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Progress in Green Chemistry: Sustainable Approaches in Organic Synthesis

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ABSTRACT
In order to create ecologically friendly procedures, guidelines, and synthetic techniques that support "global sustainability, chemists, chemists, medicinal chemists, and chemical engineers" may build upon the principles of green (sustainable) chemistry. One of the main tenets of green chemistry, catalysis, is essential for reducing environmental damage. A systemic transformation of the chemical industry is essential to achieve sustainability, with digitalization emerging as a key enabler by enhancing data accessibility and fostering innovation in chemistry and materials R&D. Advances in green organic synthesis, including the use of green solvents, recyclable catalysts, solvent-free reactions, and energy-efficient techniques such as microwave and ultrasonic-assisted approaches, offer eco-friendly alternatives to traditional methods. However, the chemical industry and academic research still predominantly rely on hazardous catalysts and solvents. The adoption of sustainable methodologies is imperative to reduce environmental harm and drive the transition toward greener, safer, and more efficient chemical processes.
Keywords: Green (sustainable) chemistry, Organic synthesis, Ultrasonic-assisted, Microwave, energy-efficient techniques, Digital technologies, etc.

I. INTRODUCTION

Previously, nature provided for all of society's material needs. Contemporary civilisation has benefited greatly from the advancements in modern chemistry, which have allowed us to change our natural resources and generate new matter from old, so dramatically raising our way of existence [1]. From the brightly coloured clothing we wear to the constantly improving electronic gadgets we play with, from the synthetic fertilisers that boost crop production to fulfil global demands to the ever-increasing speed of transportation and the ever-increasing number of skyscrapers, the heroic creativity, inventiveness, and imagination of chemists have touched every aspect of our daily lives [2]. One use of chemistry is "green chemistry," which aims to reduce environmental pollution. Chemical product and process development that does not harm the environment is more precisely what this refers to. Green chemistry encompasses all aspects and types of chemical reactions that reduce hazards to the environment and human health. At its best, green chemistry is environmentally benign and connects the design of chemical products and processes with their impacts on the environment and public health [3], [4].

A. Green chemistry

"Green chemistry" refers to the design of chemical procedures and goods that use fewer or no hazardous substances. Green chemistry covers the whole life cycle of a chemical product, including its design, manufacture, use, and final disposal [5]. The 1990s saw the rise of green chemistry, a novel method that calls for chemical synthesis to produce less waste, use less energy, and be safer for both the environment and workers. Notable efforts and breakthroughs included the 1993 report on "Chemistry for a Clean World" by the European Community's Chemistry Council and the 1994 conferences in Chicago, USA, that examined the possibilities of the "Benign by Design" idea for chemical processes. The European Commission then issued a regulation in 1996 that set out principles addressing a more integrated perspective inside the EU. In broad strokes, these principles dealt with things like making good use of energy, using the best methods currently available, and avoiding or at least mitigating the worst effects of accidents [6], [7].

"The U.S. Pollution Prevention Act of 1990" provided GC with yet another crucial foundation for consolidating. Anastas and Warner (1998) defined green chemistry as the application of a set of rules that reduces or eliminates the use or manufacturing of hazardous compounds in the design, manufacture, and use of chemical products. Based on some previous recommendations made by the European Union, the US Environmental Protection Agency, "the Organisation for Economic Co-operation and Development (OECD)", and others, they put forth 12 principles that aim to create safer products, cleaner processes, and a greater use of renewable resources as opposed to fossil fuels (Tables 1) [8].

Table 1 The 12 Principles of green chemistry [8]

S. No.	Principles of green chemistry
1	**Prevention:** Waste prevention is preferable than waste treatment or cleanup after it has been produced.
2	**Atom economy:** All materials employed in the process should be maximised in the end result via the creation of synthetic procedures.
3	**Less hazardous chemical syntheses:** Materials that are harmful to humans or the environment should not be used or produced via synthetic procedures unless absolutely necessary.
4	**Designing safer chemicals:** The design of chemical goods should minimise toxicity while influencing the intended purpose.
5	**Safer solvents and auxiliaries:** Solvents, separating agents, and other auxiliary substances should be used sparingly and avoided if possible.
6	**Design for energy efficiency:** Energy consumption in chemical processes should be as low as feasible because of their impact on the economy and environment. It is excellent to perform synthetic treatments under room pressure and temperature.
7	**Use of renewable feedstocks:** A raw material or feedstock should always be renewable instead of diminishing, if this is both technically and economically feasible.
8	**Reduce derivatives:** Derivatisation should be minimised or avoided since it may lead to waste and need more reagents. This includes blocking group use, protection/deprotection, and transitory physical/chemical process changes.
9	**Catalysis:** Stoichiometric reagents are inferior to selective catalytic reagents.
10	**Design for degradation:** When their useful life are up, chemical compounds should be designed to break down into innocuous degradation products rather than remaining in the environment.
11	**Real-time analysis for pollution prevention:** For in-process, constant control and monitoring to be possible before hazardous compounds appear, further advancements in analytical methods are needed.
12	**Inherently safer chemistry for accident prevention:** When using compounds and their forms in a chemical process, care should be taken to minimise the possibility of chemical accidents such leaks, explosions, and fires.

B. Automation and digital technologies in green chemistry

With the goal of minimising the environmental impact of chemical processes, green chemistry is increasingly relying on automation and digital technologies. Here are a few examples of how digital technology and automation are used in green chemistry [3].

- **Digitalisation:** Digitalisation is transforming the chemical industry by enabling the integration of sustainability and conventional chemistry. In addition to reducing resource and energy consumption, it is being used to accelerate the attainment of sustainability goals. Additionally, digital data on production and emission control is being gathered, which may help companies reduce their environmental effect.
- **Automated and robotic flow:** The digitalisation of chemical synthesis via automated and robotic flow has the potential to reduce waste and boost efficiency. In this technology, algorithms are utilised to search for chemical interactions, and flow platforms are used to link hardware and digital chemicals.
- **Nature-inspired technologies:** Utilising technology inspired by nature, new eco-friendly chemicals and materials are being created. These technologies are based on the principles of green chemistry, which highlight the production of naturally safer and less hazardous molecules, the use of alternative feedstocks, and environmentally friendly reaction conditions.

Green chemistry employs automation and digital technologies to lessen the negative effects of chemical processes on the environment. Digitalisation is being utilised to combine conventional chemistry with sustainability, while automated and robotic flow is being used to digitise chemical synthesis. Nature-inspired technology is being used to develop environmentally beneficial compounds [9].

II. LITERATURE REVIEW

(Fantke et al., 2021)[10] A fundamental shift in the design, development, and use of chemistry is necessary to move towards a sustainable future. To promote sustainable chemistry, we suggest that more and faster use of digitalisation and new digital technologies may lead to the critically needed systemic reforms in the "chemical industry, research and development (R&D), chemicals evaluation and management, and education". This will reduce obstacles to entry into chemical R&D and manufacturing, enable flexible data interchange, increase transparency of information flows throughout "national chemical, material, and product life cycles", create safe and sustainable chemicals by design, address the complex interactions among chemicals, the environment, and human health, and create new, more sustainable, and collaborative business models.

(Mishra et al., 2021)[11] Today, green chemistry goes beyond lab curiosity to industrial medicinal applications. However, being one of the most dynamic areas, industries usually lead major developments. The potential industrial uses of novel ideas, conventional feed stocks, less hazardous raw materials, and alternative methods tested in pilot-scale laboratories are exciting. This article presents a selected overview of green synthesis in pharmaceutical firms that have effectively used green chemistry principles. The review shows green drug synthesis methods based on the optimum yield, solvent selection, biocatalysts, and regioselectivity of various large-scale pharmaceutical goods. Green chemistry integration in the pharmaceutical industry is reviewed, along with its problems and solutions.

(Dandia et al., 2020)[12] Due to solar energy's cleanliness, affordability, limitlessness, and abundance, photoredox catalysis—which produces chemical energy from sunlight or solar energy—is a rapidly expanding and promising method of initiating chemical processes. Numerous nanoparticles, organic dyes, and transition metal-based photocatalysts catalyse photocatalytic organic reactions via electron-hole transfer for a variety of crucial chemical changes. Because of its "structural adjustability and fascinating convenient physicochemical properties," semiconductor perovskite-type catalytic materials have made great strides in organic synthesis photocatalysis. Research into the photoredox catalytic properties of perovskite-type catalytic materials has focused on them as potential substitutes for noble metals. Among the most recent developments in heterogeneous photocatalytic organic processes, photoredox catalysis using perovskites as photocatalysts has been the subject of intense study since

2017. In the last five years, perovskite-type heterogeneous photocatalysts have been used to perform "C–H activation, redox reaction, bond forming, coupling, bond cleavage, dehydrogenation, and ring–opening reactions".

(Kurniawan et al., 2020) [6] The authors stated that we face major challenges in our lives as a result of environmental degradation and global warming. Since the need for everyday appliances has grown over the years, the sectors that rely on organic chemicals have responded by expanding their manufacturing methods. As a result, the degradation of the environment is becoming worse. As a result, green chemistry was developed to encourage the chemical industry to work towards greater environmental sustainability. Since many researchers have focused on organic chemistry during the past 20 years, the area has had to be impacted by green chemistry concepts. Thus far, the synthesis process of organic molecules has been examined in terms of waste reduction, the use of renewable feedstocks, safer solvents, and high energy efficiency design. This paper provides a thorough and concise overview of the application of green chemistry concepts and how they are used in the synthesis of organic molecules.

(Kharissova et al., 2019) [2] New materials and well-known chemical compounds have been synthesised using greener methods. Aerogels, quantum dots, oxides and salts of metals and non-metals, and nanoparticles of these materials may all be synthesised using less harmful processes. Cement, ceramics, adsorbents, polymers, bioplastics, and biocomposites may also be cleaned. Greener synthesis incorporates non-contaminating physical procedures such microwave heating, ultrasound-assisted and hydrothermal processes, ball milling, and natural precursors. Solventless and biosynthetic approaches are also important. Also covered in materials manufacturing are non-hazardous solvents including ionic liquids, plant extracts, fungus, yeasts, bacteria, and viruses. Scaling green processes is considered for availability, need, and economics.

(A´.Dıaz-Ortiz et al., 2018)[13] The interaction of electromagnetic radiation with matter remains unknown despite the remarkable achievement of "microwave-assisted organic synthesis (MAOS)". Therefore, it has been very difficult to describe the chemical effects of microwave radiation, to determine if microwaves have thermal or non-thermal effects, and to develop models of prediction for the characteristics that would improve a process when microwaves are added. This has caused several disputes and hindered the development of novel chemistry when exposed to microwave radiation. The authors summarized their work on the use of computational chemistry to develop predictive models and determine parameters related to thermal and non-thermal effects, together with some recent research in the field, which has clear advantages over experimental methods where it is nearly challenging to separate these effects.

(Varma, 2016)[14] Coupling, the formation of heterocyclic compounds, and many other particular reactions that are aided by basic water or reusable magnetic nanocatalysts are examples of organic synthesis. The biomimetic methods of producing nanoparticles are advantageous because they use "vitamins, sugars, and plant" polyphenols—including residues from agricultural waste—as capping and reducing agents. The immobilisation of "metal nanocatalysts (Pd, Au, Ag, Ni, Ru, Ce, Cu, etc.)" on recyclable magnetic ferrites via ligands like glutathione or dopamine, or on biodegradable supports like cellulose and chitosan, is attracting particular interest. The goal of these strategic methods is to produce useful chemicals with the least amount of waste possible while addressing the majority of the Green Chemistry Principles.

(Deligeorgiev et al., 2010)[5] The development of the concepts of Green Chemistry and the core principles of this field are explored. Examples of the applications of these ideas may be found in several areas of chemistry. "Water, polyethylene glycol, perfluorinated solvents, and supercritical liquids" are some of the most used alternative solvents (green solvents) in the field of preparative organic chemistry.

All of the recent and planned developments in organic chemistry education and technology are considered within the context of green chemistry.

III. CONCLUSION

From the various literature's study concluded that the transformation of the chemical industry towards sustainability requires a systemic shift, with digitalization playing a crucial role in this evolution. By integrating digital tools into chemistry and materials R&D, data accessibility and knowledge interlinkage can be enhanced, making the field more inclusive and accelerating innovation. Organic chemistry with a focus on sustainability provides hope for a more sustainable future via the use of renewable resources and innovative methods such as microwave and ultrasonic-assisted synthesis, solvent-free reactions, recyclable catalysts, and green solvents. Despite advancements, dangerous catalysts and solvents are still widely used in both academic and corporate research. The promise of sustainable methods is shown by recent developments, such as the green synthesis of fluoroquinolone compounds employing microwave irradiation and eco-friendly catalysts. Our contribution, based on computational calculations, provides valuable insights into reaction mechanisms that are difficult to determine experimentally. Key factors such as molecular polarity, selective heating, activation energy, and enthalpy have been analyzed to understand their impact on thermal effects in green synthesis. These findings reinforce the necessity of computational approaches in optimizing green chemistry, ultimately contributing to safer, more efficient, and sustainable organic synthesis processes.

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