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ДОСТИЖЕНИЯ В ОБЛАСТИ ЗЕЛЕНОЙ ХИМИИ: УСТОЙЧИВЫЙ СИНТЕЗ И ХИМИЧЕСКИЕ ПРОЦЕССЫ

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Аннотация. Последние разработки в области зеленой химии были сосредоточены на экологически чистых синтезах и химических процессах, таких как эффективная трансформация возобновляемого сырья, разработка новых реакций и методов, использование экологически чистых растворителей и альтернативных источников энергии, интенсификация химических процессов и передовые экологические технологии. Эти разработки способствуют созданию устойчивости в химическом секторе и снижают воздействие химических процессов на окружающую среду.

Ключевые слова: зеленая химия; устойчивый синтез; катализ; устойчивость.

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ADVANCEMENTS IN GREEN CHEMISTRY: SUSTAINABLE SYNTHESIS AND PROCESSES

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Abstract. An emerging area of chemistry called «green chemistry» is revolutionising how environmental and sustainability issues related to chemical synthesis and processes are handled. A key tactic for improving sustainability in the chemical sector is green chemistry. Recent developments in green chemistry have concentrated on environmentally friendly synthesis and processes, such as the effective and clean transformation of renewable raw materials, the development of novel reactions and techniques, the use of eco-friendly solvents and alternative energy sources, process intensification, and cutting-edge environmental technologies. These developments are promoting sustainability in the chemical sector and lowering the environmental effect of chemical operations.

Keywords: green chemistry; sustainable synthesis; catalysis; sustainability.

Introduction

The discipline of green chemistry has emerged as a source of hope in a time when environmental concerns are on the rise and there is a pressing need for sustainable solutions. It is evidence of humanity's commitment to balancing ecological stewardship and chemical innovation. Green chemistry aims to transform how we perceive and use chemistry by reducing its negative effects on the natural world and public health [1]. This article explores the amasing developments in green chemistry, paying close attention to sustainable synthesis methods and processes that are starting to change the face of contemporary chemistry. Traditional chemical processes have a long history of unintended ecological effects, such as the production of hazardous waste, the use up of precious resources, and the discharge of pollutants into the environment. Green chemistry, in contrast, embodies a set of guiding principles intended to lessen these negative impacts. It places a focus on the development and application of chemical processes that prioritise effectiveness, safety, and environmental stewardship while also providing creative and economical answers to urgent global concerns [2]. Fundamentally, green chemistry emphasises the value of atom economy, a concept that aims to use all reactants as effectively as possible while minimising by-products or waste. Instead of relying on non-renewable fossil fuels, it promotes the use of sustainable energy sources and renewable feedstocks. In addition, green chemistry promotes the creation of catalytic processes that can greatly improve reaction selectivity and efficiency while using less severe reaction conditions and harmful chemicals. Green chemistry's dedication to the logical selection of solvents is one of its distinguishing characteristics. Traditional chemical processes frequently use dangerous solvents that are flammable and unstable, endangering both human health and the environment [3]. The aim of green chemistry is to replace or utilise less of these solvents. Green chemistry has expanded more recently, incorporating novel synthetic techniques, environmentally friendly reaction conditions, and process intensification techniques. These advancements have broad ramifications for a variety of industries, including agriculture, materials science, pharmaceuticals, and more. Researchers and businesses have started to open up new doors for sustainable innovation and product creation by incorporating the concepts of green chemistry [4].

With insights into the game-changing potential of sustainable synthesis techniques and processes, this review seeks to give a thorough exploration of these recent developments in green chemistry. Through case studies and illustrative examples, we will explore the crucial factors that characterise the development of the sector, such as catalyst design, solvent choice, renewable feedstocks, process intensification, and sustainable reaction conditions [5]. The aim of this article is to explore the advancement of green chemistry in solvent choice and processes and this review also throw light on the difficulties that lie ahead as well as the potential for a day when green chemistry will play a constantly expanding role in creating a more resilient and sustainable world.

Green chemistry: principles and core ideas

With a focus on efficiency, safety, and sustainability, the field of green chemistry seeks to create chemical products and processes with the least possible negative impact on the environment. Green chemistry depends on a number of fundamental ideas and principles to accomplish these objectives, such as the economy of the atoms, the use of renewable feedstocks, the reduction of waste, and safety and toxicity considerations [6]. Let's go over each of these guidelines in more detail.

1. Biological feedstocks. The utilisation of renewable feedstocks, or raw materials generated from sustainable sources, is encouraged by green chemistry. Natural processes can renew these feedstocks, which do not deplete as quickly as fossil resources do [7]. Biomass (plant-based materials), bio-based chemicals, and agricultural waste are a few examples of renewable feedstocks. These resources can offset or lessen dependency on non-renewable resources. Green chemistry helps to lower greenhouse gas emissions, prevent resource depletion, and promote a more sustainable and circular economy by employing renewable feedstocks [8].

2. Minimising waste. Green chemistry's guiding premise is minimising waste. It seeks to minimise or stop the production of wastes during chemical reactions.

Waste reduction tactics include things like:

a) choosing reactions with a high atom economy;

b) using catalysis to boost the selectivity and efficiency of reactions;

c) chemical and material recycling and reuse;

d) creating procedures that generate less or less hazardous waste.

Green chemistry helps to conserve resources by minimising waste, which also lessens the environmental impact of garbage disposal [9].

3. Considerations for security and toxicity. In green chemistry, safety and toxicity concerns are of utmost importance. It highlights the necessity of developing chemicals and procedures that put environmental and human safety first. Green chemistry aims to recognise and reduce any risks connected to chemical substances and processes. It encourages the use of procedures and chemicals that are intrinsically safer. Designing chemicals that are less toxic to ecosystems and living things is known as toxicity reduction. This includes reducing the use of risky drugs, preventing the production of toxic byproducts, and creating safer substitutes. To make sure that new products and processes adhere to strict safety standards, green chemistry includes safety evaluations, toxicity testing, and risk management [10].

Catalysis in green chemistry

In order to increase the efficiency and sustainability of chemical processes, catalysis is a crucial component of green chemistry. This section discusses new developments in catalytic processes, such as organocatalysis, enzyme catalysis, and the use of metal-organic frameworks (MOFs) as catalysts, as well as the significance of catalysis in sustainable synthesis. In addition, case studies that highlight catalytic advancements in green chemistry will be covered.

Role of catalysis in sustainable synthesis. In order to change conventional chemical processes into ones that are more efficient and ecologically friendly, catalysis plays a crucial part in sustainable synthesis. Through catalysis, chemical reactions can be hastened while requiring less energy, being more selective, and producing fewer unwanted by-products [11]. These advantages closely follow the sustainability and green chemistry tenets. Here is a detailed explanation of how catalysis functions in sustainable synthesis.

1. Efficiency in energy. The ability of catalysis to lower the activation energy necessary for a chemical reaction to proceed is one of its main benefits. As a result, reactions can occur at lower pressures and temperatures, which ultimately results in a decrease in energy use.

2. Milder reaction conditions. Milder reaction conditions are frequently used in sustainable synthesis, which not only saves energy but also lowers the greenhouse gas emissions linked to the high temperature processes [12].

3. Better selectivity. In nature, catalysts are highly selective, boosting just certain reactions and routes while limiting adverse effects. As it decreases the creation of undesirable byproducts, this selectivity is essential for sustained synthesis. Catalysts help chemists produce higher yields of desired products while producing less waste by directing reaction routes.

4. Atom economy. A key idea in sustainable synthesis is the atom economy. The percentage of reactant atoms that make up the finished product is quantified. Green chemistry is characterised by high atom economy. Because they effectively utilise reactant atoms, catalytic reactions frequently display great atom economy, reducing the production of waste or unreacted starting reagents [13].

5. Reduced hazardous reagents. The goal of sustainable synthesis is to employ fewer dangerous chemicals, which can be harmful to the environment and human health. Catalysts frequently allow the employment of reagents that are kinder and less harmful. Chemical processes that use catalysts instead of risky chemicals are safer and more environmentally friendly.

6. Waste minimisation. The reduction of waste produced during chemical operations is emphasised by green chemistry principles. By encouraging more effective reactions and minimising the need for extra chemicals,

catalysts make this possible. Garbage minimisation lowers costs and labour connected with garbage disposal as well as the influence on the environment [14].

7. Resource conservation. The conservation of resources is intimately related to sustainable synthesis. Catalysis makes it possible to use raw materials more effectively, which is essential for protecting finite resources. Catalysis contributes to the sustainable use of resources and lessens the environmental impact of resource extraction by increasing reaction efficiency.

8. Green product development. Catalyst use can result in the creation of products that are more sustainable and environmentally friendly. Catalysts, for instance, might make it possible to create biodegradable polymers or cleaner-burning fuels. Through the course of their lives, these green products have less of an influence on the environment.

9. Support for renewable feedstocks. Catalytic processes can be created to use renewable feedstocks like CO_2 or chemicals produced from biomass. As a result, there is less dependency on fossil fuels and a circular economy is being developed [15].

10. Innovation and versatility. Innovation in sustainable synthesis is still being driven by catalytic advancements. New catalysts and innovative catalytic methods are constantly being developed by researchers. Catalysis is a useful tool for sustainability in a variety of industries because it is versatile in addressing a wide range of chemical transformations, from organic synthesis to industrial processes.

Recent advancements in catalytic processes. Consider the following catalytic processes.

1. Organocatalysis. The efficiency and selectivity of chemical reactions have significantly improved as a result of recent developments in catalytic processes. Organocatalysis, which uses tiny organic molecules as catalysts, is one area of catalysis that has shown significant recent progress. The following are a few recent advances in organocatalysis:

a) the use of cofactor mimics in organocatalysis and biocatalysis has been the subject of recent research. Cofactors are chemicals that help enzymes catalyse processes, and by using mimics of these compounds, organocatalyst activity can be increased;

b) the immobilisation of organocatalysts is a recent advancement in organocatalysis. Catalysts can be made more stable and usable through immobilisation, which also makes it easier to separate them from reaction by-products as shown in fig. 1 [16]. The use of a single polysaccharide supports to immobilise multiple enzymes was investigated [16]. In this study, sodium alginate and glutaraldehyde-activated chitosan were used to assess their potential for immobilising three enzymes at once, namely an α-amylase, protease and pectinase, as highlighted in fig. 1. This is a useful example that highlights the potential for developing new super-biocatalysts, where a single material performs multiple biocatalytic functions. This might be, for example, to debitter, de-haze and reduce protein levels of a liquid in a single operation;

c) research has also been conducted on the creation of new organocatalytic systems. The potential of numerous organocatalysts, including chiral secondary amines, thioureas, chiral phosphoric acids, and squaramides, to catalyse diverse processes has been studied. Organocatalytic glycosylations have made recent strides as well. In these processes, glycosidic linkages are created, which are crucial for the production of carbohydrates and glycoconjugates. In these processes, catalysts such as Bransted acids, thioureas, and squaramides have been employed [17].

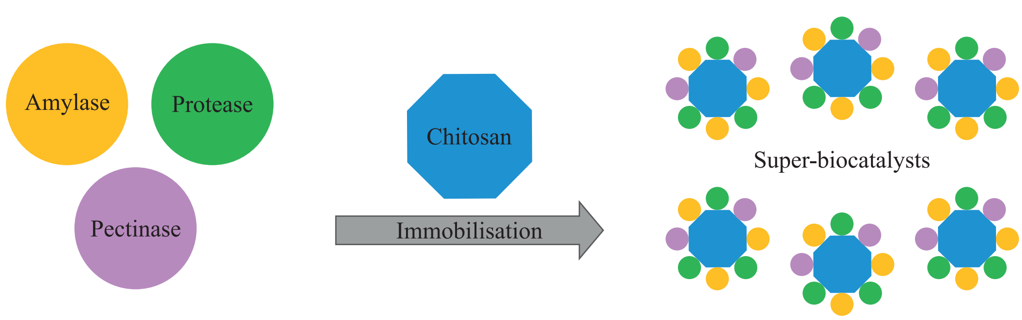

Fig. 1. Immobilisation studies using three enzymes to make super-biocatalysts.
Source: [16]

2. Enzyme catalysis. The process of accelerating a chemical reaction by a biological molecule called an enzyme is known as enzyme catalysis. Expanding the toolbox for enzyme immobilisation, employing modified enzymes for extensive bio-remediation, and increasing the efficiency and sustainability of industrial processes

have been the main recent breakthroughs in enzyme catalysis. Enzymes are increasingly employed as industrial biocatalysts due to their benefits over conventional chemical processes in terms of sustainability and process efficiency. Researchers are investigating methods for creating better biocatalysts for use in industrial applications. Enzyme immobilisation is a method for enhancing the stability and reusability of enzymes in industrial operations. Recent advancements in enzyme immobilisation use hydrogels, magnetic particles, and nanomaterials. As a long-term solution for wastewater treatment, enzyme-based catalytic remediation techniques are being investigated. The use of modified enzymes as catalysts for extensive bio-remediation efforts, showcasing the potential of biocatalytic systems in addressing environmental challenges and enhancing the sustainability of wastewater treatment processes. Energy and information metabolism depends heavily on enzyme catalysis, and most enzymes' catalytic activity depends on their cofactors [18].

3. MOFs as catalysts. The term MOF refers to a family of porous materials made up of metal ions or clusters linked by organic ligands. They have received a lot of attention recently due to prospective uses as heterogeneous catalysts in green chemistry. MOFs are desirable for catalytic processes due to a number of their favourable characteristics:

a) high surface area (MOFs frequently possess an extraordinarily high surface area, which offers a lot of active sites for catalytic reactions; increased catalytic activity is made possible by this characteristic [19]);

b) tunable pore structure (MOFs can be made with precisely shaped and sized pores that can accommodate a range of reactant molecules and aid substrate selectivity);

c) versatility (MOFs can include a variety of metal ions and organic ligands, enabling the customisation of their catalytic characteristics to fit certain processes);

d) stability (a lot of MOFs have strong stability in a wide range of circumstances, such as high temperatures and abrasive chemical environments, which makes them appropriate for catalysis);

e) recyclability (MOFs are easily recovered and repurposed, minimising the environmental impact of catalyst waste [20]).

Catalytic innovations in green chemistry. Consider the following case studies demonstrating catalytic innovations in green chemistry.

1. Photocatalysis based on MOFs for CO_2 reduction. In order to facilitate the photocatalytic conversion of CO_2 to useful compounds, such as formic acid or methane, utilising sunlight, MOFs with integrated catalytic centers have been produced. This green chemistry strategy tries to reduce CO_2 emissions while also creating useful compounds. A structured environment for effective CO_2 adsorption and activation is provided by MOFs.

2. MOFs for sustainable hydrogen production. MOFs have been looked into as potential photocatalysts or electrocatalysts for the production of hydrogen gas from water. Because they can employ renewable energy sources (like solar or wind) to power the water-splitting reaction and generate clean hydrogen fuel, MOF-based catalysts are appealing [21].

3. MOFs for catalytic water purification. MOFs have been investigated for use in water filtration systems where they function as catalysts to break down organic contaminants and remove heavy metals from sewage. By using a sustainable strategy, water treatment procedures have less of an impact on the environment and require fewer chemical additives.

4. Green chemistry and MOFs in pharmaceutical synthesis. MOFs have been used as catalysts for environmentally friendly and effective chemical processes in the manufacture of pharmaceuticals. For instance, MOFs have been utilised to synthesise pharmacological intermediates, resulting in less waste, better selectivity, and a smaller environmental effect than conventional techniques.

5. MOFs for sustainable gas separation and storage. Carbon capture and storage applications, among others, have used MOFs with adjusted pore diameters and affinities for particular gases for gas storage and separation. These MOFs can selectively absorb and release gases like CO_2, making carbon capture and storage more environmentally and energy-friendly [22].

6. MOF-catalysed green oxidation reactions. For various oxidation reactions, such as the selective oxidation of alcohols to aldehydes or ketones, MOFs have been investigated as heterogeneous catalysts. In these reactions, the use of MOFs as catalysts replaces the requirement for risky or expensive oxidising chemicals, resulting in safer, more sustainable operations. In a variety of applications related to green chemistry, MOFs exhibit their adaptability and potential. They play a crucial role in the search for more environmentally friendly chemical processes because of their capacity to improve catalytic efficiency, selectivity, and sustainability while tackling important energy and environmental concerns. As MOF-based catalysis research develops, it has the potential to help solve some of the most pressing problems in green and sustainable chemistry.

7. Green catalyst synthesis. Atorvastatin side chain process is a great example of using bioengineering and enzymes for selective transformations as shown in fig. 2 [23].

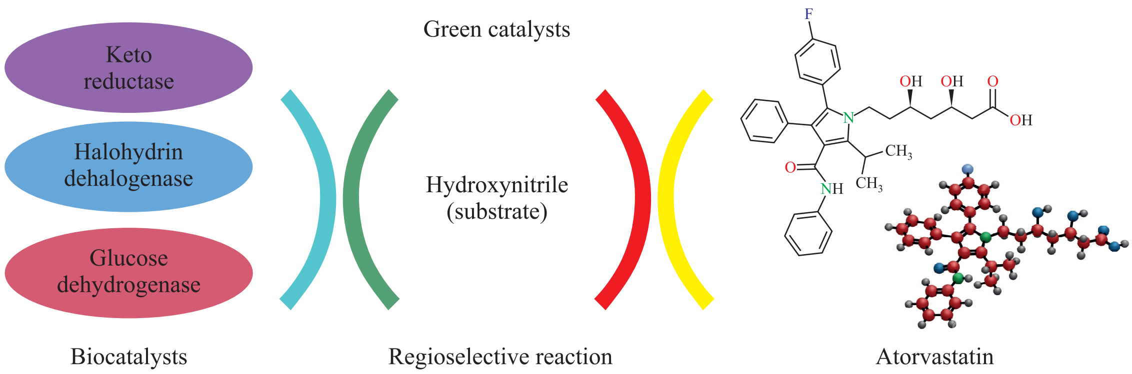

Fig. 2. Green catalyst synthesis of atorvastatin

Solvent selection and design

Most industrial and home uses need the use of solvents, yet doing so raises serious environmental issues. The effects of solvent losses and emissions motivate efforts to reduce or fully prevent them. The sustainability of a chemical production process can be significantly increased by choosing the right solvent for the job. Without proper consideration of the unique circumstances in which solvents are to be employed on an industrial scale, even at the research stage, the search for less-impactful solvents is ineffective. More significant than inherent «greenness» are broader sustainability problems, namely the utilisation of non-fossil sources of organic carbon in solvent manufacturing. To lessen the usage of the most dangerous solvents, a number of general-purpose solvent selection recommendations have been released (as shown in fig. 3) [24]. Although virtually all solvent tools are indicative of a more limited range of requirements characterising worker health and safety paired with environmental release difficulties, the absence of sustainability factors utilised in solvent selection guidelines suggests otherwise. In order to pick solvents in the future with higher sophistication and in accordance with a sustainable supply chain, further research is required in the areas of application-specific tools and life cycle assessments.

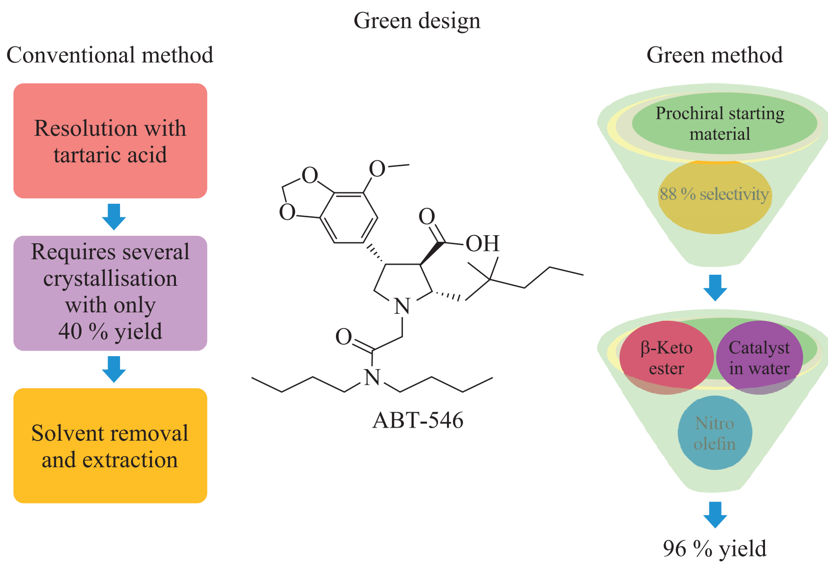

Fig. 3. Green design process for the synthesis of ABT-546.
Source: [25]

The applicability and acceptability of solvents – indeed, any volatile compound – are now more likely to be discussed at the discovery stage due to rising regulatory, customer, and user expectations, increased competitive pressure, and other factors. In fact, as laboratory programmes are developed, such variables are increasingly taken into account, frequently taking into account the notions of sustainable technology. Solvents have a considerable negative impact on sustainability, hence attempts are being made to reduce their use and find new, more sustainable solvents. The sustainability of a chemical production process can be significantly increased by choosing the right solvents for the job as shown in fig. 4. Without taking into account the unique circumstances of how solvents will be utilised on an industrial scale, the quest for less harmful solvents is ineffective. More significant than inherent «greenness» are broader sustainability issues, including the utilisation of non-fossil sources of organic carbon in solvent production [26].

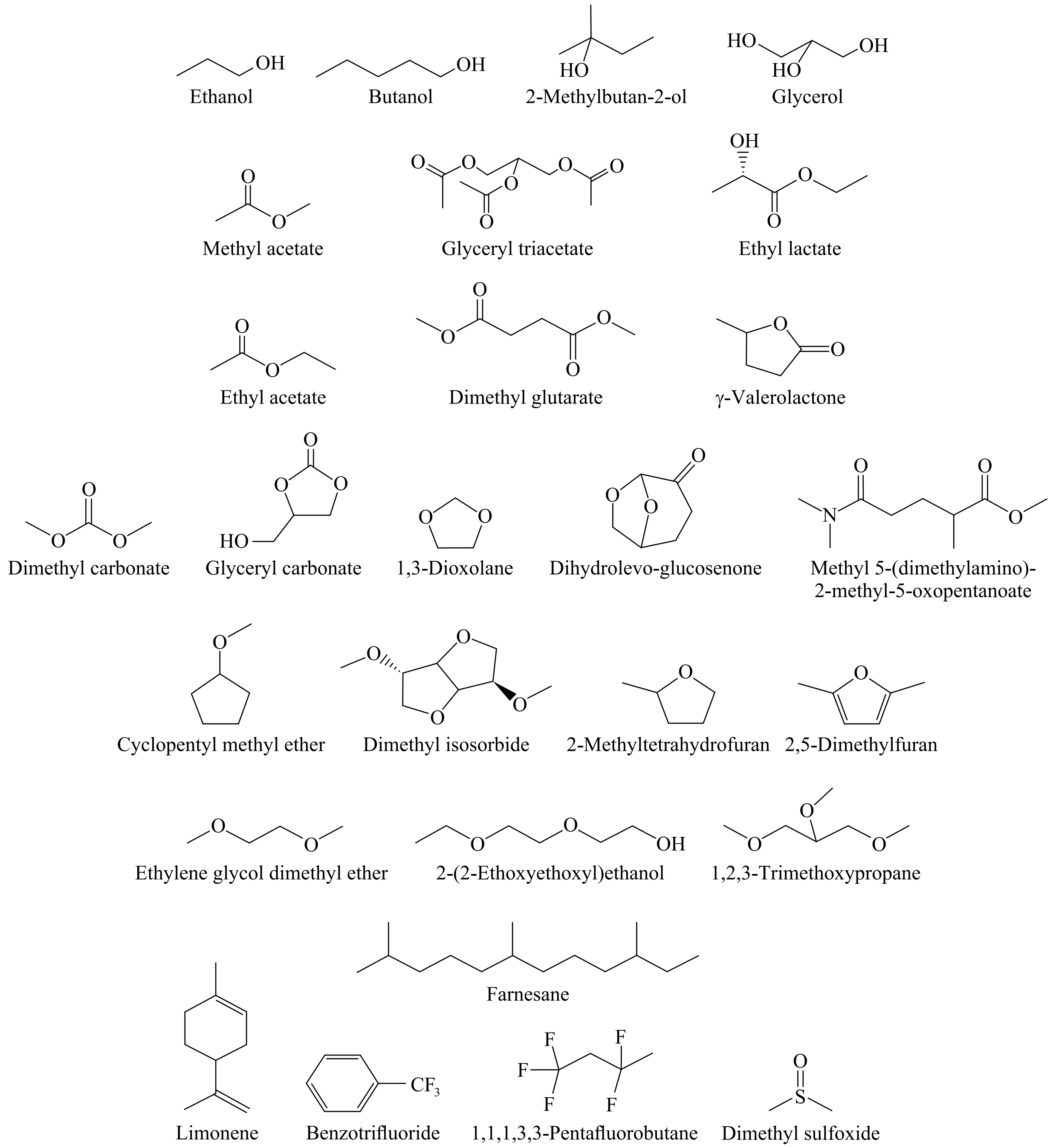

Fig. 4. Examples of solvent.
Source: [26]

Sustainable synthesis strategies

For chemical synthesis processes to have less of an environmental impact, sustainable synthesis methodologies are crucial. Here are a few techniques for sustainable synthesis.

1. Principles of green chemistry. The 12 tenets of green chemistry as shown in fig. 5 seek to limit the harm that chemical synthesis processes do to the environment. A few of these ideas are preventive, atom economy, less risky chemical syntheses, safer chemical design, and safer solvents and auxiliaries [27].

2. Alternative procedures and shorter routes. A synthesis can be made more sustainable by using a different reaction design, a different process, or a shorter path. The likelihood of the reaction producing less waste, requiring fewer chemicals, and requiring less energy increases with the number of stages.

3. Utilisation of artificial intelligence and machine learning. Before the experiment even begins, predictive approaches like artificial intelligence and machine learning can be used to develop more environmentally friendly routes and procedures and increase the likelihood of success.

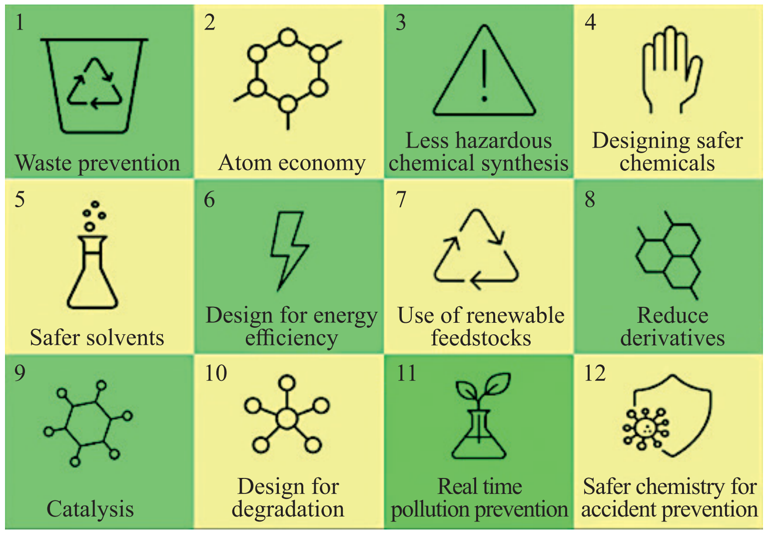

Fig. 5. Principles of green chemistry.
Source: [25]

4. Cleaner procedures. The development of cleaner procedures as alternatives to conventional chemical synthesis and transformations has been facilitated by advances in green chemistry [28].

5. Adaptive design. The goal of sustainable design is to completely remove or reduce the negative effects on the environment and human health through careful designs. Chemical synthesis procedures can be made more sustainable by using this idea.

6. Scalable manufacturing. Recent studies have concentrated on the scalable, sustainable manufacturing of nanocarbons from biomass. To make other chemical synthesis procedures more sustainable, same strategy can be applied.

For chemical synthesis processes to have less of an environmental impact, sustainable synthesis methodologies are crucial. Chemical synthesis processes can be made more sustainable by employing green chemistry concepts, quicker routes and alternative methods, artificial intelligence and machine learning, cleaner processes, sustainable design, and scalable production, to name a few tactics [29].

Sustainable reaction conditions

Energy-efficient alternatives. There are the following energy-efficient alternatives.

1. Microwave-assisted reactions. A possible environmentally friendly method to create nanomaterials and nanocomposites is microwave-assisted reactions. An oscillating microwave electromagnetic field interacts with polarisable molecules or ions to cause microwave heating of homogenous liquids. Microwaves lack the necessary energy to directly activate or break chemical bonds. Heat must first be created from microwave energy. Due to microwave flash-heating's effectiveness, reaction times have been drastically shortened from days and hours to minutes and seconds. At room temperature, it has been demonstrated that microwave-assisted reactions improve reaction efficiency. When using microwave heating to change organic matter, less energy is used than when using traditional heating [30]. Photocatalysed processes have also made use of microwave assistance. By simultaneously exposing the metal-oxide photocatalyst TiO_2 to UV light and microwave radiation in reactions occurring during wastewater treatment, the microwave effect in photocatalysed reactions was established. It was established that the microwave effect in photocatalysed reactions increases the lifetime and utilisation efficiency of electrons generated by UV light in the photocatalyst. The rate of electron transfer is accelerated by the electromagnetic wave effects in a TiO_2 photocatalysed process by reducing the recombination of excited electrons with photogenerated holes [31].

2. Photochemical reactions. Another efficient alternative is photochemical processes. They are chemical processes that light triggers. They may be used to create complicated compounds in a single step and are frequently utilised in organic synthesis. Since almost two decades ago, microwave-enhanced photochemical processes have been studied. It was established that the microwave effect in photocatalysed reactions increases the lifetime and utilisation efficiency of electrons generated by UV light in the photocatalyst. Chemical reactions can be carried out with less energy by using energy-efficient alternatives like microwave-assisted reactions and photochemical reactions. At room temperature, it has been demonstrated that microwave-assisted reactions increase reaction efficiency, and microwave heating uses less energy than traditional heating for organic transformations. Organic synthesis frequently employs photochemical processes, which can be used to manufacture complex compounds in a single step [32].

Minimising resource consumption. There are some ways to minimise resource consumption.

1. Water-saving techniques. Utilising water wisely in order to use it less is known as water conservation. Water conservation is crucial since clean, fresh water is a scarce resource that is also expensive. Using water-saving methods can help you save money and divert fewer resources from our rivers, bays, and estuaries, which promotes environmental sustainability. Toilets, washing machines, showers, baths, faucets, and leaks use the most water in the home.

Some water-saving methods that can be utilised to reduce resource use include the ones listed below [33]:

a) put a brick in the water tank of your toilet. An average of 20 gallons of water are flushed down the toilet each day. If you don't have a high-efficiency toilet, consider adding something to your tank, like a block, that will help move some of that water;

b) use proper plant watering techniques. To ensure that the water lasts and does not instantly evaporate in the sun, water your lawn or garden in the early morning or late at night;

c) fix a leak. Small domestic leaks can result in daily water losses of several litres. Therefore, every march during fix a leak week, WaterSense advises Americans to inspect their plumbing fixtures and irrigation systems;

d) install water-saving equipment. Products with the WaterSense logo not only conserve water but also cut down on energy costs. For example, installing faucet aerators.

2. Energy-efficient processes. Processes that use less energy are another approach to reduce resource consumption. The circular economy of water is a strategy that can be used in a variety of industries, such as domestic consumption with water-saving dishwashers or wellness showers that combine water and air bubbles; agricultural use with precise irrigation or crops that use less water; or industrial use with water-saving processes like solar water heating systems that don't require steam. Some energy-effective techniques that can be utilised to reduce resource usage include the ones listed below:

a) utilise energy-saving appliances (water-using appliances that are electricity STAR® rated can help conserve both water and electricity);

b) utilise solar water heating techniques without the use of steam;

c) upgrade to energy-saving fixtures (upgrading to water-saving fixtures is the best method to conserve water).

Resource consumption must be kept to a minimum for sustainable growth. It is possible to cut back on wasteful water and energy use by using energy- and water-saving methods. These methods enable us to save costs, safeguard the environment, and ensure that our natural resources are utilised effectively [34].

Case studies showcasing sustainable reaction conditions. This case study illustrates how gains in sustainability can be made in pharmaceutical production through the use of continuous manufacturing. Waste, energy utilisation, and the use of hazardous materials can all be decreased by continuous manufacturing. Additionally, it helps speed up production time and enhances product quality. This case study investigates the application of Bayesian optimisation as a sustainable technique for early-stage process development in the context of Cu-catalysed C—N coupling of sterically hindered pyrazines. By analysing a limited number of tests, Bayesian optimisation may effectively explore large reaction spaces and forecast high-yielding reaction situations. By reducing the number of trials needed, this strategy can conserve time, energy, and resources. This case study shows how green engineering may be used in industrial processes to decrease risk, cut waste, and increase efficiency in the production of chemicals [35]. The case study investigates how reactive distillation is used to make methyl acetate. Reactive distillation can manage challenging separations, increase selectivity, use less energy, consume less waste and raw materials, prevent contamination, and avoid separate reactants. Utilising this strategy can lessen how damaging chemical manufacturing is to the environment.

Process intensification

The idea of «process intensification» entails enhancing chemical processes by boosting productivity, cutting waste, and limiting environmental effect. Reactors with continuous flow and microreactors are two essential technologies for process intensification [36].

Reactors that operate continuously, as opposed to batch reactors that operate in batches, are known as continuous flow reactors. They have a number of benefits, including as enhanced heat and mass transport, improved reaction condition control, and decreased waste. Catalysis, organic synthesis, polymerisation, and other chemical processes can all be carried out in continuous flow reactors.

Small-scale reactors, or microreactors, provide a number of advantages over conventional reactors, such as enhanced heat and mass transfer, enhanced reaction state control, and decreased waste. They can be used for a variety of chemical reactions, such as organic synthesis, polymerisation, and catalysis, and are frequently built of glass or metal. Nanomaterials, biobased compounds, and fuels can be created in microreactors. To reach high conversion rates, they can also be applied in multi-reactor configurations. Microreactors and continuous flow reactors can both be extensively automated, increasing efficiency and lowering the need for manual intervention [37]. The use of highly automated industrial flow reactors in fine chemicals and the pharmaceutical industries has increased. In recent years, microreactor technology has drawn a lot of interest as an essential instrument for process intensification through shrinking. Process intensification is a crucial idea in chemical engineering that entails enhancing chemical processes by boosting productivity, cutting waste, and lowering the negative effects on the environment. The two main technologies utilised in process intensification are continuous flow reactors and microreactors, both of which have many advantages over conventional reactors. Both technologies have the potential to be highly automated, increasing efficiency and lowering the demand for manual involvement. Process intensification in industry can be seen in the use of continuous flow reactors for the production of fine chemicals like flavours and fragrances, microreactors for the production of nanomaterials, biobased chemicals, and fuels, and continuous flow reactors for the synthesis of active pharmaceutical ingredients (APIs) in the pharmaceutical industry [38]. Some examples of process intensification in industry are given below.

1. Continuous flow reactors. Continuous flow reactors are used in the pharmaceutical industry for the synthesis of APIs. They are also used in the production of fine chemicals, such as flavours and fragrances.

2. Microreactors. Microreactors are used in the production of nanomaterials, biobased chemicals, and fuels. They are also used in the pharmaceutical industry for the synthesis of APIs.

3. Static mixers. Static mixers are used in the chemical industry for mixing and reacting fluids. They are a significant improvement over mechanical agitation due to their lower energy costs and uncomplicated design with no moving parts. The petrochemical sector currently employs more than 150 reactive distillation units, the majority of which were built within the last 30 years. MTBE manufacture, acetate synthesis (methyl, ethyl, and butyl), hydrolysis reactions, and many more processes are examples of applications. Reactive distillation's intensification effort reduces capital costs and (or) energy consumption by 20–80 % [16].

4. Monolithic reactors. In the chemical industry, monolithic reactors are used to create delicate compounds like tastes and scents.

5. Compact (microchannel) process units. In the chemical industry, compact (microchannel) process units are used to produce fine compounds, such as tastes and perfumes.

6. Distillation using a divided wall column. In the chemical industry, distillation using a divided wall column is used to separate azeotropic mixtures. The synthesis of fine compounds, such as tastes and perfumes, is done in the chemical industry using ultrasonic and microwave equipment.

7. Reverse flow reactors. In the chemical industry, reverse flow reactors are used to produce fine compounds such as flavours and scents.

Process intensification is a field of study that tries to boost production effectiveness through radically improved manufacturing and processing. Continuous flow reactors, microreactors, static mixers, monolithic reactors, compact (microchannel) process units, divided wall column distillation, ultrasonic and microwave units, and reverse flow reactors are a few examples of process intensification in the industrial setting [39].

Automation and digital technologies in green chemistry

Green chemistry, which strives to lessen the impact of chemical processes on the environment, is becoming more and more dependent on automation and digital technologies. The following are some applications of automation and digital technology in green chemistry.

1. Digitalisation. By facilitating the fusion of traditional chemistry and sustainability, digitalisation is revolutionising the chemical sector. It is being utilised to speed up the achievement of sustainability objectives and cut down on resource and energy use. Data on manufacturing and emission control are also being collected digitally, which can assist businesses in lessening their environmental impact [40].

2. Automated and robotic flow. Chemical synthesis is being digitalised using automated and robotic flow, which can help to cut waste and increase effectiveness. In this technology, flow platforms are used to connect hardware and digital chemicals while algorithms are used to look for chemical interactions.

3. Nature-inspired technologies. New, environmentally friendly materials and chemicals are being developed using nature-inspired technologies. These technologies are founded on green chemistry concepts, which emphasise the use of alternative feedstocks, environmentally friendly reaction conditions, and the development of molecules that are naturally safer and less harmful [41].

Green chemistry employs automation and digital technologies to lessen the effects of chemical operations on the environment. While automated and robotic flow is being utilised to digitise chemical synthesis, digitalisation is being used to merge traditional chemistry and sustainability. Environmentally friendly chemicals are being created with the use of technology inspired by nature.

Applications of green chemistry across industries

Pharmaceuticals and drug synthesis. Pharmaceuticals and drug production are essential for enhancing healthcare and treating a range of illnesses. Using green chemistry concepts, it is possible to create chemical products and processes that are socially responsible, economically viable, and environmentally sustainable.

Applying green chemistry concepts to pharmaceutical and drug synthesis can offer a number of advantages, such as lowering the waste produced during medication production and improving the safety of pharmaceutical goods. Particularly in the synthesis of pharmaceuticals and medication development, green chemistry ideas and practices are increasingly being used in the pharmaceutical business. The following are some of the major uses and advantages of green chemistry in this industry.

1. Choosing eco-friendly solvents. Compared to dangerous or less secure solvents, water is frequently the most effective and ecologically benign solvent for generating high yields in drug production. As a result, less harmful compounds are used and the synthesis process has a less negative impact on the environment [42].

2. Alternative reaction media. Green chemistry promotes the use of alternative reaction media that can increase the effectiveness and sustainability of drug production, such as ionic liquids or supercritical fluids.

3. Resource effectiveness in synthesis methods. Green chemistry attempts to make the most of the effective use of resources, such as energy and raw materials, in the synthesis of pharmaceuticals [41].

4. Reduced environmental impact of medication development. Green chemistry principles can be used at every stage of a pharmaceutical product's lifetime, from formulation to manufacturing to packaging. This includes the design of API. This all-encompassing strategy reduces risks and environmental damage while enhancing the drug's overall sustainability. Despite the fact that the implementation of green chemistry principles may initially be seen as a barrier for the pharmaceutical industry, businesses are now realising the long-term cost savings and efficiency gains it delivers.

Materials science and sustainable materials. In order to create sustainable products and procedures with a less environmental impact, materials science can use green chemistry principles. With the intention of reducing resource use, waste production, and harmful emissions, sustainable materials are developed and produced [25]. Green chemistry has several significant applications in this industry, as well as several advantages.

1. Renewable raw materials. A major goal of green chemistry in materials science is the effective and environmentally friendly conversion of renewable raw materials into usable chemicals and fuels. This lessens the need for fossil fuels and lessens how much material manufacturing affects the environment.

2. Customising atomic characteristics. Materials science and chemistry are utilised to make artificial materials by either customising the atomic properties of a specific material or by using living organisms, like yeast, to make green chemicals. The creation of environmentally benign and sustainable materials is made possible by this method [43].

Agriculture and agrochemicals. Agriculture and the creation of agrochemicals are increasingly utilising green chemistry principles and techniques. The following are some of the major uses and advantages of green chemistry in this industry.

1. Using fewer dangerous chemicals. Green chemistry attempts to use fewer dangerous chemicals in agriculture and agrochemicals, reducing their effects on the environment and human health. This includes the creation of insecticides and fertilisers that are safer and more environmentally friendly [44].

2. Resource efficiency. Green chemistry encourages the effective use of resources, such as energy and water, in agriculture and the production of agrochemicals. This lessens trash generation and the negative effects of these operations on the environment.

3. Renewable raw materials. One of the main focuses of green chemistry in agriculture is the utilisation of renewable raw resources, such as biomass. This reduces reliance on fossil fuels and lessens the negative effects of agrochemical production on the environment [45].

4. Compound design for environmental friendliness. Compounds are designed using green chemistry concepts to be as ecologically friendly as possible, minimising their effects on human health, wildlife, and the environment. This strategy is essential for the creation of sustainable agrochemicals.

5. Pest management. Integrated pest management is the employment of a variety of pest control approaches, such as biological control, crop rotation, and the use of pheromones. Green chemistry principles are employed in integrated pest management [46].

Chemical manufacturing and industrial processes. Green chemistry ideas and methods are increasingly used in commercial and industrial chemical production. Some of the most important uses and advantages of green chemistry in this industry are given below.

1. Reduction on the use of dangerous substances. Green chemistry attempts to create chemical products and processes that cut down on, if not completely eliminate, the use or creation of dangerous compounds. By stopping pollution at the molecular level, this contributes to safeguarding both human health and the environment [47].

2. Utilisation of resources wisely. Green chemistry encourages the wise use of resources in industrial and chemical manufacturing, including energy and raw materials. This lessens waste generation and the environmental effect of these activities.

3. Renewable feedstocks. One of the main goals of green chemistry in chemical production is the use of renewable feedstocks, such as biomass. This lessens the need for fossil fuels and lessens how much chemical production affects the environment.

4. Catalytic processes. Catalytic processes, which can improve chemical reaction efficiency and lessen the demand for stoichiometric reagents, are emphasised in green chemistry. This lessens trash generation and the environmental impact of chemical production [48].

Energy and renewable energy technologies. The field of energy and renewable energy technologies is seeing an increase in the use of green chemistry ideas and practices. The following are some of the major uses and advantages of green chemistry in this industry.

1. Energy storage. The creation of efficient and sustainable energy storage technology, such batteries and supercapacitors, uses green chemistry. These technologies are essential for making use of renewable energy sources efficiently [49].

2. Renewable feedstocks. Green chemistry advocates the use of biomass and other renewable feedstocks in the synthesis of chemicals and energy. This lessens the need for fossil fuels and lessens the negative effects of energy production on the environment.

3. Renewable energy. Green chemistry has a role to play in the creation of innovative materials for applications involving renewable energy. The field of energy and renewable energy technologies is seeing an increase in the use of green chemistry ideas and practices [50].

Future prospects of green chemistry

Green chemistry has bright future possibilities thanks to growing interest and use in many different industries. The efficient and clean conversion of renewable raw materials into functional chemicals and fuels is made possible by green chemistry, which is playing a significant part in this process [51]. This lessens the need for fossil fuels and lessens how much chemical production affects the environment. Green, low-carbon, and recycling-friendly technologies will reinvent energy and chemicals in the future. The rational design of catalytic routes is based on green chemistry concepts, which can increase the effectiveness and sustainability of energy and chemical production. Green chemistry is spreading across a variety of industries, with interest rising in both academic and professional contexts. This growth is being prompted by the demand for more ecologically friendly and sustainable solutions across a number of industries, including materials science, pharmaceuticals, agriculture, and energy. Major firms in the chemical sector are concentrating on R & D to create green chemicals and technology. In the market for green chemicals, businesses like Koninklijke DSM N. V., Mitsubishi Chemical Holdings Corporation, GFBiochemicals Ltd., and Evonik Industries AG are constantly innovating their goods and technology [52].

The role of green chemistry in a sustainable future. Several examples of green chemistry's contribution to a sustainable future are given below.

1. Hazardous substance reduction. The goal of green chemistry is to create chemical processes and products with minimal or no use of hazardous materials. By lowering the possibility of negative impacts, this strategy contributes to the protection of human health and the environment [53].

2. Saving resources. Sustainability of resource use is promoted through green chemistry, which uses renewable feedstocks and more effective production methods to save and conserve resources like water and energy. This aids in developing a more environmentally and economically stable use of natural resources over the long run.

3. Reducing waste. Atom economy and the utilisation of renewable feedstocks are two green chemistry principles that help to cut down on waste in chemical processes. This not only aids in resource conservation but also lessens the negative environmental effects of garbage disposal [54].

4. Creating safer chemicals and materials. Green chemistry is concerned with creating chemicals and materials that are both safer for the environment and people. This includes the creation of more environmentally friendly manufacturing techniques for pharmaceuticals, fine chemicals, commodity chemicals, and polymers as well as the use of cleaner solvents and auxiliaries [55].

5. Enabling clean and energy-efficient processes. Green chemistry encourages the development of chemical processes and technologies that are both clean and energy-efficient, both of which are necessary for accomplishing sustainable development objectives [56].

6. Waste valorisation. Looking to the future, there is still a great need for the transition from a traditional linear flow of materials in a «take-make-use-dispose» economy to a greener, circular economy. We need to rethink how to close the loops of production chains. In particular, there is a good example when the spent coagulation bath of the new green hydrocellulose fibers production process is used as a mineral fertiliser and being mixed with hydrolysed lignin (by-product of the bioethanol production) can be used as an organo-mineral fertiliser [57].

Conclusions

The developments in green chemistry, particularly in the area of sustainable synthesis and processes, represent a profound and paradigm-shifting change in the way we view and practice chemistry. These advancements are a reaction to today's most urgent problems, such as resource depletion, environmental degradation, and public health issues. We have moved toward a more responsible and environmentally aware future thanks to the fundamentals of green chemistry, which put sustainability, safety, and efficiency first. The significant decrease in environmental impact caused by chemical processes is one of the main accomplishments of green chemistry. Green chemistry has aided in the development of cleaner and more environmentally friendly industrial processes by adding eco-friendly solvents, reducing waste production, and improving reaction routes. Green chemistry has numerous applications in a wide range of fields, including medicine, materials research, agriculture, and energy production. In the pharmaceutical industry, the creation of safer and more effective medication synthesis techniques not only assures patients' health and wellbeing, but also fits with pharmaceutical companies' ethical obligation to put environmental and human safety first. In materials science, the discovery of sustainable materials opens up new opportunities for environmentally responsible building, packaging, and product design. The materials business may considerably lower its carbon footprint and advance a circular economy by utilising renewable feedstocks, recyclable parts, and non-toxic additives. Green chemistry has also sparked innovation in energy generation and storage, enabling the creation of more effective and eco-friendly technology. In order to reduce the negative effects that energy-related processes have on the environment, it is essential to use green solvents, sustainable catalysts, and energy-efficient synthesis methods. It's important to recognise that the path to a sustainable chemical industry is one that is still being travelled. There are still obstacles to overcome, such as the need for further research, funding, and education to promote the concepts of green chemistry. Furthermore, in order to ensure that green chemistry is widely and uniformly used, regulatory frameworks and international cooperation are crucial.

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