroethylene.

Energy: Advancing clean energy technologies like solar cells, batteries, and fuel cells by using more sustainable materials and processes.

Pulp and Paper: Using hydrogen peroxide with a suitable catalyst for a safer bleaching process.

General applications:

Waste minimization: Designing processes to be more efficient, such as using catalysis to increase reaction selectivity and atom economy to ensure more of the starting materials end up in the final product.

Safer solvents and auxiliaries: Replacing toxic solvents with less harmful alternatives, including

green solvents derived from renewable resources or using supercritical fluids like or water.

Renewable feedstocks: Utilizing renewable raw materials, like biomass, instead of fossil fuels as starting materials for chemical synthesis.

Pollution prevention: Preventing pollution at its source by designing inherently safer processes and using real-time analysis to control and minimize hazardous byproducts.

ADVANTAGES OF GREEN CHEMISTRY:

Green chemistry offers advantages in environmental protection, human health, and economic efficiency. Key benefits include the reduction of hazardous waste and pollution, the creation of safer chemicals and products, and improved efficiency in manufacturing processes, which can lead to lower costs.

Environmental benefits:

Reduces pollution at the source: It minimizes or eliminates the use and production of hazardous substances from the outset.

Protects ecosystems: By designing chemicals that degrade more easily, green chemistry reduces long-term contamination and minimizes harm to wildlife and food chains.

Human health benefits:

Increases safety for workers: It reduces the use of toxic materials, leading to a safer workplace with less need for personal protective equipment and a lower risk of accidents.

Improves public health: It leads to cleaner air and water by reducing the release of hazardous chemicals into the environment.

Economic and industrial benefits:



Lowers costs: Reduced waste disposal costs and increased process efficiency can lead to significant savings.

Increases efficiency: It often results in higher yields, faster manufacturing times, and uses less energy and water.

LIMITATIONS OF GREEN CHEMISTRY:

Catalyst deactivation:

Poisoning and fouling: Impurities can irreversibly "poison" a catalyst or cause fouling from deposited byproducts, leading to a loss of activity.

Sintering: High temperatures can cause active catalyst particles to lose surface area as they coalesce, a process called sintering, which reduces efficiency.

Selectivity and efficiency:

Formation of byproducts: Achieving 100% selectivity is often not possible; most catalysts can produce small amounts of unwanted side products, complicating purification.

Imbalance of binding: A catalyst that binds reactants too weakly won't speed up the reaction, while one that binds too strongly can become "clogged" or poisoned.

Cost and separation:

High costs: Many highly effective catalysts use expensive and rare materials like noble metals or require complex, costly synthesis procedures.

Separation challenges: Removing homogeneous catalysts from the reaction mixture can be difficult, often requiring energy-intensive separation methods like distillation.

FUTURE PROSPECTS:

Future research focuses on integrating green catalysis with renewable energy sources, such as solar and biomass-derived feedstocks. The use of artificial intelligence and nanotechnology in catalyst design promises to further enhance process sustainability.

Future trends in green chemistry include AI and machine learning for designing sustainable processes, the use of renewable feedstocks and biomass to replace fossil fuels, and advancements in solventless reactions like mechanochemistry. Other key areas are carbon capture and utilization, green nanotechnology, biocatalysis, and the development of biodegradable materials and PFAS-free alternatives.



Key future trends:

Circular economy Artificial Intelligence and Machine Learning: AI is being used to accelerate the discovery of new green chemicals and processes, simulate reactions, and optimize them for sustainability.

Solventless Reactions: Techniques like mechanochemistry allow for chemical synthesis without solvents, which helps reduce waste and product isolation issues.

Green Nanotechnology: Nanomaterials are enabling more efficient catalysts and pollution cleanup systems.

Biocatalysis and Bio-based Materials: The use of biological catalysts and the development of biodegradable polymers are increasing to replace traditional chemical methods and plastics.

Sustainable Drug Manufacturing: The pharmaceutical industry is adopting green chemistry principles to create more efficient and less toxic synthesis methods, including the use of biocatalysis and continuous flow chemistry.

Circular Chemistry: This trend focuses on designing chemical processes to be circular, where waste is minimized and can be valorized into valuable products.

CONCLUSION

Green chemistry and catalysis represent the future of sustainable chemical and pharmaceutical production. By following green principles and using advanced catalytic methods, industries can reduce environmental pollution while maintaining economic and operational efficiency.

The goal of green chemistry as mentioned early is based on twelve principles which aim to reduce

harmful materials from the production, and application of chemical products. It is well known that when designing a green chemistry process, it is impossible to find the requirements of all twelve principles of the process at the same time. Nevertheless, it attempts to apply as many principles as possible during certain steps of synthesis. The goal of green chemistry in both environmental protection and economic gain can be achieved via many directions. For instance, chemical products would be prepared so that at the end of their function was not persist in the environment and instead break down into unharmed degradation products. As well as, the goals of green chemistry are as follows: to meet the wants of society in ways without harmful or depleting natural resources on earth which are the main objective of green chemistry.

In this case, the focus is being shifted on manufacture products that can be fully reclaimed or re-used. Via changing patterns of production and consumption, steps are being taken to reduce pollution and waste, as one of the significant goals of green chemistry. It is critical to develop alternative technologies to prevent any further damage to health and the environment. It can be summarised that environmental conservation can be possible via the introduction of a green chemistry process. However, the green chemistry alone cannot solve the pressing environmental concerns and influences on our modern era but applying the twelve-principles of green chemistry into practice will finally help to pave the system to a world where the grass is greener.

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