

# Green Chemistry Innovations for Global Sustainability: Pathways to Safer Materials and Processes

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**Dr. Arvind Kumar Pandey**

Department of Chemistry,  
Kashi Naresh University, Bhadohi  
arvindauchem@gmail.com

## Abstract

*Sustainability in the 21st century has become essential for governments, civil society, and businesses worldwide. Green chemistry is vital because it provides a foundation for creating safe materials and processes that minimise environmental impacts. The chemicals and processes produced by humans today have significantly changed the Earth. Despite their advantages, they still cause widespread pollution, which has greatly cost society. Early sustainability efforts focused on clean environments, food, and energy, but now they extend to the management of human-environment interactions. Chemical use has expanded to meet a broad range of human needs, posing a major challenge: designing safer chemical materials and processes. In this context, we explore how green chemistry can help address these issues. Green chemistry also promotes designing chemical products, manufacturing methods, and industrial systems that avoid or reduce hazardous substances throughout their lifecycle. It aims to develop new scientific knowledge and awareness, ensuring that chemicals support sustainable development by minimising health risks, ecological impacts, and resource use, while maximising their benefits. Additionally, it sets a research and practice agenda that includes principles of operation, progress measurement, sectoral application, educational outreach, and policy engagement (Mech et al., 2022).*

**Keywords:** *Green chemistry, sustainable development, safer materials, environmentally friendly processes, life cycle assessment, policy and regulation, green innovation, chemical safety.*

## 1. Introduction

Green chemistry serves as a guide for designing chemical products and processes that prioritise human and

environmental safety throughout their life cycle (Jen Mendelsohn Matus et al., 2013). Although the field of green chemistry has progressed quickly since the initial 12 principles were introduced in 1998, defining it precisely remains difficult (Mech et al., 2022). However, with suitable metrics, scientists and policymakers can systematically evaluate proposed green chemistry applications, create specific incentives, and develop formal education programs to encourage innovation and adoption.

Beyond the flexible definition, the shape and structure of green chemistry have also evolved to include four widely used design goals, known as the 4S, which are connected to environmental, social, and economic sustainability aims. The development of the safe-and-sustainable-by-design principle at a European workshop on smart nanomaterials indicates a growing awareness of the need to balance safety and sustainability with functionality and performance from the outset.

## **2. Underpinnings of Green Chemistry.**

The multilateral goals are sustainable development and chemical safety, which governments and international organisations are striving to achieve through state policy, scientific research, and social participation. Green chemistry aims to replace hazardous substances and toxic reactions, protecting workers, consumers, and the environment in

manufacturing processes and product use. These alternatives promote sustainable development by enabling the three pillars of society: the economy, the environment, and society. The classical concepts of sustainability are intertwined and mutually reinforce one another, accentuating the systemic character of the problem and the heightened significance of safety concerns and multi-beneficial solutions (Jen Mendelsohn Matus et al., 2013).

The desire to replace old and unsafe procedures and materials stems from ongoing mechanisms and increasing manifestations worldwide, such as the toxicity of chemical substances to humans and the environment, waste production, and greenhouse gas emissions. The long-term solutions need to be innovative, such as benign-by-design chemicals, cradle-to-grave life-cycle analysis, and cross-disciplinary systemic thinking, particularly in synthesis and design.

## **3. More harmless Chemical Design and Synthesis.**

Increasing the diversity of safe chemicals and developing safer synthesis routes are complementary strategies to reduce societal risk and environmental impact. Green Chemistry also emphasises broader, more practical strategies for safer chemical design, such as the formulation of a metric based on the persistence, bioaccumulation, and

ecotoxicity (PBE) of organic chemicals (Asif et al., 2019) and the development of a twelve-principle set that addresses safety considerations throughout the entire chemical life cycle (Lee & Marrocchi, 2024).

### **Safer Chemicals**

Human exposure to toxic and hazardous substances throughout the chemical life cycle, including feedstock extraction, production, transportation, utilisation, storage, and disposal, poses serious social and environmental risks. Addressing this issue by designing and synthesising safer chemicals is a primary strategy for achieving the Green Chemistry goal of eliminating hazardous substances in future production and consumption. Basic methods for safer chemical design involve reducing inherent toxicity by avoiding high-hazard functional groups, creating chemicals that naturally decompose into harmless by-products, and conducting thorough hazard assessments before commercialisation. Significant progress has been made in systematically designing materials that decrease environmental persistence, bioaccumulation, and acute toxicity. An additional approach promotes hazard reduction and 'Benign by Design' strategies, which use a combination of toxicology and exposure models to guide the removal of hazardous molecular motifs. Once the initial hazard is

mitigated, advanced design templates can be used to meet other performance, economic, and social objectives. Cradle-to-grave design methodologies applying Green Chemistry principles have been implemented in polymers, a widely used product whose prevalence makes reducing material use challenging. The extensive design options, including biodegradable and non-biodegradable polymers and polymer additives, along with quantitative measurement models, enable identification of environments and organisms of concern and support compliance with safety, performance, and process goals. Emerging computational technologies will facilitate the identification of safer, more sustainable alternatives with shorter life cycles.

#### **3.1. Safety Principles and Metrics of Safer Materials.**

Substituted benzenes remain and accumulate in sediment, sludge, and biota. Bioaccumulation of heavy metals by organisms causes health hazards to both humans and animals through the food web. Environmental persistence is minimised through safe design and the use of biodegradable materials. The assessment covers performance and environmental aspects, including persistence, bioaccumulation, and environmental toxicity, of target chemicals and alternatives.

A safer substitutes strategy, as part of the synthesis route benchmarks, identifies chemicals with a lower environmental impact throughout their life cycle. The route from ethylene/acetylene and methanol to methylamines and methyl isocyanate, and from methylamines and methyl isocyanate to high-density polyethylene, emphasises safety, performance, and environmental factors. Other direct routes involving methylamine and ammonia or phenol and ammonia offer numerous benefits.

The production of indigo, a pigment, shows that ecologically friendly practices offer significant advantages over mainstream practices. There are three alternatives to the traditional phosgene-based process: a single-step synthetic process and two two-step processes. Green substitutes use less toxic reagents, fewer total process steps, better mass recovery and lower toxicity.

**Table 1: Key Safety Metrics for Safer Material Design**

<b>Metric / Concept</b>	<b>What it measures</b>	<b>Design goal in green chemistry</b>
Persistence (P)	How long a chemical remains in the environment	Reduce long-lived pollutants and encourage degradability
Bioaccumulation (B)	Tendency to build up in organisms and food webs	Avoid chemicals that concentrate in tissues over time
Ecotoxicity (E)	Toxic effects on aquatic and terrestrial organisms	Minimise ecosystem-level damage

Metric / Concept	What it measures	Design goal in green chemistry
Safe-and-sustainable-by-design	Integration of safety and sustainability from the start	Balance function, safety, and environmental performance
Benign-by-design chemicals	Inherent hazard of molecules and their breakdown products	Design molecules that degrade into harmless substances

### 3.2. Safer Synthesis Pathways Case Studies.

A greater emphasis can be placed on safer synthesis routes by using tools and methods to minimise risks, reformulate chemicals to be inherently safe, eliminate toxicological endpoints in chemicals, and ensure that chemical reactions and materials have a cradle-to-cradle lifecycle. Substituting hazardous solvents, reagents, process pathways, and synthetic plans reduces pollutant formation in chemical production, thereby enhancing overall sustainability.

The initial case study describes a method for preparing 5-hydroxymethylfurfural (5-HMF), a versatile biofuel and bio-based chemical feedstock. The standard method uses 5-(hydroxymethyl)furfural (HMF) and formaldehyde (formalin)

(aqueous) as the only materials. The hydroxyalkylation of HMF is an unwanted step that requires high acidity for catalysis. To distinguish between the 5-HMF and the aqueous-phase formalin, liquid-liquid separation is necessary. Achieving this involves replacing the aqueous phase of the system in batches, which is cumbersome due to the buildup of polymerisable aldehyde impurities (Chen, 2008). Instead, glucose was used as the starting material in this study. Several process schemes were evaluated, and the chosen one involved hydrolysing glucose in the presence of acid catalysts to produce hydroxymethylfurfural, followed by acetalization with methanol. This process avoids the four main disadvantages of the earlier formalin-based method, namely:

(1) no complex separation of a water phase,

(2) both the reactants are solid, and can be easily pre-mixed,

(3) the activation energy is much lower and more amenable to low-temperature-high-pressure operation, and

(4) The catalytic activity of most acid catalysts is greatly increased. A toxicology clipboard is a list of chemical ingredients and toxicological endpoints; the tick is not shown next to any important part.

The second case study involves producing p-nitrobenzoic acid (PNBA) from toluene through nitration and oxidation. A common method uses fuming nitric acid and concentrated sulfuric acid. Because fuming acid poses safety risks, colourimetric testing shows that high concentrations persist until the final drop. The acid's toxicity and fumes are also highly hazardous, increasing the risk of harm. Additionally, toluene and its nitro derivative pose further safety concerns that remain unaddressed. Overall, the environmental health safety index indicates an unacceptable risk. A safer alternative is using mixed acid ( $\text{HNO}_3/\text{H}_2\text{SO}_4$ ) in the initial step, followed by low-temperature sodium dichromate in water in the second step. Hazard indicators are heightened, and a broad spectrum of hazard issues,

reflected in a larger table, are expanded (Ibrahim Samli, 2011).

#### **4. Environmentally-Friendly Process Engineering.**

Sustainable process engineering measures production by analysing energy, waste, and hazard data; promotes innovation for industrial viability; enables significant safety, efficiency, and environmental benefits; and systematically optimises the environment, economy, and society (Ibrahim Samli, 2011). Improving energy, waste, and hazard management is especially crucial for safety, efficiency, and environmental goals. For catalysts, design aims to minimise consumption and hazards, increase selectivity and throughput, and extend lifespan.

Sustainable Process Engineering and Independent Research. A sustainable process engineering approach evaluates production based on energy, waste, hazard, and economic factors; promotes innovation that boosts industry competitiveness; and creates opportunities for comprehensive safety, efficiency, and environmental enhancements. Systems accounting enables the simultaneous optimisation of environmental, economic, and social aspects. Relevant literature has examined nineteen energy efficiency measures, eight waste reduction strategies, and thirty-two catalytic technologies, leading to significant expected changes in energy

demand, hazardous waste, and overall hazards; monitoring devices are becoming accessible for all three.

#### **4.1. Energy Conservation and Minimisation of Waste.**

It has, as part of its core principles, the implementation of more efficient energy use and the reduction of waste; the idea of green engineering focuses on sustainability through improved life-cycle practices (Stewart Slater et al., 2005). By determining, quantifying, and analysing energy and waste inputs, it is possible to evaluate environmental sustainability properly. Recent findings suggest that the chemical sector can potentially cut energy use and gas emissions by up to 60 per cent and waste by more than 50 per cent, which could also be economically beneficial (Lee & Marrocchi, 2024). Choosing key performance indicators and monitoring tools is essential for measuring energy intensity, waste production, and process sustainability, and several instruments are available to facilitate this process.

Improvements in energy and resource efficiency are essential for climate and sustainability because the chemical industry significantly contributes to fossil fuel use, energy consumption, and greenhouse gas emissions. Therefore, better energy management is crucial. Unnecessary energy consumption can occur at various stages, such as heating,

intermediates, and harmful additives. Significant energy reductions can be achieved through effective lifetime extension and performance-driven design. The development of green models and reactive undergreen models minimises the need for energy-intensive processes, thus reducing energy use. Additionally, unselected pathways can be minimised, which decreases process waste (Summerton et al., 2019).

#### **4.2. Catalysis and Reaction Engineering.**

Sustainable process engineering, with a balanced focus on safety, efficiency, and environmental goals, is an important aspect of green chemistry. Along with encouraging the design of safer chemicals and synthesis pathways, much consideration is also justified on the design of benign processes towards safe products, as the ability to scale to industrial applications may rely on such a process-based view.

A fundamental principle of green chemistry is catalysis, which facilitates efficient reactions, reduces byproducts, and improves sustainability. Historically, catalytic systems have been divided into heterogeneous and homogeneous, based on whether the catalyst is in the same phase as the reagents (solid, liquid, or gas). To enable methods with greater selectivity and throughput, significant advances have been made in integrated reaction engineering and reactor design

over the last decade. High on-the-fly reaction ceiling conditions, together with the integration of reaction and separation, have also been designed using novel reactor configurations and biocatalytic conversion methods that do not require substantial downstream separation of feedstock, intermediates, solvent, or co-reactants. These cases indicate that well-designed reactors and plans could improve safety and be highly cost-effective for environmental protection.

### **4.3. Choices and Alternative Media.**

The common use of chemicals in manufacturing and utilisation has led to a high rate of solvent consumption, as solvents are essential to numerous processes. One of the most vivid examples states that more than half of the chemical products, including pharmaceuticals, pesticides, and plastics, are produced through processes that involve solvents (Winterton, 2021). Ordinary measures show that over 90 per cent of the waste of a chemical industry location, the resultant global direct and indirect expenses of 6-10 per cent of sales, and the wasting of solvents add to approximately a quarter of industrial VOC emissions (Anon, 2015).

In a nutshell, solvent selection is an urgent and difficult challenge that affects safety, environmental operations, and the economic feasibility of chemical processes and product formulations. The

principles of green chemistry (periodic table, design to degrade, and less-hazardous synthetic methods) aim to eliminate solvents or use them more effectively (free of waste) and sustainably (biobased). Instead, a service-product paradigm shifts the emphasis from raw materials and intermediate products to essential functionality, where solvents may, in some cases, be eliminated, used merely to formulate, or provided in an undiluted form to meet processing needs.

### **5. Life Cycle Thinking and Evaluation.**

Despite chemists often viewing a chemical process as a series of reactions and decoupling the synthesis and consumption of substances from their subsequent fate, the life cycle of a chemical product extends from cradle to grave (Summerton et al., 2019). To that end, a comprehensive life-cycle assessment (LCA) evaluates the potential environmental impacts of each stage of a product's life cycle, including raw material extraction and processing, manufacturing, distribution, use, repair and maintenance, recycling, and final disposal (Fernando Morales-Mendoza et al., 2018). Likewise, chemical engineering has embraced a broader definition of a chemical process with the development of green chemistry. The system-wide insights provided by life cycle assessment are linked to alternative designs rather than the optimal

conditions as the ultimate goal, further reinforcing a systems approach in chemical engineering and expanding the analysis of possible chemical losses-central to green chemistry- to encompass the entire life cycle and the global chemical systems. The limitations of life cycle assessment have increased interest in risk management and hazard assessment as key areas of chemical engineering. Like process design, these assessments can employ very broad definitions, focusing on specific regulations or issues, and are often categorised as either quantitative or qualitative. Choosing appropriate approaches, modelling systems, and data

sources is crucial, as the simplicity and subjectivity of qualitative methods often make them more consistent and rigorous overall than complex quantitative techniques. Both qualitative and quantitative procedures are used interchangeably, with recent innovations leading to combined qualitative decision-support systems. These frameworks facilitate decision-making by generating and evaluating ideas collectively, rather than focusing solely on individual priorities, and by embracing the life-cycle concept, which in some cases requires close collaboration with risk management and hazard assessment in chemical engineering.

**Table 2: Main Stages of Life Cycle Assessment**

LCA stage	Short description	How it relates to green chemistry
Goal and scope definition	Define purpose, functional unit, and system boundaries (e.g. cradle-to-gate, cradle-to-grave)	Ensures that sustainability questions are clear and comparable
Life Cycle Inventory (LCI)	Quantify inputs (materials, energy) and outputs (emissions, wastes)	Identifies where major resource use and pollution occur
Impact assessment (LCIA)	Translate inventory flows into impact categories (e.g. climate change, toxicity)	Links process design choices to environmental and health impacts

LCA stage	Short description	How it relates to green chemistry
Interpretation	Analyse results, identify hotspots, and support decision-making	Guides selection of safer materials, routes, and technologies

### 5.1. Life Cycle Assessment Methodologies.

The technique used in conducting Life Cycle Assessment (LCA) is based on the ISO 14040 standard (ZHANG, 2012). The analysis involved two stages: total environmental cost and life-cycle energy use, according to the criterion set up by Barjoveanu et al. (2023). The SimaPro software has been employed to support the setup of life-cycle inventories and to perform the LCA. The cradle-to-gate scenario adopted in this research involved the manufacture of polyelectrolyte A, neutraliser B, and other standard consumables for wastewater treatment.

Existing LCA techniques are not effectively used to evaluate the environmental impact of releasing nanomaterials throughout their life cycles because of the lack of characterisation factors, fate data, and toxicity information (Fernando Morales-Mendoza et al., 2018). To address this issue, interpretations and scenarios that can help overcome these deficiencies are

suggested when performing LCA of wastewater treatment materials.

### 5.2. Risk Management and Hazard Assessment.

Several risk management and hazard assessment techniques are successfully implemented in chemical industries and research labs to identify process hazards, assess risks associated with selected materials, and define processes for chemical and hazardous waste management. One of the most popular hazard assessment approaches is characterised by a combination of inherent safety principles and quantitative safety indicators derived from process simulation. Instruments such as chemical hazard assessment are useful in the initial phase of process design, when a list of possible chemicals is still being compiled, and the underlying chemical reactions of the process remain unknown.

Risk management falls into two broad categories based on their approach to application: the quantitative approach,

which provides a quantitative assessment of the material used and the process risk, and the qualitative approach, which provides a rank-based assessment rather than numeric values. They can both be incorporated into the decision-support systems in the process design to compare numerous schemes against chemical hazards and material use in the initial phase of the design stage (Lu, 2011).

## **6. Policy, Economics, and International Adoption.**

The concept of sustainable development is gaining prominence on the political agenda of the 21st Century and is receiving particular attention from the scientific community and the general population. The concept of sustainable development has economic, social, and environmental features. It includes the following dimensions: the Equitable Distribution of Resources, the Reduction of the Gap between Developing and Emerging Nations, the Enhancement of Quality of Life, and the Guarantee of Food Security for the World Population.

- The volatility of chemicals and energy resources has had a significant influence on human beings. The most significant problems of contemporary civilisation that require effective solutions from the academic community are identified as environmental degradation, energy

resources depletion, and climate change.

- Safety chemical action is one of such approaches to these challenges. The International Year of Chemistry (IYC) event established Global Chemical Safety as a site to organise the scientific community to promote safe chemicals, hazardous chemicals, and safe chemistry.
- Sustainable Design of Materials is another line of work aimed at addressing one of the major problems posed by the volatility of chemical and energy resources. The essence of this concept, currently being felt throughout the world, is the materials society uses, which can be recycled and produced with lower chemical and energy inputs.
- The two activities are essential to address challenges such as the burning of fossil and chemical resources and to achieve the Sustainable Development Goals (SDGs) suggested by the United Nations in 2015. They should be highlighted in Articles on major IYC-related issues.
- The Green Chemicals design may be viewed as even more critical than safer chemical design (Jen Mendelsohn Matus et al., 2013).

The Chemical Industry is currently entangled in the regulatory framework of Chemical Control, which is inevitable and even interferes with Chemical Research and Development (P. Wilson & R. Schwarzman, 2009). Several former Chemists of Generation-1 who trained during the period from Molecule Science to Material Chemistry (1955-1975) have been engaged in safe chemical exploration.

### **6.1. Regulatory Frameworks and Standards.**

Green chemistry solutions are adopted through regulatory frameworks and standards that promote the development of safer materials and processes. The shift to compliant product design can help existing safety endeavours involving chemicals. The example of chemical legislation in the European Union is considered a case study of how green chemistry can provide substantial benefits to both business and general health.

Legislation on chemicals in the European Union has advanced its current requirements to analyse the safety in the past which was required by the previous Directive on Dangerous Substances to the present day regulations known as the Reach, on which manufacturers and importers of substances must guarantee safe usage of the marketed substances throughout the entire life cycle, including those incorporated into articles (Mech et

al., 2022). Those laws have, in turn, been incorporated into the European Commission Action Plan on the Circular Economy (2016), which acknowledges that innovation is necessary to minimise the total impact of chemicals on the environment and human health (Jen Mendelsohn Matus et al., 2013). The creation of naturally safer or harmless chemicals intrinsically has therefore come to be one of the most viable pollution-prevention measures. The foundations of green chemistry, namely waste reduction, synthetic pathways that conserve energy and transform chemicals into innocuous products that are readily disposed of and have renewable-resource origins, are hence the core of the concept of Safe-by-Design. This technique seeks to detect and reduce hazards to human health and the environment at the earliest stage of innovation by conducting an iterative sequence of safety evaluations at predetermined stages of research and development.

### **6.2. Economic Incentives and Market Transformation.**

The benefits of green chemistry innovations are well documented across health, environmental, and security aspects, yet obstacles remain (P. Wilson & R. Schwarzman, 2009). Regulations can be supplemented with greater economic incentives, market changes, and other market-based tools to hasten the spread. Various financing mechanisms, subsidies, and incentives will help direct

private-sector investment toward promoting and embracing safer methods (Matus et al., 2017). Ideally, the amounts of money needed to fund greener strategies should be treated as investments rather than recurring grants or other obligations with specific terminations. With appropriate changes to chemical-related taxes to make them more favourable to safe design and sustainable procurement, government agencies can utilise existing funds and align economic indicators with national policy goals.

### **6.3. Capacity Building and Technology Transfer.**

The work on enhancing innovation, ensuring that green chemistry reaches the people who can utilise it, and developing human capital capable of harnessing such advances to their fullest potential should be augmented by greater efforts. The success of green chemistry in society cannot be achieved without the regular implementation of the relevant technologies. This movement, therefore, necessitates allocating more resources to technology transfer, capacity building, and the diffusion of knowledge, in particular between developing countries. Hurdles to such endeavours include poor knowledge-creation and knowledge-sharing systems, reduced research and development, unduly unregulated chemical imports, high expenditure and insufficient attention to ongoing

education, lack of coordination in the region, and other related factors.

There is a set of possibilities that may contribute to the transfer of technology, capacity building, and the dissemination of knowledge. There is a need to have policies that facilitate the integration of green chemistry into schools, facilitate the sharing of innovations through established channels, foresee implementation challenges and devise ways to address them, encourage regional knowledge exchange, invest in developing a changing yet adequate public-sector R&D base, encourage long-term public-private and research-enterprise alliances, and establish networks and form alliances among stakeholders. Even though these measures cannot remove the barriers during the process, they can be effectively used to advance green chemistry on a broader scale in some key areas (Jen Mendelsohn Matus et al., 2013).

### **7. Cases and Practices.**

Traditionally, green chemistry has evolved experimentally along a variety of paths, with pathetically few high-throughput screening studies or systematic methods. It is difficult to generalise the idea in a nutshell because of the numerous past case studies that touch on it but do not necessarily spell out the concept. However, four comparatively ubiquitous inventions are

quite useful as systematic designs in microelectronics and pharmaceuticals, and, to a lesser extent, in agrochemicals and speciality formulations. Unless otherwise mentioned, these contributions are syntheses, based on publicly available, peer-reviewed information.

This section of the case studies identifies target inputs, intermediates, or products of large substance classes, serving as a guide in the original development of new products and as candidate substitutions. The supply of conversion halftimes will not delay the focus on the important target chemicals. In the chemical business, inventing new uses on a completely new level and finding a substitute for current dangerous materials are both parallel but different issues, which further indicate the independent but complementary presidency of chemicals, on the one hand, and processes that are used to produce chemicals, on the other hand (Jen Mendelsohn Matus et al., 2013).

### **7.1. Pharmaceuticals and Chemicals.**

The pharmaceutical industry differs in its issues related to designing safer materials and creating lower-impact materials and processes. The new therapeutic molecule requirements are also tough, as the search space for new synthetic methods and reagents must be constrained by safety, health, and environmental concerns. Extended extensions of these measures have seen the methodical removal of

dangerous synthetic approaches, intermediates, and reagents using more environmentally friendly alternatives; processes that have not been abandoned continue to be used. At the same time, the linked technological advances diminish the accessibility of effective, greener substitutes and create opportunities to embrace more feasible, safer, and cleaner artificial processes (P. Wilson & R. Schwarzman, 2009; Stewart Slater et al., 2005).

### **7.2. The Agrochemicals and Materials.**

Amplified exploitation of crop varieties, fertilisers, irrigation, and pesticides has increased agricultural productivity worldwide over the last few decades. There has also been a growing number of environmental toxicants through such agricultural practices. As a rule, migrant residues and non-degradable pesticide residues in agricultural products harm human and animal health and the environment. Currently, a wide variety of crops, pesticides, and fertilisers are on the market and in use, with uneven consumer awareness of their safety and environmental impact. Rather than resorting to the intensive use of agrichemicals, greater attention should be paid to designing agrichemical products and processes that are less hazardous to the environment and human beings. The problem lies in the fact that it is necessary to start implementing green principles into the

design and production procedures for agrichemical products. One of the most important missions has been to bring sustainable solutions and green chemistry products to the masses by chemists and chemical engineers.

First, there should be an effort to analyse the agricultural life cycle, appropriate design principles, and hazard classification systems in light of greener chemistry to develop eligible sustainable products with reduced environmental impacts. The life cycle of crop production consists of pre-harvest, harvest, and post-harvest. Some of the pre-harvest activities include nursery preparation, transplanting (direct-seeding), fertilisation, planting (seeding), and weed and pest control. It seems that this is the period when more chemical inputs are used, with growth enhancers, fertilisers, herbicides, and insecticides applied extensively. Considering sustainability and green chemistry, the pre-harvest period should receive greater attention. In such a sustainable life cycle, green principles for agricultural chemicals can be adopted to reduce environmental impacts. To further curb human health and environmental issues, a classification system for hazards such as deterrents, toxicity, eco-incidents, bio-accumulation, and persistence can also be employed to classify various types of agricultural chemicals. Coupled with other chemical design approaches,

integration with the structure of the hazard classification system enables the development of a framework to reduce the hazards posed by agricultural chemicals (BHANDARI, 2018).

### **7.3. Energy, Electronics and Packaging.**

The priority areas of green chemistry innovations include energy technologies, electronics, and sustainable packaging. The extraction and consumption of fossil fuels have led to the emergence and investment in alternative energy production technologies due to externalities. These new-generation fuels are accompanied by batteries, hydrogen, and other storage technologies that enable energy storage in a more portable and safer manner. Dielectric materials in condensers and other electronic equipment are based on a great variety of polymers. The question of what happens to these materials after the product life is not a big concern, as it is usually not considered in view of the performance benefits or external economies. Available measures provide quantitative data to inform the choice of materials (Mullen & A. Morris, 2021).

### **8. Education, Communication and Stakeholder Engagement.**

The proper implementation of green chemistry principles and practices includes education and outreach (A. Lasker et al., 2019) ; (Jen Mendelsohn Matus et al., 2013). Improved education

will lead to greater awareness of green chemistry and help engage stakeholders in the chemical science community and beyond. Risk-benefit analysis is included in public knowledge associated with materials and processes, and it is used to inform discussions of science policy (Summerton et al., 2019). The possibilities of working outside of the field of a scientist promote involvement in discussions within broader forums and contribute to the general educational systems at any level.

Learning must begin earlier and incorporate interdisciplinary and systems-thinking concepts from physics, biology, mathematics, information technology, and economics. Improving the general public's understanding of the fundamental chemical principles, already a topic in political discussions, will also foster smarter engagement in more technical debates about green chemistry. The chemical community remains somewhat insular in a world where direct experience with chemistry is often used to promote extensive toxicological knowledge. Engaging stakeholders can increase acceptance of green chemistry innovations, and conversations with policymakers and legislators can clarify the political landscape. Exposure to sociological perspectives and social scientists further makes these arguments relevant to cultural contexts. It enables viewing green chemistry innovations not just as chemical challenges but also as

part of the larger sustainability movement and related to the emergence of a new economy.

## 9. Conclusion

The world's efforts to achieve sustainability are driven by the development of materials and processes that reduce the risks of chemical exposure. Green chemistry focuses on designing chemicals and processes to prevent hazards and is widely adopted worldwide. The European Chemicals Regulation EC 1907/2006 (REACH) includes safer alternatives in the Substance of Very High Concern (SVHC) list of hazardous chemicals. The focus on green chemistry in selecting innovations, as seen in the choice of pre-registered Substances of Very High Concern, is also increasingly common in response to U.S. Toxic Substances Control Act (TSCA) directives promoting safer chemicals.

The essential role of chemical processes and products in sustainable development has driven an international movement toward green chemistry, which, however, is only partially adopted in industry (Jen Mendelsohn Matus et al., 2013). The push to reduce risks is intensified by the widespread occurrence of high-risk chemicals in both the developed and Developing Worlds. The risk level from existing chemicals and processes remains high due to scale and inertia, making it crucial to explore new alternative pathways and address past issues.

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