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Review Article

GREEN CHEMISTRY: A REVIEW

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ABSTRACT
Chemical goods and processes that are created from the ground up by principles that make them favorable to life will serve as the material foundation upon which a sustainable society will be built. To determine whether compounds and processes are depleting or renewable, harmful or benign, and persistent or rapidly degradable, it is necessary to take into consideration the important intrinsic features of molecules from the very beginning, which is the design stage. The ideas of green chemistry and green engineering will need to be incorporated into products, feedstocks, and manufacturing processes to meet the requirements of an enlarged definition of performance that considers sustainability considerations. To accomplish this change, it will be necessary to combine the most successful aspects of scientific and innovative traditions with the most recent developments in systems thinking and design. This transformation will begin at the molecular level and will ultimately have a positive impact on a global scale.

Keywords: *Food technology, Green Chemistry's Principles, Pharmaceuticals, Sustainable Chemistry*

INTRODUCTION
Green chemistry, also known as sustainable chemistry, is a field of chemistry that focuses on designing products and processes that minimize the use and generation of hazardous substances[1]. The overarching goal of green chemistry is to reduce the negative impact of chemical processes on human health and the environment[2]. This discipline emerged as a response to the growing awareness of the environmental and health risks associated with traditional chemical practices[3]. There are twelve principles of green chemistry, established by Paul Anastas and John Warner, which serve as guidelines for creating more sustainable chemical processes[4]. These principles include the prevention of waste, the use of safer

chemicals, and the incorporation of energy-efficient methods[5]. The aim is to promote the development of products and processes that are economically viable, environmentally friendly, and socially responsible[6].

One key aspect of green chemistry is the consideration of the entire life cycle of a chemical product. This involves evaluating not only the immediate impact of the production process but also the potential environmental and health effects during the use and disposal phases[7]. By adopting a holistic approach, researchers and practitioners in green chemistry strive to create solutions that are not only efficient but also have minimal long-term consequences[8].

Several industries have embraced green chemistry principles to varying extents. For example, pharmaceutical companies are exploring sustainable synthesis routes to reduce the environmental footprint of drug manufacturing[9]. Additionally, the development of green solvents, renewable feedstocks, and biodegradable materials are becoming integral parts of research and development across different sectors[10].

In essence, green chemistry represents a shift in mindset within the chemical industry, emphasizing the importance of sustainability, safety, and environmental stewardship. As the field continues to evolve, it plays a crucial role in addressing global challenges such as pollution, resource depletion, and climate change[11]. The adoption of green chemistry practices is not only beneficial for the planet but also contributes to the creation of a more resilient and responsible chemical industry[12].

EVOLUTION OF GREEN CHEMISTRY

Industrialization advanced global economic growth. Industrial operations have increased quality of life, but global government policies have not addressed their environmental impacts. Over industrialization and food production caused pollution and resource depletion due to population increase. Natural resources were employed without considering environmental impact. Environmental issues were first mentioned at the 1949 UNSCCUR in the US and highlighted at the 1968 Intergovernmental Conference of Experts on the Scientific Bases for Rational Use and Conservation of Biosphere Resources (Biosphere Conference). In the 1960s, "Silent Spring" started an environmental movement. The historical book raised ecological awareness and urged government action to address natural resource overexploitation[13-15]. Robert Downs dubbed it "the book that changed America," while John Kenneth Galbraith deemed it a major Western novel[16].

Representatives from the UN and non-governmental organizations debated environmental law during the 1972 Stockholm Conference in Sweden[17]. After this conference, the world learned about ecosystem depletion's environmental risks[18]. Multiple global environmental conferences occurred in the 1980s. After analyzing 10 years of planned activities at the Stockholm Conference, the UN created the World Commission on Environment and Development in 1983 to report on global development and the environment. The group was formed amid global environmental pressure and knowledge of unsustainable development[18]. The 1987 Brundtland Report combined environmental and socioeconomic considerations to propose sustainable development, addressing current needs without harming future generations. The study stresses ozone depletion and global warming threats, claiming experts' inability to give remedies owing to climate change speed[19]. In 1985, the OECD Environment Ministers decided on Economic Development and Environment, Pollution Prevention and Control, and Environmental

Information and National Reviews. These judgments lasted until 1990. These interventions were essential for minimizing chemical product danger and contamination[20].

The 1991 US Environmental Protection Agency (EPA) "Alternative Synthetic Routes for Pollution Prevention" initiative stressed the significance of preventing harmful chemical compounds from being created[21]. The program was renamed Green Chemistry in 1992 after adding safer and greener solvents. Environmental protection was a 1990s global focus. Brazil hosted the 1992 UN Conference on Environment and Development. Heads of state created Agenda 21, which commits countries to sustainable development through environmental, economic, and decision-making factors. Despite worldwide environmental progress, corporations' environmental consciousness was weak. Almeida claims that media and civil society pressure forced corporations to follow government environmental regulations. In 68 countries, the 1984 Canadian initiative "Responsible Care" has transformed corporate behavior. This plan invested in infrastructure security, energy efficiency, employee safety records, and hazardous emission reductions to improve quality of life and safety. The 1994 European Chemical Industry Council (CEFIC) study found that the public disliked the chemical industry, notwithstanding environmental issues in industrial and commercial sectors. Population focused on the pharmaceutical and plastics sectors due to perceived benefits (Pandey, 2015). Most interviewees didn't think the chemical sector prioritized sustainability. Oil, gas, power, wood, and paper were preferred over transportation, safety, and waste. In 1995, the US government created the Presidential Green Chemistry Challenge (PGCC). Technological advances in the chemical sector reduced waste in various manufacturing areas. The works are honored annually in five categories: Academic, small company, alternative synthetic methods, reactive circumstances, and safer chemical designs are covered by Cann (1999).

The non-profit Green Chemistry Institute (GCI) was created in 1997 to promote chemical company sustainability and green chemistry applications (ACS Chemistry, 2017). The GCI joined the ACS in 2001 to address global chemistry and environmental issues. Green chemistry research has reached industries, businesses, education, conferences, and international networks (ACS Chemistry, 2017). Green chemistry advanced with Paul Anastas and John C. Warner's 1998 book Green Chemistry: Theory and Practise. The book promotes academic and corporate environmental responsibility through the 12 Principles of Green Chemistry (ACS Chemistry, 2017). Rio + 10, the World Summit on Sustainable Development, was held in Johannesburg, South Africa, with thousands of attendees 30 years after Stockholm. Building on ECO-92 debates, government and non-governmental organizations, large enterprises, sectoral associations, delegations, and media discussed Agenda 21 government and public implementation alternatives.

ACS Green Chemistry Institute (GCI) and international pharmaceutical companies held a panel discussion in 2005 to promote green chemistry and engineering in the pharmaceutical industry. Panelists believed "continuous processing" was essential to "the green"; Constable, 2007). IUPAC, ACS, and GCI held four Green Chemistry conferences from 1997 to 2011. According to Lenardão, the symposia covered green goods, processes, energy sources, waste sources, policies, and education in green chemistry.

Chemical and ecological engineering research has used sustainable methods, however industrial processes and policies are needed for environmental benefits[18].

PRINCIPLES OF GREEN CHEMISTRY

The Twelve Principles of Green Chemistry provide a comprehensive framework for designing chemical processes and products that are environmentally sustainable and socially responsible[20-22]. The first principle, prevention, emphasizes the importance of avoiding waste generation whenever possible. The second principle, atom economy, encourages the efficient use of raw materials to minimize by-products and resource consumption. Less hazardous chemical syntheses, the third principle, underscores the need to design methods that utilize substances with minimal toxicity to human health and the environment[23]. The fourth principle, designing safer chemicals, focuses on creating chemical products that are effective in their function while minimizing any potential harm. Safer solvents and auxiliaries, the fifth principle, advocate for the use of auxiliary substances that are benign and do not pose risks to human health or the ecosystem[24]. Designing for energy efficiency, the sixth principle emphasizes optimizing processes to reduce energy consumption, favoring conditions of ambient temperature and pressure. The use of renewable feedstocks, the seventh principle, promotes the adoption of raw materials that are sustainable and renewable. The eighth principle, reducing derivatives, urges the minimization of unnecessary derivatization steps, which can contribute to waste generation[25]. Catalysis, the ninth principle, recommends the use of catalytic reagents over stoichiometric reagents to enhance reaction rates, reduce energy consumption, and minimize by-products. Design for degradation, the tenth principle, calls for the development of chemical products that break down into innocuous degradation products at the end of their functional life, avoiding persistence in the environment. Real-time analysis for pollution prevention, the eleventh principle, encourages the development of analytical methods for in-process monitoring to prevent the formation of hazardous substances. The twelfth principle, inherently safer chemistry for accident prevention, suggests choosing substances and forms that minimize the potential for chemical accidents, such as releases, explosions, and fires[26].

Collectively, these principles provide a roadmap for researchers and industry professionals to integrate sustainability into their practices, fostering the development of safer, more environmentally friendly chemical processes and products[27].

DIVERSE APPLICATIONS OF GREEN CHEMISTRY

- **Pharmaceuticals:**
  Designing environmentally friendly synthesis routes for pharmaceutical compounds.
  Reducing the use of toxic solvents and reagents in drug manufacturing.
  Developing greener methods for waste disposal in pharmaceutical production[28].
- **Agrochemicals:**
  Creating environmentally benign pesticides and fertilizers.
  Designing crop protection chemicals with reduced ecological impact.
  Developing sustainable practices in agriculture to minimize chemical inputs[29].
- **Materials Science:**

Innovations in the production of polymers, plastics, and composites with reduced environmental impact.
Recycling and upcycling strategies for materials to minimize waste.

- **Energy Production:**
  Developing green technologies for renewable energy sources, such as solar cells and batteries.
  Designing catalysts for cleaner and more efficient energy conversion processes.
- **Water Treatment:**
  Developing environmentally friendly methods for water purification.
  Designing new materials for efficient removal of pollutants from water.
- **Textile Industry:**
  Implementing sustainable practices in dyeing and finishing processes.
  Developing eco-friendly alternatives to traditional textile treatments.
- **Food Industry:**
  Designing green processes for food preservation and packaging.
  Developing sustainable practices for agriculture and food processing[30].
- **Cleaning Products:**
  Designing environmentally friendly cleaning agents with reduced toxicity.
  Innovating in the production of detergents and other household products.
- **Waste Management:**
  Implementing green chemistry principles in the treatment and disposal of hazardous waste.
  Designing processes to minimize waste generation and promote recycling.
- **Education and Research:**
  Integrating green chemistry principles into academic curricula.
  Conducting research to discover and promote sustainable chemical processes.
- **Policy and Regulation:**
  Influencing and shaping regulations to encourage the adoption of green chemistry practices.
  Supporting initiatives that promote sustainable and responsible chemical manufacturing.

Pharmaceuticals

The application of green chemistry in the pharmaceutical industry not only aligns with sustainability goals but also contributes to the development of cost-effective and efficient processes for drug synthesis. As the industry continues to evolve, the integration of green chemistry principles is likely to play an increasingly significant role in shaping the future of pharmaceutical manufacturing[31].

Safer Solvents and Reaction Conditions:

Replacement of traditional, hazardous solvents with greener alternatives, such as water or bio-based solvents[32].

Optimization of reaction conditions to reduce energy consumption and minimize environmental impact.

Catalysis:

Implementation of catalytic processes to increase reaction efficiency and reduce the need for high temperatures and pressures.

Development of recyclable and sustainable catalysts to minimize waste.

Atom Economy:

Emphasis on maximizing the incorporation of reactant atoms into the final product to reduce waste generation.

Minimization of by-products and side reactions through efficient synthetic routes.

Green Synthesis of Active Pharmaceutical Ingredients (APIs):

Designing environmentally friendly synthetic routes for the production of pharmaceutical compounds.

Utilization of renewable feedstocks and bio-based starting materials.

Biocatalysis:

Integration of enzymes and other biocatalysts in pharmaceutical synthesis to enhance selectivity and reduce the need for harsh reaction conditions.

Enzymatic processes often result in fewer by-products and milder reaction conditions[33].

Microwave and Ultrasound-Assisted Synthesis:

Application of microwave and ultrasound energy for efficient and rapid synthesis of pharmaceutical compounds.

Reduction in reaction times and energy consumption.

Continuous Flow Chemistry:

Adoption of continuous flow processes to enhance reaction control and reduce the environmental impact.

Enables the synthesis of pharmaceuticals with improved efficiency and reduced waste.

Green Analytical Techniques:

Utilization of environmentally friendly analytical methods to monitor and control pharmaceutical processes.

Implementation of techniques such as green chromatography and spectroscopy.

Waste Reduction and Recycling:

Development of processes that minimize the generation of waste by-products.

Exploration of methods for recycling and reusing solvents and other materials[34].

Eco-friendly Packaging:

Consideration of green chemistry principles in the design and production of pharmaceutical packaging.

Exploration of sustainable and biodegradable packaging materials.

Life Cycle Assessment (LCA):

Integration of life cycle thinking to assess and minimize the environmental impact of pharmaceutical products from raw material extraction to disposal.

Regulatory Compliance:

Alignment of pharmaceutical processes with regulatory requirements and guidelines that encourage the adoption of green chemistry practices.

Collaboration with regulatory bodies to promote sustainable pharmaceutical manufacturing.

Agrochemicals

Applications of green chemistry principles in agrochemicals contribute to more sustainable and environmentally friendly agricultural practices, ensuring the health of ecosystems and promoting the well-being of both farmers and consumers[35].

Atom Economy: Designing agrochemical synthesis routes that maximize the utilization of starting materials, minimizing the generation of waste products. This reduces environmental impact and promotes resource efficiency.

Solvent Selection: Choosing environmentally friendly solvents or water-based formulations for agrochemicals. This minimizes the use of toxic solvents, reducing harm to ecosystems and promoting the safety of agricultural workers.

Catalysis: Implementing catalytic processes in the production of agrochemicals. Catalysis can enhance reaction rates, increase efficiency, and reduce the need for high temperatures, lowering energy consumption and minimizing environmental impact.

Renewable Feedstocks: Incorporating renewable raw materials, such as bio-based feedstocks, in the synthesis of agrochemicals. This reduces dependence on finite fossil resources and promotes sustainability.

Safer Chemicals: Designing agrochemicals with reduced toxicity to non-target organisms, including humans and beneficial insects. This minimizes the environmental impact and potential harm to ecosystems[36].

Precision Agriculture: Developing agrochemical formulations that enable precision application, ensuring that chemicals are used efficiently and sparingly. This reduces the overall environmental footprint of agricultural practices.

Biodegradable Formulations: Creating agrochemical formulations that are easily biodegradable, reducing their persistence in the environment and mitigating long-term ecological impacts.

Green Analytical Techniques: Using environmentally friendly analytical methods for monitoring and testing agrochemical residues in soil, water, and crops. This ensures accurate assessment while minimizing environmental harm.

Integrated Pest Management (IPM): Promoting the use of agrochemicals within the context of IPM. This approach combines biological, cultural, and chemical control methods for a holistic and sustainable pest management strategy[33-36].

Efficient Delivery Systems: Developing innovative delivery systems, such as controlled-release formulations, to enhance the targeted delivery of agrochemicals. This minimizes wastage and reduces the overall amount of chemicals needed.

Materials science

It focuses on designing products and processes that minimize environmental impact, reduce the use of hazardous substances, and promote sustainability. When applied to materials science, green chemistry principles offer innovative and eco-friendly solutions for the development and manufacturing of materials.

Biodegradable Polymers: Green chemistry promotes the use of biodegradable polymers as an alternative to traditional, non-biodegradable plastics. These polymers break down naturally, reducing the environmental burden of persistent plastic waste. Biodegradable materials can find applications in packaging, disposable products, and medical devices.

Renewable Resources: Green materials science emphasizes the use of renewable resources, such as plant-based feedstocks, in the production of materials. By reducing reliance on fossil fuels, this approach contributes to sustainability and helps mitigate the environmental impact associated with the extraction and processing of non-renewable resources.

Safer Solvents: Traditional solvents used in materials synthesis often pose health and environmental risks. Green chemistry advocates for the use of safer and more sustainable solvents, such as water or bio-based alternatives. This reduces the exposure of workers to harmful substances and minimizes the release of volatile organic compounds (VOCs) into the atmosphere.

Energy-Efficient Processes: Green chemistry promotes energy-efficient manufacturing processes to reduce the carbon footprint of material production. Techniques like microwave-assisted synthesis, which can significantly decrease reaction times and energy consumption, are being explored to enhance the sustainability of materials synthesis.

Catalysis: Green chemistry encourages the use of catalysis to enhance reaction efficiency and selectivity. Catalytic processes reduce the need for high temperatures and pressures, leading to energy savings and minimizing the production of by-products. This approach is particularly relevant in the synthesis of various materials, including catalysts themselves[37].

Recyclable Materials: Designing materials with recyclability in mind is a key aspect of green chemistry in materials science. This involves developing materials that can be easily disassembled, separated, and recycled at the end of their life cycle. This approach aligns with the principles of the circular economy.

Reduced Toxicity: Green chemistry aims to minimize the use of toxic substances in materials manufacturing. By selecting less hazardous components and avoiding toxic by-products, the environmental and health impacts associated with materials production can be significantly reduced.

Life Cycle Assessment (LCA): Incorporating life cycle assessment principles into materials science allows for a comprehensive evaluation of the environmental impact of a material from raw material extraction to disposal. This holistic approach enables researchers and industry professionals to make informed decisions regarding the sustainability of materials[38].

Energy production

applying green chemistry principles to energy production involves a holistic approach. It encompasses the development of sustainable materials, processes, and technologies across various energy sectors, contributing to a more environmentally friendly and sustainable energy landscape.

Renewable Energy Sources:

Solar Energy: Green chemistry emphasizes the use of renewable resources. In solar energy, this could involve the development of sustainable materials for photovoltaic cells. Researchers are exploring organic and bio-inspired materials that are non-toxic, abundant, and energy-efficient in their production.

Wind Energy: Green chemistry can be applied in the manufacturing of materials used in wind turbines. This includes the development of environmentally friendly lubricants and coatings, as well as the use of recyclable materials in turbine construction.

Bioenergy: Green chemistry principles can guide the sustainable production of biofuels. This involves using non-food feedstocks, minimizing water and energy consumption in the production process, and reducing the environmental impact of biofuel production.

Energy Storage:

Batteries: Green chemistry encourages the development of environmentally benign materials for batteries. This includes exploring alternative electrode materials, non-toxic electrolytes, and recyclable components. Designing batteries with a reduced environmental footprint is a key aspect of green chemistry in energy storage.

Hydrogen Storage: Green chemistry plays a role in the development of safe and efficient materials for hydrogen storage. This involves researching materials that are abundant, non-toxic, and capable of storing hydrogen at lower pressures, reducing the energy required for storage[39-40].

Fuel Production:

Hydrogen Production: Green chemistry promotes sustainable methods for hydrogen production. Electrolysis using renewable energy sources and the use of catalysts made from earth-abundant materials are examples of green chemistry applications in hydrogen production.

Biofuel Production: The principles of green chemistry guide the development of sustainable biofuel production processes. This includes using environmentally friendly solvents, optimizing reaction conditions to sminimize waste, and selecting feedstocks that have a lower environmental impact.

Carbon Capture and Utilization:

Carbon Capture: Green chemistry principles can be applied to develop efficient and environmentally friendly methods for capturing carbon emissions from power plants. This involves the use of eco-friendly solvents and processes that reduce energy consumption.

Carbon Utilization: Green chemistry also plays a role in utilizing captured carbon dioxide. This includes converting CO2 into valuable products such as chemicals or fuels through environmentally friendly catalytic processes[41].

Materials Innovation:

Catalysts: Green chemistry focuses on the development of catalysts that are less toxic, more efficient, and made from sustainable materials. This is crucial in various energy production processes, including the synthesis of fuels and the production of clean energy.

Materials for Infrastructure: The construction of energy infrastructure, such as power plants and transmission lines, can benefit from green chemistry by using sustainable and recyclable materials. This extends to the design of energy-efficient buildings and facilities.

Water Treatment

Green chemistry principles can be effectively applied in water treatment processes to address environmental concerns and promote sustainable practices[42].

Alternative Water Treatment Agents: Traditional water treatment methods often involve the use of chemicals that can be harmful to the environment. Green chemistry encourages the development and use of alternative water treatment agents that are less toxic and more environmentally friendly. For example, bio-based polymers and natural coagulants can be employed as alternatives to conventional coagulants in water treatment.

Minimizing Chemical Waste: Green chemistry emphasizes the importance of minimizing waste generation. In water treatment, this principle can be applied by optimizing chemical dosages to ensure that only the necessary amount is used. Additionally, the use of recyclable or biodegradable materials in water treatment processes helps reduce the environmental impact.

Energy-Efficient Treatment Processes: Green chemistry promotes energy-efficient processes. In water treatment, this can involve the use of advanced technologies such as membrane filtration, ultraviolet (UV) disinfection, and electrochemical treatment, which can be more energy-efficient compared to traditional methods. Energy-efficient processes contribute to sustainability by reducing overall resource consumption.

Green Solvents: Solvents play a crucial role in various water treatment processes. Green chemistry encourages the use of environmentally benign solvents that have minimal impact on human health and the environment. This includes the exploration of water as a solvent in certain treatment applications, reducing the reliance on organic solvents[43].

Biological Treatment Methods: Biological treatment methods, such as phytoremediation and biofiltration, align with green chemistry principles by harnessing natural processes to remove contaminants from water. Microorganisms and plants can be employed to degrade or absorb pollutants, offering a sustainable and cost-effective approach to water treatment[44].

Food Technology

Green chemistry principles can play a significant role in improving sustainability and reducing environmental impact in the field of food technology.

Sustainable Agriculture: Green chemistry promotes the use of eco-friendly and sustainable agricultural practices. This includes the development of organic fertilizers, biopesticides, and environmentally benign cultivation methods. These practices contribute to reducing the environmental impact of food production.

Food Processing and Packaging: Green chemistry is applied in the development of sustainable and biodegradable packaging materials to replace traditional, non-biodegradable options. Additionally, the use of environmentally friendly processing methods, such as supercritical fluid extraction, can reduce the use of hazardous solvents in food production.

Waste Reduction: Green chemistry encourages the reduction of waste in food processing. This involves designing processes that generate fewer by-products and finding innovative ways to repurpose or recycle waste materials. Minimizing waste contributes to a more sustainable and efficient food production system.

Alternative Energy Sources: Implementing green chemistry principles involves using renewable energy sources in food processing operations. This includes the use of solar, wind, or biomass energy to power manufacturing plants, reducing dependence on non-renewable resources and lowering the carbon footprint of the food industry.

Green Ingredients and Additives: The development of green ingredients and additives involves using renewable resources and minimizing the use of harmful chemicals. This includes the exploration of natural antimicrobial agents, antioxidants, and preservatives that are safe for consumers and the environment[44].

Water Conservation: Green chemistry emphasizes the importance of water conservation in food processing. Technologies that reduce water usage, such as water recycling and the optimization of cleaning processes, contribute to sustainable practices in the food industry.

Biotechnology Applications: Green chemistry promotes the use of biotechnological processes to produce food ingredients. This includes the use of enzymes, microorganisms, and fermentation processes to replace traditional chemical methods, resulting in reduced energy consumption and environmental impact.

Carbon Footprint Reduction: By optimizing production processes and supply chain management, green chemistry helps to minimize the carbon footprint of the food industry. This involves efficient transportation, reduced energy consumption, and overall resource optimization.

Life Cycle Assessment (LCA): Green chemistry incorporates life cycle thinking into food production, considering the environmental impact of a product from raw material extraction to end-of-life disposal. LCA helps identify areas for improvement and guides the development of more sustainable food products.

Educational Initiatives: Green chemistry principles are integrated into educational programs for food technologists and scientists. This ensures that future professionals are equipped with the knowledge and skills to implement sustainable practices in the food industry.

CONCLUSION

Research progress has facilitated the development of sustainable processes over time, through investments in ecologically sound analytical and policy methods, in accordance with global conferences since 1968. However, enterprises must assess the economic feasibility of implementing green chemistry in their operations, which hinders our capacity to fully utilize this idea. Investments and promotion of the significance of green chemistry and its direct impact on pharmaceutical analysis, employee well-being, patient health, and environmental sustainability are crucial for future advancements.

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Table 1: Principles of Green Chemistry

Principle	Description
1. Prevention	Minimize or eliminate the generation of waste products during chemical processes.
2. Atom Economy	Maximize the incorporation of all materials used in a process into the final product, reducing by-products and resource consumption.
3. Less Hazardous Chemical Syntheses	Design synthetic methods that use and produce substances with minimal toxicity to human health and the environment.
4. Designing Safer Chemicals	Develop chemical products that are effective while minimizing their toxicity.
5. Safer Solvents and Auxiliaries	Avoid or minimize the use of auxiliary substances, such as solvents, that are harmful to human health and the environment.
6. Design for Energy Efficiency	Optimize processes to minimize energy consumption, favoring ambient temperature and pressure conditions.
7. Use of Renewable Feedstocks	Prioritize the use of raw materials that are renewable rather than depleting.
8. Reduce Derivatives	Minimize or eliminate unnecessary derivatization steps, which can generate waste.
9. Catalysis	Prefer the use of catalytic reagents over stoichiometric reagents to increase reaction rates, reduce energy consumption, and minimize by-products.
10. Design for Degradation	Develop chemical products that break down into innocuous degradation products at the end of their functional life, avoiding persistence in the environment.
11. Real-time Analysis for Pollution Prevention	Develop analytical methods for in-process monitoring and control to prevent the formation of hazardous substances.
12. Inherently Safer Chemistry for Accident Prevention	Choose substances and forms of substances that minimize the potential for chemical accidents, such as releases, explosions, and fires.

Table 2: Utilization of Green Chemistry in Pharmaceuticals

Green Chemistry Principle	Application in Pharmaceuticals
Atom Economy	Designing synthetic routes with minimal waste, optimizing reactions to maximize the incorporation of starting materials into the final product.
Solvent Selection	Choosing environmentally benign solvents or water as a solvent to reduce the environmental impact of pharmaceutical processes.
Catalysis	Implementing catalytic processes to enhance reaction rates, selectivity, and efficiency while minimizing the use of hazardous reagents.
Energy Efficiency	Employing energy-efficient processes, such as microwave or ultrasound-assisted synthesis, to reduce energy consumption in manufacturing.
Biocatalysis	Utilizing enzymes and other biological catalysts to perform specific reactions, reducing the need for traditional chemical catalysts.
Renewable Feedstocks	Incorporating renewable raw materials derived from biomass or other sustainable sources in drug synthesis.
Safer Chemicals	Designing and selecting chemicals with reduced toxicity to humans and the environment, prioritizing safer alternatives.
Process Monitoring	Implementing real-time monitoring techniques to optimize processes, reduce waste, and ensure product quality.
Green Analytical Techniques	Using environmentally friendly analytical methods, such as green chromatography or spectroscopy, for quality control and analysis.
Reducing Derivatives	Minimizing the use of protective groups and unnecessary derivatization steps in synthesis to streamline processes and reduce waste.

Table 3: Utilization of Green Chemistry in Agrochemicals

Type of Agrochemical	Application
Fertilizers	- Provide essential nutrients to promote plant growth and development.
	- Improve soil fertility by replenishing nutrient levels.
Pesticides	- Control and manage pests such as insects, weeds, and diseases.
	- Prevent crop damage and loss, ensuring higher yields.
Herbicides	- Target and eliminate unwanted weeds that compete with crops for resources.
	- Facilitate weed control for better crop establishment.
Insecticides	- Combat insect infestations that can harm crops and reduce productivity.
	- Protect crops from damage caused by various pests.
Fungicides	- Manage and prevent fungal diseases that can affect crop health.
	- Preserve crop quality by controlling fungal infections.
Growth Regulators	- Influence plant growth processes, such as flowering and fruit development.
	- Enhance overall crop yield and quality.
Soil Conditioners	- Improve soil structure and water retention capacity.
	- Enhance nutrient availability for plant uptake.

Table 4: Utilization of Green Chemistry in Material Science

Green Chemistry Principle	Application in Material Science	Benefits
Atom Economy	Efficient use of raw materials, minimizing waste production.	Reduces resource consumption and promotes sustainability.
Catalysis	Use of catalysts to enhance reaction rates and selectivity.	It lowers energy requirements, reduces waste, and improves efficiency.
Safer Solvents	Replacement of hazardous solvents with environmentally friendly alternatives.	Enhances safety for both workers and the environment.
Renewable Feedstocks	Incorporation of renewable raw materials in material synthesis.	Reduces dependence on non-renewable resources and minimizes environmental impact.
Energy Efficiency	Implementation of energy-efficient processes and technologies.	Lowers carbon footprint and overall environmental impact.
Design for Degradation	Development of materials that can be easily recycled or biodegraded.	Reduces end-of-life environmental impact and promotes circular economy.
Minimize Derivatives	Focus on direct synthesis methods to minimize by-products and waste.	Improves overall efficiency and reduces environmental impact.
Biobased Materials	Utilization of materials derived from biomass as alternatives to conventional sources.	It supports sustainable agriculture and reduces dependence on fossil fuels.

Table 5: Utilization of Green Chemistry in Energy Production

Green Chemistry Application	Description	Benefits
Renewable Energy Sources	Development and utilization of renewable energy sources such as solar, wind, and hydropower.	Reduces dependence on fossil fuels, mitigates climate change, and promotes sustainability.
Catalysis in Fuel Production	Use of catalysis in the production of biofuels and hydrogen from renewable feedstocks.	Enhances efficiency, reduces energy consumption, and minimizes environmental impact.
Safer Battery Technologies	Development of environmentally friendly and safer battery technologies, such as solid-state batteries.	Improves safety, reduces reliance on toxic materials, and enhances recyclability.
Energy-Efficient Processes	Implementation of energy-efficient processes in the production of fuels and energy storage systems.	Lowers overall energy consumption and carbon emissions.
Green Fuels and Synthesis	Synthesis of fuels using sustainable and biobased feedstocks, such as algae-based biofuels.	Reduces greenhouse gas emissions, supports sustainable agriculture, and promotes circular economy.
Carbon Capture and Utilization	Application of green chemistry in the development of carbon capture and utilization technologies.	Mitigates carbon dioxide emissions and contributes to climate change mitigation.
Materials for Energy Efficiency	Design of energy-efficient materials for applications like insulation and energy storage.	Enhances energy efficiency and reduces environmental impact in various sectors.

Green Chemistry Application	Description	Benefits
Biomimicry in Energy Systems	Drawing inspiration from nature to design energy systems and materials, improving efficiency and sustainability.	Promotes innovative and sustainable solutions inspired by natural processes.

Table 6: Utilization of Green Chemistry in Water Treatment

Green Chemistry Principle	Application in Water Treatment	Benefits
Safer Solvents	Replacement of traditional, hazardous solvents with environmentally friendly alternatives in water treatment chemicals.	Enhances safety for workers and reduces environmental impact.
Catalysis in Water Purification	Use of catalysts to accelerate water treatment processes, such as degradation of pollutants.	Improves efficiency, reduces energy consumption, and minimizes the need for harsh chemicals.
Renewable Feedstocks	Utilization of renewable raw materials in the synthesis of water treatment chemicals.	Reduces dependence on non-renewable resources and promotes sustainability.
Design for Degradation	Development of water treatment agents that break down into non-toxic by-products after use.	Minimizes environmental impact and enhances the overall safety of water treatment processes.
Minimize Derivatives	Focus on direct and efficient water treatment methods to minimize the generation of harmful by-products.	Reduces waste production and lowers environmental impact.
Biobased Treatment Agents	Use of biobased materials in water treatment, such as bioflocculants for wastewater treatment.	Enhances sustainability, promotes circular economy, and reduces the use of synthetic chemicals.
Energy-Efficient Processes	Implementation of energy-efficient technologies and processes in water treatment systems.	Lowers energy consumption, reduces operational costs, and minimizes carbon footprint.
Biomimicry in Water Filtration	Drawing inspiration from natural processes for water filtration technologies.	Promotes innovative and sustainable solutions for water treatment.

Table 7: Utilization of Green Chemistry in Food Technology

Aspect of Food Technology	Application of Green Chemistry
Food Processing	**Utilization of environmentally benign solvents and catalysts in extraction processes.**
	Minimization of waste generation by employing efficient separation techniques.
Food Packaging	**Development of biodegradable and compostable packaging materials.**
	Reduction of packaging waste through the use of eco-friendly alternatives.
Food Preservation	**Application of natural antimicrobial agents and preservatives.**
	Optimization of processing conditions to reduce energy consumption.
Food Additives	**Exploration of green alternatives for food colorings, flavorings, and texturizers.**

Aspect of Food Technology	Application of Green Chemistry
	Consideration of the environmental impact of additives throughout their lifecycle.
Waste Management	Implementation of strategies to reuse and recycle by-products from food production.
	Conversion of organic waste into value-added products through green technologies.
Water and Energy Use	Efficient use of water resources in food processing through recycling and conservation.
	Adoption of energy-saving technologies to minimize the carbon footprint.
Supply Chain Sustainability	Promotion of sustainable agricultural practices, such as organic farming.
	Encouragement of fairtrade practices for the ethical sourcing of food ingredients.