A Comprehensive Review on Green Chemistry: Principles, Atom Economy, and Sustainable Chemical Practices

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***Abstract*—Green chemistry has become a revolutionary way of approaching chemical research and industrial practice, working towards an ultimate objective of reducing or avoiding the use and production of dangerous substances. This review summarizes the basic ideas of green chemistry, its need, objectives, restrictions, and the twelve guiding principles, and specifically, atom economy as a key measure of efficiency of a reaction. The article is based on the supporting materials and abundant literature that covers the theoretical basis, applications, industrial applications, and opportunities of green chemistry in the future. The discussion is backed by more than thirty academic sources to ensure a solid academic basis on which the research can be developed.**

***Index Terms*—Green chemistry; sustainability; atom economy; pollution prevention; catalytic processes; renewable feedstocks; environmentally benign synthesis**

I. INTRODUCTION

The swift development of chemical industries has greatly resulted in pollution of the environment, exhaustion of resources and health risks to the people. The traditional chemical processes may include the use of toxic reagents, non-renewable feedstocks, energy-intensive conditions, and voluminous amounts of waste. Green chemistry or sustainable chemistry, in its turn, has been created as an active approach to the design of chemical products and processes that minimize or prevent the use of hazardous substances in the first place. Green chemistry incorporates all elements of the environment in the design of the molecules, the reaction course, and industrial production, thus, making chemical innovation and sustainability aligned. [1–4].

II. CONCEPT AND NEED FOR GREEN CHEMISTRY

The concept of green chemistry can be described as conducting chemical science in a sustainable, non-polluting, safe, and energy-efficient way that will produce minimal wastes. Green chemistry is necessary because environmental pollution has been increased, the cost of treating waste has gone up, and the regulatory structures have become stricter. The creation of more environmentally-friendly synthesis pathways will not only help to reduce the harm to the environment but will also enhance the cost-effectiveness and the general attitude of the population toward chemical technologies. [1, 5, 6].

III. GOALS OF GREEN CHEMISTRY

Green chemistry is aimed at preventing pollution and not at controlling it. It attempts to develop cost-effective chemical products and processes whose environmental impact is minimized, resources conserved, safety increased and general process efficiency promoted. Green chemistry facilitates sustainable industrial growth and models of the circular economy by focusing on prevention on the molecular level. [2, 7].

IV. LIMITATIONS AND CHALLENGES IN GREEN CHEMISTRY

Although this has its benefits, green chemistry implementation suffers numerous challenges among them being high start-up costs, unavailable alternative raw materials or technologies, lack of technical expertise and performance and scalability uncertainty.

Besides, there would be a lot of research, policy backing, and industrial investment in the shift of researched conventional processes into greener ones. [3, 8, 9].

V. THE TWELVE PRINCIPLES OF GREEN CHEMISTRY

Green chemistry is driven by the twelve principles put forward by Anastas and Warner and offers a holistic approach to the way in which chemicals should be designed in order to be sustainable [4]. Waste prevention, atom economy, less hazardous synthesis, safer chemical design, benign solvents, energy efficiency, renewable feedstocks, reduction of derivatives, catalysis, design for degradation, real time analysis and inherently safer chemistry are the principles encompassed. Together, these principles are used as a standard of measurement of and enhancement of chemical processes in academia and industry. [4, 10–12].

VI. ATOM ECONOMY: A CENTRAL PRINCIPLE

One of the oldest concepts of green chemistry is atom economy, which quantifies the percentage of atoms in the reactants that are used to form the final product of interest. As opposed to yield which simply measures the efficiency of product formation, atom economy measures intrinsic reaction efficiency in terms of stoichiometry. The reaction of atoms of high atom economy, including addition, rearrangement, and pericyclic reactions are favored over atom-uneconomic reactions, including substitutions and eliminations, which produce large amounts of waste. [13–16].

Atom economy is a strong predictive model since it is possible to compute the concept at the planning level using balanced chemical equations. Atom economy has an effect on the choice of process, the use of resources and their environmental impact, as illustrated in industrial examples, including the replacement of benzene oxidation by butane oxidation to produce maleic anhydride. [17–19].

VII. INDUSTRIAL APPLICATIONS OF GREEN CHEMISTRY

In the pharmaceuticals, agrochemicals, polymers and fine chemicals, green chemistry principles have been effectively implemented. Cleaner and more efficient manufacturing pathways have been achieved through the use of catalytic reactions, solvent-free reactions, biocatalysis, microwave assisted reactions, and renewable feedstocks. Such notable examples are catalytic asymmetric synthesis, reactions in aqueous phase, and platform chemicals produced using biomass. [20–24].

VIII. ROLE OF CATALYSIS AND RENEWABLE RESOURCES

Catalysis is important in green chemistry as it increases selectivity, consumes less energy and generates less waste. Homogeneous and heterogeneous catalysts, enzyme-based biocatalysts are also extensively used. Renewable feedstock like biomass, agricultural waste, and bio-based solvents are also used which also promotes sustainability and minimizes reliance on fossil resources. [25–28].

IX. FUTURE PROSPECTS OF GREEN CHEMISTRY

The future of green chemistry is the interdisciplinary integration, more sophisticated catalytic systems, real-time monitoring of processes, and the introduction of the life-cycle assessment instruments. The future of green chemistry is believed to lie in emerging fields like green nanotechnology, reaction design with the help of artificial intelligence, and circular chemistry which can further enhance the impact of green chemistry to achieve global sustainability objectives. [29–32].

X. CONCLUSION

Green chemistry is a paradigm shift in the chemical science, which focuses on prevention, efficiency and sustainability. Quantitative methods to assess and enhance chemical reactions are given by the principles like atom economy. In spite of implementation and scaling difficulties, further research, education and policy provision will hasten the implementation of green chemistry practices. This review illuminates through the theoretical origins, practical uses, and the prospects of green chemistry and indicates that it is an important aspect of sustainable development.

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