

Role of Green Chemistry in Environmental Conservation and Sustainable Development

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www.jrasb.com || Vol. 4 No. 3 (2025): June Issue

Received: 16-06-2025

Revised: 21-06-2025

Accepted: 26-06-2025

ABSTRACT

Green chemistry has become a vital strategy for encouraging sustainable development and lowering environmental pollution. It focuses on creating chemical processes and products that reduce the production and use of dangerous materials. The fundamentals of green chemistry are examined in this study, along with its application to sustainable development and environmental preservation. It also emphasizes important uses of green chemistry in resource management, waste reduction, energy production, and industry. According to the study's findings, implementing green chemistry techniques can greatly lessen environmental deterioration while promoting social progress and economic expansion. Although rapid industrialization and technical advancement have greatly raised human living standards, they have also led to major environmental issues like pollution, climate change, and resource depletion. Conventional chemical processes frequently use hazardous materials and produce toxic byproducts that endanger human health and ecosystems. To address these problems, green chemistry was invented. It is described as the development of chemical goods and procedures that minimize or completely do away with the production and use of dangerous materials. Paul Anastas and John Warner popularized the idea of "green chemistry" by putting forth twelve guiding principles for the creation of safer and more environmentally friendly chemical processes. Instead than managing garbage after it has been produced, these concepts seek to prevent pollution at the source. Because green chemistry incorporates social welfare, economic progress, and environmental conservation, it is strongly related to sustainable development.

Keywords- Green chemistry, hazardous materials, sustainable, photocatalytic processes, auxiliary materials, Ibuprofen.

I. INTRODUCTION

In industrialized regions of the world, rapid advancements in science and technology during the second half of the 20th century have significantly boosted economic growth and raised living standards. However, significant environmental deterioration has also resulted from such economic expansion, as seen by the formation of ozone holes, more noticeable climate change, and the buildup of non-destructive organic contaminants throughout the biosphere. Finding a way to balance the use of natural resources, economic expansion, and environmental preservation was necessary given the current circumstances. The necessity for environmental preservation has grown as a result of these observations during the past 20 years, and as a

result, "green and viable technologies" have received a lot of attention. While the chemical community is focused on creating new compounds and methods that are less hazardous to human health and the environment through green chemistry, the new laws and regulations seek to protect the ecosystem from hazardous chemicals. The term "green" or "sustainable" chemistry refers to the development of chemical processes and products that minimize or completely do away with the usage of hazardous materials. Reducing or eliminating the use of hazardous materials in chemical processes as well as lowering hazardous and toxic intermediates and products are key components of this emerging area of chemistry with ecological techniques. For a reaction to be considered "green," it must contain three green elements: energy consumption, reagent/catalyst, and solvent.

Green chemistry is founded on twelve principles that can be utilized to produce or replicate molecules, materials, reactions, and processes that are safer for the environment and human health. To far, green chemistry procedures have been developed in almost every area of chemistry, including Biochemical, polymeric, organic, inorganic, toxicological, environmental, physical, technical, etc. Green chemistry is also interested in developing the process of chemical product degradation after use and the most efficient way to dispose of waste, all in line with sustainable development and pollution control strategies [1]. A number of prominent approaches, including catalysis, biocatalysis, the use of alternative renewable raw materials (biomass), alternative reaction media (water, ionic liquids, supercritical fluids), alternative reaction conditions (microwave activation, mechanochemistry, and ultrasound), and novel photocatalytic reactions, are used to accomplish the goals of green chemistry in terms of environmental protection and financial gain [2, 3]. In addition to demonstrating how green chemistry lessens the environmental impact of chemical processes and technology through examples and prevailing trends, this study seeks to advance knowledge of the concepts and procedures that underpin green chemistry.

II. GREEN CHEMISTRY

Chlorophyll and the dollar are both coloured green. Being green has become a fad in product marketing, and it is a battleground for environmental activists. Additionally, it becomes crucial for chemists to use green chemistry concepts in all facets of the chemical sciences, including manufacturing, teaching, and fundamental and applied research. [4].

III. DEFINITION OF GREEN CHEMISTRY

Green chemistry is defined by the EPA as a branch of chemistry that creates environmentally safe chemical processes and products, hence preventing pollution. Chemical products should be manufactured so that, upon completion of their use, they are broken down into environmentally safe components and do not linger in the environment. Even at the laboratory level, savings based on effective synthesis without the use of "exotic" chemicals, lowering energy requirements, and substituting organic solvents with water could result in millions of savings on an industrial scale [5]. Green chemistry is an ethical multidisciplinary approach to science founded on chemical, ecological, and social responsibility that fosters innovation and the development of cutting-edge research rather than a distinct scientific field [6]. Finding and maintaining a balance between the use of natural resources, economic expansion and preservation of the environment.

IV. TRENDS IN GREEN CHEMISTRY

The "program for the design, development, and application of chemical products and processes that reduce or eliminate the use or production of substances that are hazardous to human health and the environment" is known as "green chemistry," and its primary objectives are achieved through a number of prevailing trends [2]:

- research on catalytic and biocatalytic reactions to produce pure, highly selective chemicals without producing hazardous byproducts;
- Looking for new, safe, sustainable raw materials, like biomass
- creating environmentally friendly, less hazardous compounds;
- Identifying and evaluating novel, renewable, non-toxic reaction media, such as water, ionic liquids, and supercritical fluids
- Identifying and evaluating novel alternative reaction conditions, such as light, ultrasound, and microwave
- investigation of several methods, like photocatalytic processes, for the cleaning of contaminated water and air to enhance their quality [2].

Achievement of the established objectives, "green chemistry changes steady industrial practice - produces, pollutes, and then cleanses, and in the late twentieth century becomes the heart and soul of industrial ecology" [2]. Green chemistry is a Hippocratic oath for chemists, and in order to protect the environment and natural resources, a new generation of scientists and engineers is emerging who economically assess the materials and processes utilized in development and production. Green chemistry, also known as ecologically harmless, harmless, and sustainable chemistry, is the production and use of chemical products and processes that minimize or completely do away with the production and use of harmful compounds. Green chemistry aims to lessen and potentially eliminate the risk, negating the need for exposure control, rather than reducing it by limiting exposure to hazardous chemicals. "Green chemistry is about reducing waste, raw materials, risks, energy, environmental impact and cost" [2]. If no hazardous substances are used or produced, the risk is zero and there is no need to worry about removing hazardous substances from the environment or limiting exposure to them.

V. PRINCIPLES OF GREEN CHEMISTRY

Paul Anastas and John Warner of the EPA created twelve principles of green chemistry and described their practical applications in their 1998 book *Green Chemistry Theory and Practice*. The reduction or elimination of hazardous or harmful compounds from

the synthesis, manufacture, and use of chemical products is discussed in the concepts of green chemistry; consequently, the usage of substances hazardous to the environment and human health is decreased or eliminated. When creating a process for green chemistry, it is not feasible to fulfil all twelve of the process's needs at once, but it tries to use as many principles as you can at specific synthesis stages.

VI. PREVENTION

Preventing waste is preferable to treating or cleaning it up after it has been produced. The primary tenet of green chemistry is the notion of prevention, or the avoidance of waste production, which is ultimately less expensive than treating and discarding garbage after it has surfaced and more beneficial for both people and the environment. The fact that the United States produces around 12 billion tonnes of waste annually—roughly 300 million tonnes of hazardous waste for human health and the environment—confirms the rationale behind the establishment of this principle. Methanol and xylenes predominate in the chemical industry, which generates 70% of all hazardous waste and the largest amount of organic toxic waste (about

150,000 tons). Sanitation of waste "consumes about 2.2 percent of gross US product, and costs continue to grow". Organic waste is mostly created at specific stages of synthesis, which are detrimental to both individuals and the environment. "Dirty reactions" involve the employment of hazardous reactants and solvents, and as a result of the severe reaction conditions, many hazardous byproducts are produced. These basic organic synthesis reactions—halogenation, oxidation, alkylation, nitration, and sulfonation—are most frequently used in many industrial sectors [7]. One of the pharmaceutical industry's greatest problems, in addition to discovering new medications, is creating and implementing production processes that have as little of an impact on the environment as possible. This mostly entails cutting back on the quantity of trash produced during production procedures. Given that solvents account for almost 80% of waste in the pharmaceutical sector and that roughly 60% of their energy is used, the answer is to utilize less solvents. A good example is the new "green" method of producing sertraline (Figure 1), which reduces solvent consumption by 250 to 25 liters per kilogram of sertraline by using ethanol as the only solvent instead of the four solvents (methylene chloride, tetrahydrofuran, toluene, and hexanes) for distillation and recovery [8].

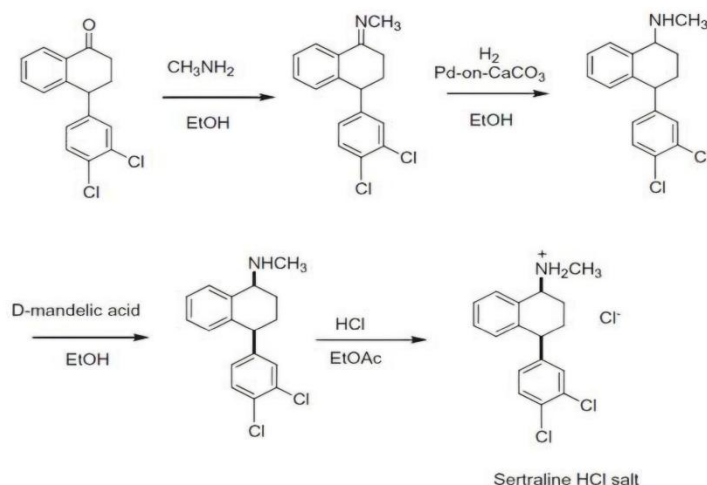


Figure 1. "Green" hesis of sertraline[8]

VII. ATOM ECONOMY

Since the Atom Economy concept demands that all raw materials used in production be maximally utilized or included in the end product in order to ultimately limit the quantity of waste, it is logically related to the waste prevention principle. This means that the design of the chemical synthesis should either maximize the input of raw materials in the final product or create synthetic products that utilize all of the elements utilized in the synthesis. The synthesis of ibuprofen is known to have advanced [9]. Because only around 40% of the input raw materials are used, the primary issue with the traditional synthesis (boots

method) is its low economic cost. A new "green" method of ibuprofen synthesis was developed in the 1990s; it only required three steps, and nearly all transitional materials were either converted to the product (up to 99%) or regenerated and returned in the process, virtually eliminating the generation of waste materials [10]. The novel method contributes to the prevention of pollution since it has a significantly greater atomic efficiency and virtually no waste (waste materials are recycled in the process). The ratio of the relative molecular masses of the intended product to all reactants, stated in percentages, is known as atom economy. of atomic efficiency = $(\text{Mr of the intended product} / \text{Mr of all reactants}) \times 100$ The Hoechst method

of producing ibuprofen only requires three steps and produces a reaction of 77%, or 99% if the acetic acid is generated in the first step. In contrast, the Boots method requires six synthetic steps and yields 40%. In production, the synthesis step is removed and repurposed. For this reason, getting ibuprofen from Hoechst is more affordable and environmentally friendly.

VIII. LESS HAZARDOUS CHEMICAL SYNTHESSES

Synthetic processes should, if possible, be created to employ and produce materials with minimal toxicity to the environment and human health. Toxic reagents are used in the majority of chemical synthesis reactions, which often occur in several phases. Redesigning these processes is a challenge of green

chemistry since, even though the result does not include these dangerous compounds, there is a risk of its contamination. Whenever feasible, the Less Hazardous Chemical Synthesis promotes the development of synthetic processes for the use and production of compounds that pose little to no threat to human health and the environment. Many industrial processes can be made cleaner and more affordable by substituting biological enzymes for hazardous chemicals [6]. For instance, Asahi Kasei's novel polycarbamate synthesis (PC) technique, which substitutes CO₂ for hazardous carbonyl dichloride (COC₂), is conceptually straightforward. Dichloromethane (CH₂Cl₂) is also eliminated as a solvent as a result of this procedure. Ethylene oxide (CH₂)₂, CO₂, and bisphenol-A (C₁₅H₁₆O₂) combine to form polycarbamate and ethylene glycol (C₂H₆O₂) [11].

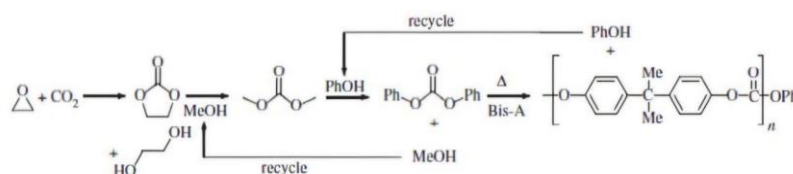


Figure 2: Synthesis of polycarbamate [12]

IX. DESIGNING SAFER CHEMICALS

Chemical products should be made with the least amount of toxicity possible while yet achieving their intended purpose. One of the most difficult parts of creating safer goods and procedures is minimizing toxicity while preserving function and efficiency. To do this, one must grasp not only chemistry but also the fundamentals of toxicology and environmental science. Designing Safer Chemicals promotes the creation of chemical products that are less harmful while still being effective. The balance between optimal performance and chemical product function is the aim of creating safe chemicals (non-carcinogenic, mutagenic, neurotoxic), making sure that risk and toxicity are minimized. This idea is applied in the creation of novel insecticides and pesticides that are target-specific, meaning they are only harmful to the target organisms and break down into compounds that are safe for the environment. The usage of extremely hazardous organic tin-based organic chemicals (Sn) that were previously put on the outside to stop plankton and seaweed from being captured is another example. Sea-Nine, a fully biodegradable and non-toxic substance, has taken the place of these chemical compounds. The creation of an oxidant activator for hydrogen peroxide is another illustration. This makes it possible to substitute hydrogen peroxide for chlorine bleaches—preparations that harm the ozone layer—in the manufacturing of paper [6]. As an illustration, consider the manufacturing of polyphenylene sulfone (PPSU) polymers, which are now

commonly utilized for interior airplanes and underground trains, where the employment of non-flammable materials is crucial. It is a novel engineering plastic with a special blend of practical mechanical, flame-resistant, and environmental qualities [13].

X. SAFER SOLVENTS AND AUXILIARIES

Whenever feasible, auxiliary materials (such as solvents, separation agents, etc.) should be utilized sparingly and safely. Environmental contamination makes chromatographic separations, which require a lot of solvents, challenging. The majority of traditional organic solvents are corrosive, flammable, and poisonous. The creation of environmentally friendly solvents is required because their recycling is associated with energy-efficient distillation with significant losses. Safer Solvents and Auxiliaries advises minimizing the synthesis process and avoiding the usage of auxiliary chemicals (such as solvents, separating agents, etc.) whenever possible. These compounds should be safe to use. The selection of appropriate organic solvent substitutes is based on worker safety, process safety, environmental safety, and process sustainability, in accordance with green chemistry principles. The solvent should be simple to use, easy to recycle, low volatility, and stable both chemically and physically. Ionic liquids, or salts at room temperature in the liquid state, are recyclable solvents that show promise for replacing

known organic solvents. Ionic liquids have a lower vapor pressure than volatile organic chemicals and evaporate more readily, making chemical reactions safer [14].

XI. DESIGN FOR ENERGY EFFICIENCY

Chemical processes' energy needs should be minimized because of their negative effects on the environment and the economy. Synthetic techniques should ideally be carried out at room temperature and pressure.

With the goal of utilizing every kJ of energy in the production process, a number of energy-saving procedures have been developed since the 1973 oil crisis. Minimizing energy consumption is a basic criterion of adhering to the aforementioned Principle of Energy Efficiency, often known as Design for Energy Efficiency. Tomatoes are grown in a greenhouse that is heated by ammonia produced from waste steam from a neighbouring chemical facility. Plant development is possible in greenhouses with CO₂ concentrations below 50%, and carbon dioxide is used as a bi-activator for tomato seed growth through extrusion from greenhouse gas [15].

XII. USE OF RENEWABLE FEEDSTOCKS

When it is both technically and financially feasible, feedstock or raw materials should be renewable rather than depleting. When it is both technically and financially feasible, the seventh principle of green chemistry promotes the use of renewable feedstocks. For instance, using renewable raw resources instead of a range of plastic materials and then discarding the waste materials is more convenient. As a result, creating biodegradable plastic materials is currently popular. There is a future for biodegradable packaging in the food sector. The development of biodegradable packaging is undoubtedly impacted by a number of issues, including politics, legislative changes, and the worldwide demand for food and energy resources [16]. Utilizing renewable energy technologies, such as solar, wind, hydropower,

biomass, and biofuels, is also implied by this notion. The development of fuels, chemicals, and materials from renewable raw resources has advanced significantly over the last ten years. The use of renewable raw materials in the production of bioplastics has a favourable impact on CO₂ emissions and energy consumption. While the American company NatureWorks uses bottles made of lactic acid polymers (PLA), which are made from lactic acid obtained by fermenting dextrose obtained from starch, most commonly corn, Coca-Cola, a globally recognized corporation, currently produces bottles made of 30% polyethylene (PE) blends. About 2.5 kilograms of corn are needed to produce 1 kg of PLA [17].

XIII. REDUCE DERIVATIVES

It is best to minimize or avoid unnecessary derivatization (application of blocking groups, protection/deprotection, temporary modification of physical/chemical processes), as these steps can result in waste and require additional reagents. Avoiding the usage of chemical derivatives in the production of target molecules is one of the main tenets of green chemistry (Reduce Derivatives). The idea promotes avoiding physical-chemical procedures wherein the necessary groups are blocked and unblocked during the synthesis, that is, whenever If at all possible, the biological processes involved in the synthesis should be utilized to prevent the production of compounds for which enzymes are available to break them down. Group blocking, protection/elimination protection, and transitory physicochemical alteration are examples of needless derivatization that should be minimized or avoided wherever possible because they can produce waste and require additional reagents. The synthesis of penicillin-based antibiotics (Figure 3) or the substitution of traditional chemical enzymatic procedures, which provide 6-aminopenicillic acid by reacting with the catalysed immobilized enzyme, are typical examples As a result, an enzymatic reaction took the place of multiple chemical processes, and no longer needed organic solvents, a low temperature (-60°C), and entirely inappropriate conditions, which raised and complicated production in the case of chemical synthesis [18].

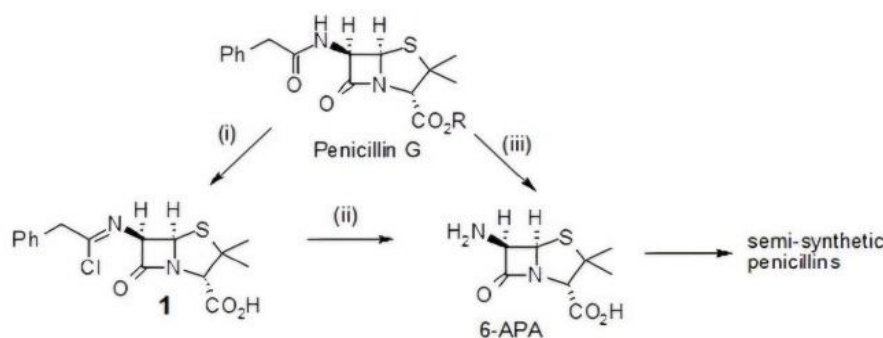


Figure 3. Synthesis of 6-aminopenicillic acid catalysed by immobilized penicillin G amide [18]

XIV. CATALYSIS

Stoichiometric reagents are inferior to catalytic reagents (as selective as feasible). The catalysis principle encourages the use of biodegradable catalysts, which means using less energy, avoiding the usage of organochlorine compounds, and using less water or waste water to safeguard the environment. Enzymes, like other catalysts, work by lowering the activation energy of a single reaction, which causes it to speed up to several million times. By doing this, the enzyme doesn't change during the course of the reaction it influences, which enables it to remain unaltered at the conclusion of the reaction. Also, enzymes do not affect the relative energy between the reactants and the products, nor to the

related reactions. However, the stereochemistry, chemical selectivity, and specificity of enzymes distinguish them from all other catalysts. Biocatalysts are superior to non-biological catalysts in terms of reaction rate, catalytic specificity, cost, etc., but they are less stable and less sensitive to heat. The traditional catechol synthesis uses benzene, a non-renewable fuel, in a number of reaction steps that call for harsh reactions that result in the production of unwanted byproducts. It is substituted with a biocatalytic synthesis of D-glucose (renewable raw materials) in the presence of genetically engineered *Escherichia coli*, which is carried out in a single reaction stage (Figure 4), produces no byproducts, and is economically feasible [12].

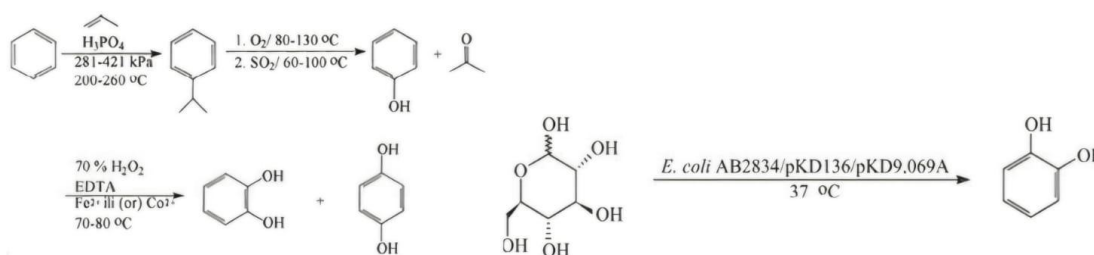


Figure 4. Catechol synthesis-classical(left) and biocatalytic(right) [19]

XV. DESIGN OF DEGRADATION

Chemical products should be made to decompose into harmless degradation products at the end of their useful lives and not linger in the environment. The idea of designing for degradation or producing degradable chemicals and products necessitates the development of chemical products that, when their activity is stopped, can transform into environmentally safe products. This criterion can be addressed by altering the process management's technological parameters and "so-called." auxiliary materials that are added during specific phases of the manufacturing process. The goal is to stop dangerous compounds from forming and to recycle as much trash as possible back into production [20].

XVI. REAL-TIME ANALYSIS FOR POLLUTION PREVENTION

To enable real-time, in-process monitoring and control before hazardous compounds arise, analytical methods must be further developed. Conventional analytical chemistry requires a lot of energy and solvents, as well as a lot of sample for analysis. The analyses may be able to use much less solvent and a smaller sample size at the sampling location because to the development of novel techniques and precise mobile instruments. In order to prevent the formation of hazardous substances, the Real-Time Analysis for Pollution Prevention principle necessitates further

development of analytical methodology to enable real-time monitoring of the chemical production process; in other words, the production process must be continuously monitored at every stage. would stop mistakes from happening that could result in the creation of hazardous materials that are bad for the environment and people's health.

XVII. INHERENTLY SAFER CHEMISTRY FOR ACCIDENT PREVENTION

The idea of Inherently Safer Chemistry for Accident Prevention is the Twelfth Principle of Green Chemistry. Reducing the usage of compounds in chemical processes that can have negative impacts (explosion, fire, and hazardous vapor) is the fundamental necessity. As an illustration, supercritical CO_2 is being used more and more in place of organic solvents. Unlike organic solvents, supercritical CO_2 is safe for the environment and neither harmful nor explosive. At various degrees of the least amount of personal protective equipment, safety can be described as the control of recognized dangers by obtaining an acceptable level of risk. In order to prevent workers from being overexposed to the effects of hazardous chemicals, it follows the level of Administrative and Work Practice Controls and entails creating efficient procedures, rotating work tasks, modifying work schedules, etc. Expert Engineering Controls, which entails implementing physical process changes, are the next

higher degree of security control. Isolate the process, employ moist techniques to minimize dust production, ventilation, digesting, etc. to lessen interaction with dangerous chemicals.

XVIII. DISADVANTAGES OF GREEN CHEMISTRY

Designing chemical products and processes that minimize or eliminate the usage or production of hazardous and dangerous compounds is the fundamental goal of green chemistry. The largest obstacle to achieving this goal is the lack of green chemistry, which manifests itself in terms of time, expenses, and information. More precisely, it takes a lot of time to transition from an old, conventional product or process to a new "green" product or process; designing or redesigning a new product or process is frequently challenging and costly; and there is a lack of consensus over what is deemed safe. The lack of green chemistry is also a result of the high implementation costs and information gaps, as there are no known substitutes for chemical raw materials or alternative technologies for green processes. Furthermore, there is a shortage of human resources and expertise. There are insufficient resources for additional research, and the risks associated with moving to green products and processes are not distributed throughout the supply chain. Ionic liquids are thought to be the green chemistry of the future. They are undoubtedly helpful in chemical synthesis, but whether they live up to expectations is a subject that is being asked more and more. Ionic liquids do not appear particularly green when the twelve principles that define green compounds are applied. Some believe that it is unreasonable to anticipate widespread use of ionic liquids in the next ten years given the current state of scientific advancement. Ionic liquids are known to be somewhat volatile because of their low vapor pressure, yet this is just one of several elements that give a substance its green hue. Ion-based, imidazole-based, and fluoro-anion-based liquids, for instance, are probably toxic yet cannot evaporate into the environment. The majority of ionic liquids are water soluble, which makes it easy for them to enter the biosphere [21].

XIX. CONCLUSION

Each industry's main objective is to make money through sustainable industrial activity using readily available raw materials and basic capital. Chemical processes must employ raw materials, water, and energy in a way that is both economically feasible and does not negatively impact the environment in order to be considered sustainable industrial activity. The introduction of a green chemistry method, whose goal is to create chemical processes and products that are safe for human health and the environment, can help establish

a balance between the use of natural resources, economic growth, and environmental protection. Adequate legal support is required for the application of the green chemistry concept, which introduces chemical safety, through the legal control of certain processes and activities that are necessary for its implementation. The twelve guiding principles of "green chemistry" refer to the reduction or elimination of hazardous or harmful substances from the synthesis, production, and application of chemical products, thereby reducing or eliminating the use of substances that pose a risk to human health and the environment. A green chemistry method aims to apply as many principles as possible during certain stages of synthesis, however it is difficult to satisfy all twelve principles at once. Green chemistry aims to safeguard the environment and benefit the economy in a number of key ways. These include new photocatalytic processes, the use of alternative renewable raw materials (biomass), alternative reaction mediums (water, ionic liquids, supercritical fluids), alternative reaction circumstances (microwave activation), and biocatalysis. In terms of process utilization, selectivity, energy reduction, and the use of alternative reaction media, catalysis as the basis of green chemistry with new catalytic reactions and types of new catalysts offers several advantages. Biocatalysts hold a prominent position in the "green" agenda due to the enormous potential of microorganisms and enzymes in the selective transformation of synthetic compounds. Green chemistry contributes to the creation of sustainable circumstances through photocatalytic processes, which are novel ways to purify contaminated water and air.

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