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A Comprehensive Review On: Green Chemistry

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

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

INTRODUCTION-
The term Green Chemistry is defined as -"The invention, design and application of chemical products and processes to reduce or to eliminate the use and generation of hazardous substances". While this short definition appears straightforward, it marks a significant departure from the manner in which environmental issues have been considered or ignored in the up-front design of the molecules and molecular transformations that are at the heart of the chemical enterprise. Looking at the definition of Green Chemistry, the first thing one sees is the concept of invention and design. By requiring that the impacts of chemical products and chemical processes are included as design criteria, the definition of Green Chemistry inextricably links hazard considerations to performance criteria. Another aspect of the definition of Green Chemistry is found in the phrase "use and generation".

Rather than focusing only on those undesirable substances that might be inadvertently produced in a process; Green Chemistry also includes all substances that are part of the process. Therefore, Green Chemistry is a tool not only for minimizing the negative impact of those procedures aimed at optimizing efficiency, although clearly both impact minimization and process optimization are legitimate and complementary objectives of the subject.

Fig 1: Aim Of Green Chemistry

Finally, the definition of Green Chemistry includes the term "hazardous". It is important to note that Green Chemistry is a way of dealing with risk reduction and pollution prevention by addressing the intrinsic hazards of the substances rather than those circumstances and conditions of their use that might increase their risk. The definition of Green Chemistry also illustrates another important point about the use of the term "hazard". This term is not restricted to physical hazards such as explosiveness, flammability, and corrodibility, but certainly also includes acute and chronic toxicity, carcinogenicity, and ecological toxicity. Furthermore, for the purposes of this definition, hazards must include global threats such as global warming, stratospheric ozone depletion, resource depletion and bioaccumulation, and persistent chemicals. To include this broad perspective is both philosophically and pragmatically consistent. It would certainly be unreasonable to address only some subset of hazards while ignoring or not addressing others. But more importantly, intrinsically hazardous properties constitute those issues that can be addressed through the proper design or redesign of chemistry and chemicals.

History

The term green chemistry was first given by Poul .T. Anastas in 1991 in special program launched by the US environmental Protection Agency (EPA) to implement sustainable development in chemistry ,chemical technology by industry ,academia and government.

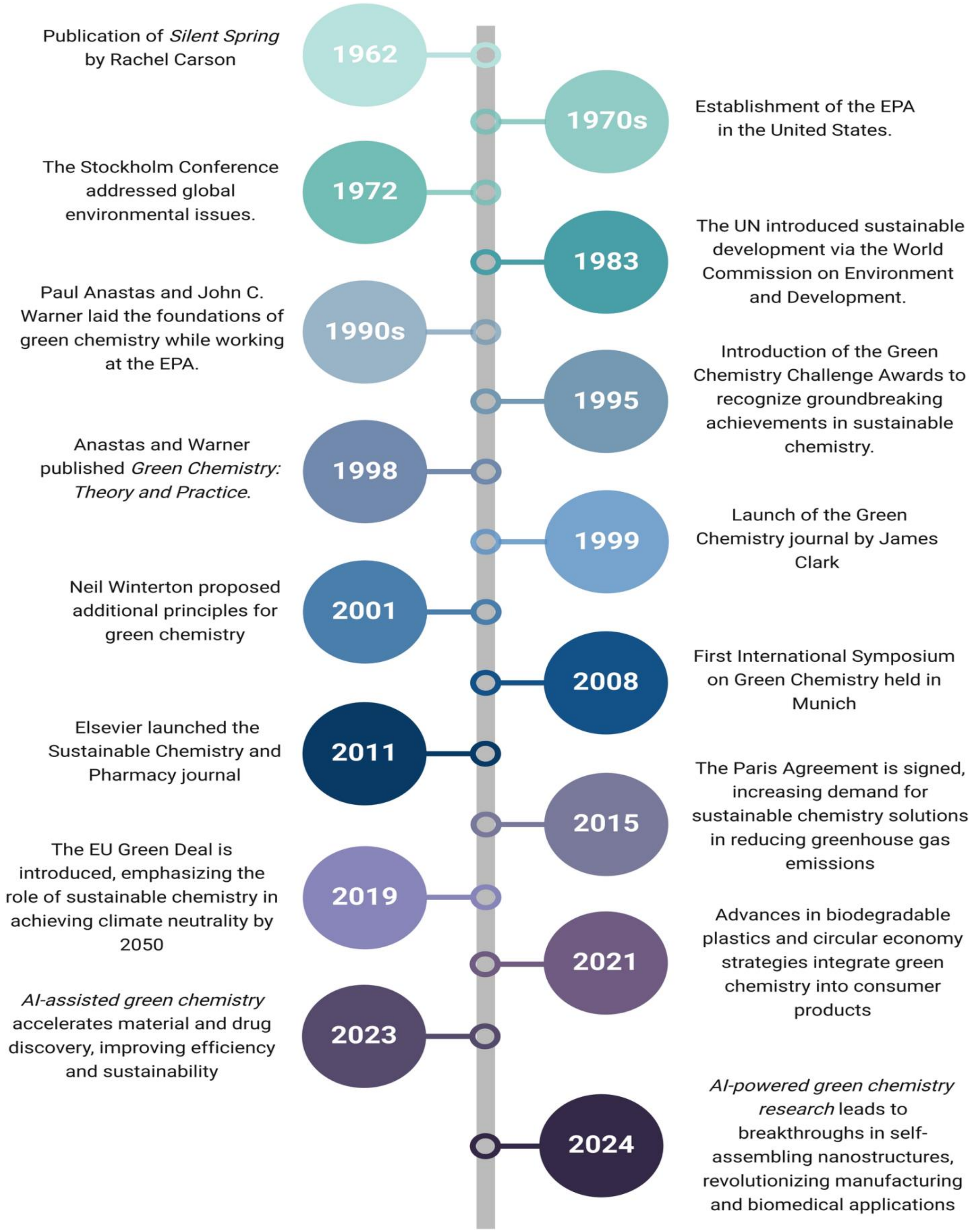

Fig 2: Historical Development of Green Chemistry

Green chemistry emerged from a variety of existing ideas and research efforts in the period leading up to the 1990s, in the context of increasing attention to problems of chemical pollution and resource depletion. Idea of green chemistry was initially developed as a response to the Pollution Prevention Act of 1990.

Green chemistry is an approach developed to minimize the environmental impacts of chemical production and use. The environmental movement was initiated in 1962 with the publication of Rachel Carson's book Silent Spring, which highlighted the adverse effects of chemicals on the environment [5]. In the 1970 s, the establishment of the Environmental Protection Agency (EPA) in the United States marked a significant step toward environmental protection [6]. The 1972 Stockholm Conference addressed global environmental issues and environmental law, and it was followed by the establishment of the World Commission on Environment and Development by the United Nations in 1983, introducing the concept of sustainable development. Figure presents a timeline illustrating key milestones in the development of green chemistry.

Global Recognition of Green Chemistry

Australia: The Royal Australian Chemical Institute (RACI) presents Australia's Green Chemistry Challenge Awards; Canada: The Canadian Green Chemistry Medal is an annual award given to any individual or group for promotion and development of green chemistry;

Italy: Green Chemistry activities in Italy centre on inter- university consortium known as INCA. In 1999, INCA has given three awards annually to industry for applications of green chemistry;

Japan: In Japan, The Green & Sustainable Chemistry Network (GSCN), formed in 1999, is an organization consisting of representatives from chemical manufacturers and researcher;

UK: In the United Kingdom, the Crystal Faraday Partnership, a non-profit group founded in 2001, awards businesses annually for incorporation of green chemistry;

USA: United States Environmental Protection Agency (EPA); Nobel Prize: The Nobel Prize Committee recognized the importance of green chemistry in 2005 by awarding Yves Chauvin, Robert H. Grubbs, and Richard R. Schrock the Nobel Global Recognition of Green Chemistry

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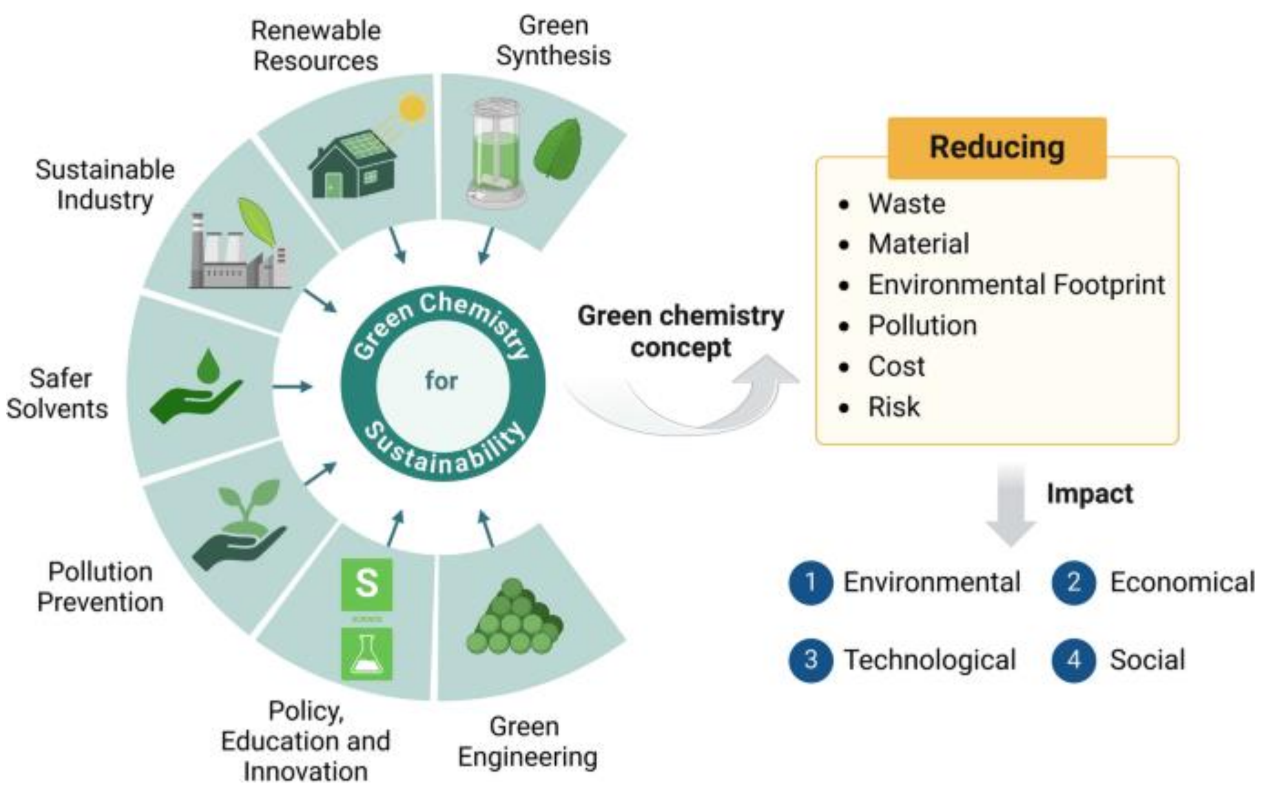
Global recognition countries of green chemistry-

- **United States**: The concept of "green chemistry" originated in the US in the early 1990s, driven by the Environmental Protection Agency (EPA). The US government established the prestigious Presidential Green Chemistry Challenge Awards in 1996, and the non-profit Green Chemistry Institute (GCI) later became part of the American Chemical Society (ACS).
- **China**: China has shown consistent growth in high-quality chemistry research and leads globally in the number of green chemistry studies published. It is also the world's largest chemical producer and exporter.
- **India**: India ranks highly in both research output and market size for green chemistry. Indian

researchers contribute significantly to the global body of knowledge and are frequent recipients of international awards.

- **Germany**: A major developed country with a strong focus on sustainable chemistry and significant R&D investment. Germany scores high in environmental performance indexes and works on industry-academia partnerships to advance the field.
- **United Kingdom**: Home to the Royal Society of Chemistry's influential journal Green Chemistry and the Green Chemistry Network, the UK is a prominent hub for research and education in the field.
- **Japan**: Japan has an established Green and Sustainable Chemistry Network (GSCN) and is a top producer of chemicals with high R&D spending.
- **Italy and Spain**: Both countries have strong academic and industrial roots in green chemistry, with early pioneers and national networks established in the early 2000s.
- **Denmark, Sweden, and other Nordic countries**: These nations are consistently top-ranked in overall environmental consciousness and sustainability, operating programs to promote the replacement of hazardous chemicals and low-carbon energy sources.



Scope

This focus area involves designing and implementing a novel, green pathway to produce a new or existing chemical substance. Chemistry plays an important and useful role towards the development and growth of a number of industries. Green Chemistry provides a unique forum for the publication of innovative research on the development of alternative green and sustainable technologies. Green Chemistry is at the frontiers of this continuously-evolving interdisciplinary science and publishes research that attempts to reduce the environmental impact of the chemical enterprise by developing a technology base that is inherently non-toxic to living things and the environment. Submissions on all aspects of research relating to the endeavour are welcome.

Need of Green chemistry

- **Pollution Prevention:** It focuses on designing chemical products and processes that reduce or eliminate hazardous substances, stopping pollution before it starts.
- **Health & Safety:** It creates safer workplaces and consumer products by minimizing exposure to toxic chemicals, reducing risks of accidents, fires, and explosions.
- **Resource Conservation:** It promotes using renewable feedstocks (like plants) and reduces reliance on finite resources, conserving energy and raw materials.
- **Waste Reduction:** It aims to minimize by-products and waste, cutting down on expensive disposal and remediation costs, moving towards a circular economy.
- **Economic Benefits:** Less waste, higher efficiency (fewer steps), and reduced costs for disposal and safety measures make green processes more economical.
- **Sustainable Innovation:** It drives the development of new technologies like better solar cells, fuel cells, batteries, and biodegradable materials.
- **Environmental Impact:** It reduces the environmental footprint across industries, from pharmaceuticals and textiles to agriculture and energy, fostering sustainability.

Principal of Green chemistry

The principles of green chemistry speak about the reduction or removal of dangerous or harmful substances from the synthesis. Green chemistry is basically a proactive approach aimed at designing asynthesis/process in a sustainable way right from the beginning. synthesis/process in a sustainable way right from the beginning.

- **Less hazard-** Synthetic methods should, where practicable, use or generate materials of low human toxicity and environmental impact.
- **Safer chemicals**- Chemical product design should preserve efficacy whilst reducing toxicity.
- **Safer solvents-** Avoid auxiliary materials – solvents, extractants – if possible, or otherwise make them innocuous.
- **Energy efficiency-** Energy requirements should be minimized: conduct synthesis at ambient temperature and pressure.
- **Renewable feedstocks-** Raw materials should, where practicable, be renewable.
- **Reduce derivatives-** Unnecessary derivatization should be avoided where possible.
- **Smart catalysis-** Selectively catalyzed processes are superior to stoichiometric processes.
- **Degradable design-** Chemical products should be designed to be degradable to innocuous products when disposed of and not be environmentally persistent.
- **Waste prevention-** Avoiding the creation of garbage products is always better than cleaning up waste after it has been formed.
- **Atom economy-** The synthetic procedures and methods used in green chemistry must always strive to optimize the consumption and incorporation of all raw materials into the end product. Design synthetic methods to maximize incorporation of all material used into final product.
- **Incorporation of safe chemistry for accident prevention-** When building chemical processes, it is critical to ensure that the compounds employed in the processes are safe to use.
- **Avoiding the production of hazardous chemicals-** reactions and processes that entail the synthesis of certain toxic compounds that are detrimental to human health must be optimized to avoid the

production of such substances.

- **Real-time analysis for pollution prevention-** Monitor processes in real time to avoid excursions Waste prevention: Avoiding the creation of garbage products is always better than cleaning up waste after it has been formed. eading to the formation of hazardous materials.
- **Hazard and accident prevention-** Materials used in a chemical process should be chosen to minimize hazard and risk for chemical accidents, such as releases, explosions, and fires.
- **Designing chemicals for degradation-** When developing a chemical product to perform a certain purpose, attention must be given throughout the design process to ensure that the chemical is not an environmental contaminant.

Fig 3: Principles of Green Chemistry

Relationships between green chemistry, sustainable chemistry, and circular chemistry

Green chemistry, sustainable chemistry, and circular chemistry are three approaches that share the common goal of reducing the environmental impact of chemical production and consumption processes .Green chemistry aims to minimize the use and production of hazardous chemicals by employing innovative approaches in the design and implementation of chemical processes. It focuses on reducing harm through process innovation and safer chemical designs. Sustainable chemistry, on the other hand, represents a broader approach that emphasizes environmental, economic, and social sustainability. Circular chemistry adopts a more efficient and cyclic approach throughout the lifecycle of products and materials—from design to use and recycling—to reduce waste and pollution. Circular chemistry challenges the traditional linear"take-make-use-dispose"economy, which typically generates"waste"as human-made materials discarded into the environment. According to the Law of Conservation of Matter, matter cannot be created or destroyed; therefore, the option of"disposal"is not feasible within a long-term system. Consequently, all forms of human-generated waste to contribute a range of environmental crises on a rapidly evolving planetary scale. The growing global concern over human-induced climate change and other planetary boundaries has become the driving force behind the transition from a traditional linear material flow ("take-make-use-dispose") to a circular economy [8].

Industrial Applications

- **Pharmaceuticals:** More efficient synthesis routes, reduced waste, biodegradable drugs, and safer processes using catalysts and green solvents.
- **Energy:** Manufacturing solar cells, fuel cells, and batteries using earth-abundant materials and eco-friendly processes.
- **Textiles:** Developing eco-friendly dyes, reducing water usage, and sustainable finishing processes to minimize toxic runoff.
- **Polymers & Materials:** Replacing hazardous blowing agents (like CFCs) with supercritical for foams; using bio-based feedstocks.
- **Agriculture:** Creating safer, biodegradable pesticides and fertilizers that are toxic only to pests and degrade rapidly.
- **Paints & Coatings:** Using water-based or bio-based solvents instead of volatile organic compounds (VOCs).
- **Chemical Manufacturing:** Catalysis for higher efficiency (e.g., enzyme catalysts), microwave synthesis, and continuous flow reactors to reduce energy and waste.

Future Prospects of Green Chemistry

1. **Green Nanotechnology**

Green Nanotechnology is an emerging innovation of the 21st century and has sparked global interest. It dramatically reduces waste generation and applies effective recycling methods for nanoproducts. Recycled carbon nanotubes have low metal content and are used for energy storage, electronics, and additives. Pharmaceutical startups are developing smart barrier nanocoatings for food packaging without altering biodegradability.

Metal-organic framework (MOF) crystals, carbon fiber reinforced polymers (CFRP), and nano-ceramics are finding different use cases in the automotive and aerospace industries. Biotech startups use polymer and organic nanocomposites for regenerative medicine, drug delivery, tissue engineering, and cellular therapies.

2. **Biometric Multifunctional Reagents**

Biometric multifunctional reagents are designed to perform multiple functions in a single molecule, enabling improved efficiency, safety, and sustainability in various industries.

Some of the recent innovations in biometric multifunctional reagents include:

- Stimulus-responsive polymers: They change their properties in response to environmental stimuli, such as temperature, pH, or light. These polymers are used for drug delivery, sensing, and imaging.
- Bio-based reagents: Bio-based reagents are made from renewable resources, such as biomass or agricultural waste. They offer a more sustainable alternative to traditional chemicals and can help reduce carbon emissions and dependence on fossil fuels.
- Nanoparticle-based reagents: Nanoparticle-based reagents target specific cells or tissues, enabling targeted drug delivery and diagnostics.
- Supramolecular chemistry: Supramolecular chemistry uses molecular recognition and self-assembly to create complex structures and functions. It is developing sophisticated biometric multifunctional reagents with enhanced properties.
- DNA-based reagents: DNA-based reagents use DNA as a building material to create complex structures and functions. Their use cases are applied to drug delivery, gene therapy, and biosensing.

- Advanced synthesis methods: Advanced synthesis methods, such as 3D printing and microfluidics, proactively reduce waste, energy consumption, and environmental impact.

3. Combinatorial Green Chemistry

Combinatorial green chemistry is expected to increasingly use artificial intelligence and machine learning to optimize and accelerate the discovery of new sustainable chemical processes. It addresses concerns about climate change and environmental emissions.

In the coming years, it will be integrated with various fields, such as materials science, biotechnology, and environmental science. Combinatorial green chemistry allows for the synthesis of compounds at the same time. The pharmaceutical industry makes libraries, finds active compounds, and reduces the time and costs of producing competitive new drugs.

4. Oxidation Reagents and Catalysts

Future innovations in oxidation reagents and catalysts for green chemistry are expected to play a crucial role in reducing the environmental impact of chemical processes. Here are some potential trends in this field:

- Nature's enzymes inspire biomimetic catalysts and can mimic their structure and function. These catalysts can provide high selectivity, specificity, and stability, making them ideal for various oxidation reactions in green chemistry.
- AI can help researchers predict and design optimal catalysts with specific properties, leading to more efficient and sustainable oxidation reactions.
- Enzymes are highly efficient biological catalysts that can inspire the design of new oxidation catalysts. Researchers may explore mimicking enzymatic structures and functions to create more efficient and selective oxidation catalysts.
- Solar-driven catalysts can harness solar energy to drive chemical reactions, reducing the need for external energy sources.
- Self-healing catalysts can regenerate or repair themselves during or after a reaction, ensuring their activity and stability over extended periods. This feature can minimize the need for catalyst replacement, reducing waste and costs.
- Single-site catalysts are designed to maximize the efficiency of catalytic reactions by minimizing the number of active sites. These catalysts will enhance the stability and selectivity of oxidation reactions.

Conclusion

The future of green chemistry looks promising, with many exciting developments on the horizon. Advancements in bio-based building blocks, digitalization, and personalized medicine are driving innovations in this segment. Specialty chemicals play a crucial role in developing advanced materials, and the future will witness an integration of Industry 4.0 applications with automation and manufacturing processes.

There may be an increased demand for bio-based specialty chemicals and cross-industry partnerships for emerging markets to foster further innovation. Developing sustainable product life cycles through implementing circular economy initiatives by specialty chemical companies is also expected to gain precedence.

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

There can be economic challenges, such as the cost of implementing new technology in the first place and regulatory overhead that can hinder growth, especially for small to medium-sized enterprises. Moreover, much new progress must be made in developing new catalytic processes and sustainable synthesis methods if the promises of green chemistry are not to be empty. In a broader sense, all stakeholders i.e. policy makers, industries and researchers need to be on the same page and work together to develop a platform through which green chemistry can grow rapidly. We cannot solve all the economic, regulatory and technical challenges, but by promoting the further integration of green chemistry with circular economy principles we hope to create processes that benefit society as a whole and create a cleaner environment.

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