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Review

Sustainable Catalysis: Navigating Challenges and Embracing Opportunities for a Greener Future

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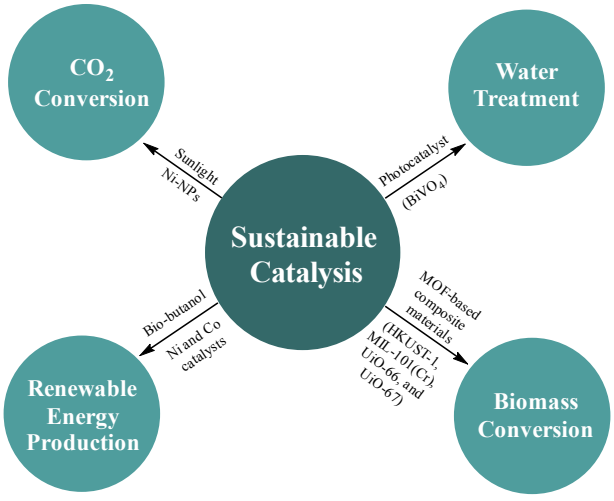
Abstract

Catalysis plays a crucial role in sustainable chemistry, as demonstrated in this review article. The introduction highlights the importance of catalysis in sustainability and summarizes catalysis research. In this review, we discussed sustainable catalysis, including green chemistry, sustainable catalysis criteria, and catalytic reactions. These examples demonstrate CO_2 conversion, alcohol dehydrogenation, alkene oxidation, and biomass-to-biofuel conversion using zeolites. This study also examines sustainable catalysis difficulties like stability, synthesis, design, recovery, reuse, scale-up, and commercialization. Sustainable catalysis can be achieved via bio-inspired catalysts, renewable energy sources, nano-catalysis methods, computational methods, and innovative catalysts developed for sustainable chemistry. This study also includes sustainable catalysis case studies for CO_2, biomass, water treatment, and renewable energy conversion. The review finishes with sustainable catalysis research directions. These directions include studying metal-free catalysis, integrating catalysis with other sustainable fuel cell technologies, implementing sustainable catalysis in industry, and its environmental and societal impacts. The topic covers photocatalysis, heterogeneous catalysis, and electrocatalysis, highlighting their environmental and economic effects. This comprehensive study of sustainable catalysis shows its potential to transform chemical reactions while emphasizing environmental and social concerns, improving green chemistry.

Keywords: Catalysis, Sustainable Chemistry, Green Chemistry, Catalyst recovery, Bio-inspired Catalyst

Graphical Abstract:



1. Introduction

Catalysis is a fundamental area of chemistry [1]. The term catalysis originates from the Greek word katalysis, which means dissolution or decomposition [2]. Jöns Jacob Berzelius, a chemist from Sweden, is credited with the earliest recorded use of catalysis in chemistry during the beginning of the 19th century [3]; they coined the term to describe the acceleration of chemical reactions by substances that were not exhausted in the response itself [4]. Catalysis increases the reaction rate by including a small quantity of purported catalyst that remains unaltered throughout the process. Oswald demonstrated the kinetic character of catalysis phenomena and defined in 1895, around 60 years after Berzelius*, "A catalyst is a material that can enhance the pace of a chemical reaction without being consumed in the reaction or becoming a part of the resulting products"*. By the International Union of Pure and Applied Chemistry (IUPAC), it is a material that, existing in small amounts, accelerates the pace at which chemical equilibrium is reached without undergoing chemical change itself [1].

The crowning achievement of chemical reactions is the catalyst. The utilization of catalysts is prevalent in chemical industries. The need for environmental stimuli has risen since around 1970 to preserve living standards and safeguard the environment. The industrial sector is continuously seeking new catalysts that can decrease production expenses, minimize environmental contamination, possess high energy efficiency, and resist catalytic poisoning while also being reusable [5].

Industries such as agriculture, food, fruit, pulp, and dead organic matter generate copious amounts of waste daily. Waste management is a global problem, and waste deposition may be quite concerning if it needs to be adequately handled. Recycling waste into valuable items has gained much attention nowadays [6]. Solid waste is a source for both alternative renewable feedstock and catalyst production in the context of organic conversions. Such catalysts made from waste can increase the energy and atom efficiency of established and inventive chemical methods [7].

According to a recent study, catalysis is responsible for producing 95% of products by volume and 70% by methods, which make up almost 80% of the industry's added value. Most chemical processes necessitate heterogeneous catalysts, which account for 80% of the stimuli. Homogeneous catalysts comprise 15% of the catalysts employed, while bio catalysts constitute only 5% [8].

The catalyst and reactants are in a similar phase during homogeneous catalysis [9]. The catalyst, typically a soluble molecule [10,11], combines with the reactants to create an intermediate complex that produces the desired product. Homogeneous catalysts are complexes of an organic ligand ring around a metal center. The ligands give the metal complex solubility and stability and may be employed to adjust a catalyst's selectivity to produce a specific desired product [12]. Numerous sectors, including those that make plastics, medicines, and fine chemicals, have employed homogeneous catalysis extensively [13-16].

In heterogeneous catalysis, the catalyst is often solid in a liquid or gaseous reaction mixture, existing in a distinct stage from the reactants [14]. Heterogeneous catalysts are not dissolved in the media where the reaction occurs [17]. Typically, heterogeneous catalysts are solids that fall into one of three categories: insulators, semiconductors, and conductors. Insulators include metal oxides, solid acids or bases (including heteropolyacids), natural clays, silica-alumina, and zeolites. Semiconductors include oxides and sulfides, while conductors comprise metals and alloys. Oxides catalyze oxidation processes, while sulfide catalysts are used for desulfurization reactions. Acid/base solids work in procedures with carbocationic/carbanionic mediators, and insulator oxides catalyze dehydration. Heterogeneous catalysis has been extensively exploited in several sectors, including the creation of chemicals, fuels, and polymers [1].

An essential strategy in sustainable chemistry is enzyme catalysis. By reducing the activation energy necessary for a process, enzymes and biological macromolecules can speed up the pace of biochemical reactions. High selectivity, high efficiency, the capacity to function in a moderate environment, and catalytic recyclability are only a few benefits that enzymes provide [18]. Enzymatic methods are adopted for the production of bio-based monomers [19], the transformation of biomass into value-added chemicals [20], the degradation of plastic waste [21, 22], and the production of biodegradable

surfactants [23]. An essential component of enzymatic catalysis is the reduction of harmful chemicals and energy-intensive processes using enzymes rather than conventional chemical catalysts. Many firms, including those that produce food, medications, and biofuels, have extensively used enzyme catalysis [24].

1.1 Significance of catalysis in the context of sustainable chemistry

Catalysis is a key enabling technology that underpins the global economy and is crucial in sustainable chemistry for human well-being [25]. Catalysis is fundamental to many sectors, notably chemical, petroleum, agricultural, polymer, electronics, and medicines. Catalytic reactions account for more than 90% of all compounds. With a predicted CAGR of 4.9% from 2021 to 2030, the worldwide catalyst market, valued at $35.5 billion in 2020, would increase to $57.5 billion by 2030. Catalysis offers several benefits to businesses, including cost reductions, time savings, and waste reduction [26]. It is well acknowledged that at least one catalytic phase is involved in 85–90% of commercial chemical processes. The primary goals of using a catalyst are to achieve the high activity or conversion of reactants and overall high selectivity to a desired product [27]. The latter property avoids or limits the need for a separation/purification procedure, which involves significant steps to consider, especially considering economic and general environmental concerns [28]. One of the 12 green chemistry principles is catalysis [29]. Catalytic transformations, as contrasted with stoichiometric, non-selective reactions, avoid waste at the source and improve the yield of the valuable product in less time and with less energy. Additionally, catalysis makes clever synthetic design possible, allowing for shorter paths to high-value products and reducing the overall carbon footprint of chemical production [30, 31].

1.2 Brief overview of the current state of catalysis research

Catalysis research is presented at the forefront of academic studies into sustainable chemistry and energy generation. A thorough investigation of the function of transition metal oxygen anion clusters as homogeneous catalysts may be found in (Hill & Prosser-McCartha, 1995) work. The work also addressed the processes and chemical interactions that produce various sorts of oxygen anion clusters, such as mononuclear and polynuclear complexes, and the methods used to analyze these compounds, such as X-ray crystallography, spectroscopy, and electrochemistry [32]. Lignin is a significant part of lignocellulose and has a strong, asymmetrical polymeric structure that makes it a potential sustainable source of aromatics. Sun and his co-workers examined recent methods for depolymerizing lignin into distinct compounds using catalytic or biocatalytic techniques. The formation of polymers or pharmaceutically effective compounds was one possible use for novel aromatics, which was discussed. A summary of the current methods for functionalizing or DE functionalizing lignin-based compounds was also provided. Whenever possible, the entire sequence of processes involved in producing and applying lignocellulosic materials was traced, from the initial raw material to the DE polymerization stage and eventual utilization in various applications. This allowed identifying specific lignin-based compounds that may serve as lignin-derived platform chemicals.

Chemical processes and reactions require one or more liquid phases, which help to supply. Most solvents are synthetic, while some are found in nature and can even be found in huge quantities. In the past, chemists exclusively chose solvents that would support their goals. The possible effects of solvents have developed into crucial selection criteria due to the growing significance of regional, national, and international health and environmental concerns. Utilizing eco-friendly solvents benefits both the chemical sector and the scientific research community [33]. Biomass, a sustainable and renewable resource, holds great potential as a feedstock for synthesizing carbon compounds and might replace fossil fuel-based processes shortly. In 2018, Mika et al. provided a detailed overview of various catalytic processes that convert carbohydrates into strategy chemicals. Their work included analyzing pertinent mechanistic details and biochemical production routes and methods. Several factors will determine the sustainability of the chemical industry utilizing biomass,

such as the accessibility of the feedstock, the viability of the conversion techniques, and the distribution of the resource across various regions, in addition to the impact of weather-induced replacement cycles. Energy needs, trash generated during manufacturing, and environmental cleanup of these wastes all impact sustainability. It also included a summary of the various sustainability measures [34].

Metal-organic framework (MOF) catalysts' crystalline nature allows for a detailed comprehension of the molecular configuration of the catalytically active site. In their research published in 2022, Goetjen and his colleagues examined the creation and analysis of a catalyst that utilized MOFs. Their investigation included the use of Transmission Electron Microscopy (TEM) and X-ray diffraction to analyze the structure of the catalyst. Following activation using $AlEt_2Cl$ (DEAC), the Cr-SIM-NU-1000 catalyst, MOF-based and containing Cr^{+3}, proved to be a viable option for the polymerization of ethylene and the production of crystalline linear polyethylene (PE). Cr-SIM-NU-1000 can be utilized for atomically accurate analysis of the pre-catalyst configuration in an olefin polymerization system. In their study, the researchers also investigate the catalyst's selectivity and polymerization activity, demonstrating that it has high activity and generates high molecular weight polyethylene with low molecular weight ranges. The development of next-generation heterogeneous catalytic system mechanism and inputs were also briefly discussed [35].

Xiao and his co-workers investigated the immobilization of Ag nanoparticles (NPs) on MOFs that had been functionalized with amines and were used to explore the catalytic degradation of organic contaminants in water. The authors emphasize the necessity for efficient and long-lasting remediation solutions and the rising worry about water contamination brought on by the discharge of organic pollutants from diverse businesses. The work focuses on using MOFs as catalytic supports since they can improve the stability and activity of metal NPs for the oxidation of organic impurities. Experimental findings provide evidence for the enormous catalytic activity of the immobilization of Ag NPs on MOFs that had been functionalized with amines for the degradation of two commonly used organic pollutants, methylene blue and rhodamine B. The authors additionally address the mechanism of the catalytic process, emphasizing the way amine-functionalized MOFs help with the adsorption and activation of organic pollutants along with the way Ag NPs assist with producing reactive oxygen species, which are beneficial with the degradation of pollutants [36].

KILIC and his colleagues demonstrated sustainable catalytic methods for altering carbon dioxide (CO_2) to value-added compounds, utilizing effective and solvent-free catalysts based on double complex salts (DCS) containing cobaloxime. Their research objective was to aid in the battle against climate change by diminishing the amount of greenhouse gas emissions. To mitigate the environmental impact of chemical manufacturing and reduce their dependence on fossil fuels, utilizing CO_2 as a raw material for producing chemicals with high value has been formulated as a conceivable solution. For the transformation of CO_2 into methanol and dimethyl carbonate (DMC), two precious compounds with copious commercial applications, cobaloxime-based DCS as catalysts, show potential. Experimental results show that these catalysts have excellent selectivity, catalytic activity, and capacity to function. They also explored the role of the anion in the DCS, which they claim may be crucial in stabilizing the intermediates and boosting the total catalytic activity.

Overall, the work reveals significant illumination on the usage of MOF-based metal nanoparticles as water remediation catalysts and emphasizes the potential of this strategy for creating efficient and long-lasting water treatment solutions [37].

The fundamental goal of current research is to create more effective, selective, and long-lasting catalysts for diverse chemical reactions and molecular catalysis processes. The use of renewable feed stocks and sustainable procedures, which could help mitigate the environmental effect of chemical synthesis, is one of the main topics of research in catalysis. New catalyst materials with unique catalytic capabilities and more design liberty, including MOFs, zeolites, and carbon-

based substances, are also being studied by researchers for their potential. Catalysis research also significantly benefits from developments in computational approaches that make predicting and refining catalyst structures and reaction pathways easier and more accurate. These initiatives could significantly advance sustainable chemistry and energy production in future decades.

2. Sustainable catalysis, an overview

The scientific community coined the term "green chemistry" in the early 1990s, which journalists immediately embraced as an innovative approach. This approach was in contrast to the established industrial practice of polluting first and then cleaning up, which was then considered the norm. The idea quickly acquired momentum, and numerous research institutions, publications, and journals now use this definition, though with a different meaning. According to the definition provided by the US Environmental Protection Agency (EPA), it refers to the utilization of chemical principles to prevent pollution and design chemical processes and products that are environmentally benign.

To advance green chemistry, EPA outlined the alternative synthetic pathways, including using sustainable and less hazardous starting materials such as biomass or natural processes like photochemistry and biomimetic synthesis. Alternate reaction conditions include enhanced selectivity, lower waste and emission levels, or solvents with less adverse environmental and human health effects. Creating sustainable chemicals less hazardous than existing substitutes or naturally less likely to cause accidents [38].

In some cases, "green chemistry" and "sustainable chemistry" are mutually exclusive terms [39]. The definition has a significant distinction: whereas sustainable chemistry involves a cost/benefit evaluation that integrates eco-efficiency, monetary progress, and integrity of life, green chemistry envisions the potential for a chemical manufacturing process that is risk-free and free from pollution. The paradigm of sustainable chemistry accentuates the concept of sustainable threat, which means that every chemical process is intrinsically associated with a level of risk during production. To maintain a high quality of life while reducing risks and minimizing the environmental impact to a level acceptable to the ecosystem, chemists and engineers must play a crucial role [40]. An analysis of the chemical industry's progress over the last four decades reveals that the motivation behind each new process was to minimize environmental impacts and hazards while enhancing resource efficiency.

Nevertheless, these advancements were only achievable with a better understanding of process economics that considered social and environmental factors when evaluating costs. Environmental preservation and monetary growth sometimes conflict, but combining them would only be possible by deploying new, enhanced chemical technology. Therefore, R&D is essential for sustainable growth. Recent instances show that innovative eco-efficient processes might allow businesses to take on new market positions [41, 42]. Table 1 shows examples of novel catalytic processes that are environmentally friendly and sustainable.

2.1 Principles of green chemistry

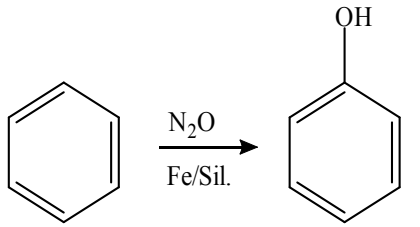
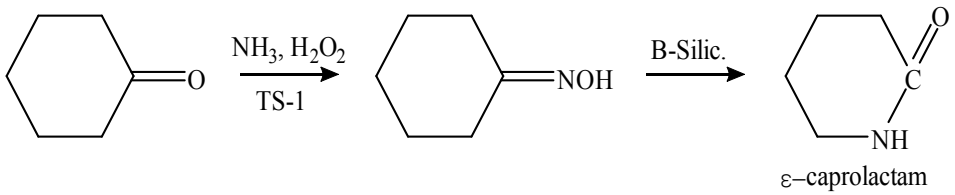
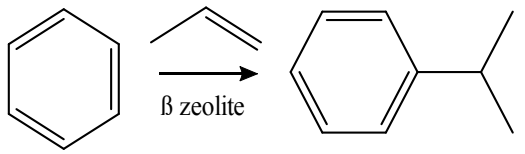
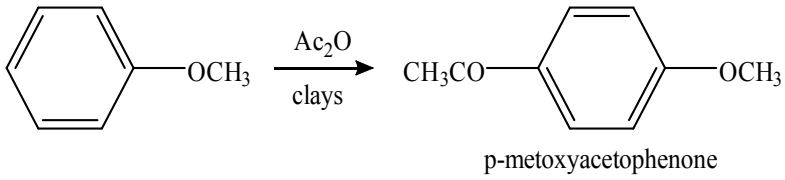
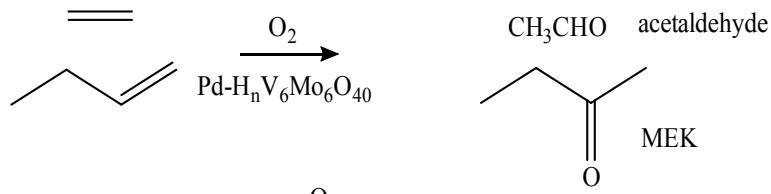
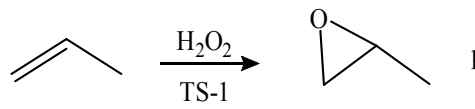
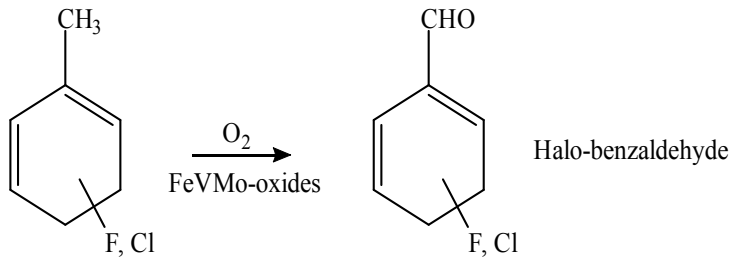
Paul Anastas and John Warner from the EPA established twelve green chemistry principles (GCPs) and illustrated in their practical significance in their 1998 book "Green Chemistry Theory and Practice" [43].

These principles propose that chemicals that pose a danger to the climate must be removed or minimized at every stage of chemical product synthesis, production, and utilization [44].

Green chemistry involves designing chemical products and procedures to minimize or eliminate the use and production of harmful substances. It entails using twelve principles that direct scientists towards more ecologically responsible and sustainable chemical synthesis methods [45]. The twelve principles are;

Waste prevention entails developing procedures that reduce or completely stop the generation of waste material. Do not produce any waste requiring cleaning or treatment [46]. The concept of atom economy emphasizes the efficient utilization of raw materials and minimization of waste generation by maximizing the incorporation of atoms into the final product.

Table 1. Examples of novel catalytic processes that are environmentally friendly and sustainable**.**

Process	Key Characteristics
	**Solutia process** Reusing as a reactant reduces N_2O emissions, a greenhouse gas
	**EniChem process** Waste ammonium sulfate reduction Avoids toxic hydroxylamine use
	**EniChem process** Polyalkylate Waste Reduction
	**Rhodia process** avoids using potentially hazardous catalysts like BF_3, $AlCl_3$ Reduction in waste production
	**Catalytica process** Reduction in the chlorinated waste production
	**EniChem process** Restricts the use of chlorinated organic byproducts in the chlorohydrin process
	**Aventis process** Reduction in waste generation Corrosion Reduction

This strategy seeks to minimize environmental effects, reduce waste production, and use raw materials most efficiently [47]. Create new combinations of safe substances for humans and the environment, and ensure that the production process does not result in any hazardous byproducts [48]. Green chemistry promotes the advancement and application of less detrimental, biodegradable, and ecologically responsible compounds. This strategy attempts to reduce the dangers of chemical manufacturing, utilization, and disposal and their adverse effects on the climate and human health [49]. Avoid

employing auxiliary chemicals such as solvents or separating agents. Use safer chemicals for those who must use these [50]. It is preferable to conduct chemical processes at standard temperature and pressure whenever possible [51]. It is advisable to prioritize the use of renewable feed stocks, which are typically sourced from agricultural waste or products, instead of finite resources like fossil fuels (such as coal, petroleum, or natural gas) or those obtained from mining activities. Depletable feed stocks can be replaced with renewable sources to promote resource sustainability and reduce environmental impact [52]. To reduce waste and promote sustainability, it is suggested to prevent the use of blocking or protective groups, as well as other temporary adjustments, whenever possible. Derivatives can produce waste and require more reagents, negatively impacting the environment. Therefore, it is important to consider alternatives that can minimize waste and resource consumption [53]. Replace stoichiometric reagents with catalytic methods. Catalysts can perform a single reaction repeatedly. Unlike overused reagents, they are efficient in small amounts and can only perform a reaction once, resulting in increased waste generation. Therefore, catalytic methods are more efficient and environmentally friendly [54]. To prevent environmental pollution, it is advisable to create chemical goods and items that can break down into safe substances once they have served their purpose [55]. Incorporate real-time scrutinizing and management during synthesis to minimize the formation of byproducts [56]. By designing chemicals and determining their physical states, such as solid, liquid, or gas, it is possible to minimize chemical accidents such as environmental discharges, fires, and explosions [57]. Figure 1 shows the diagram of green chemistry principles (GCPs).

2.2 Criteria for sustainable catalysis

Sustainable catalysis can help to promote the creation of chemical procedures that are both economically and environmentally reasonable. Efficiency is paramount, requiring high catalytic activity, stability, and selectivity [58]. The catalyst should resist deactivation and maintain stability during reaction conditions to allow for reuse [59]. Figure 2 depicts the diagram of sustainable catalysis criteria.

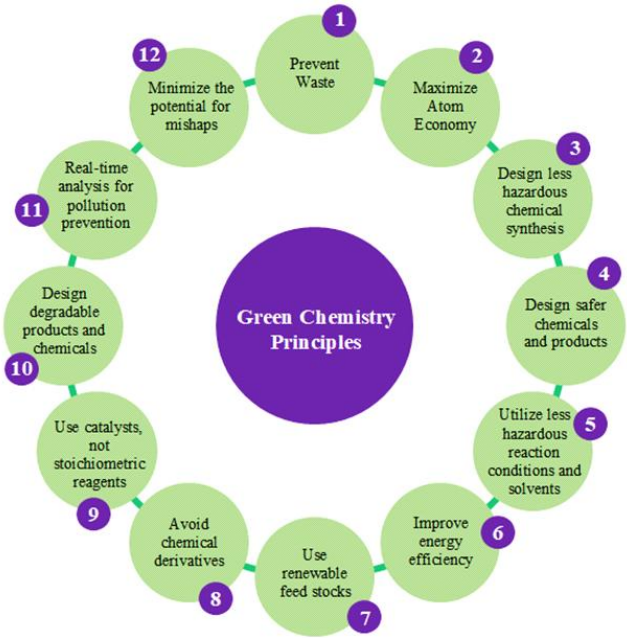


Figure 1. Diagram of Green Chemistry Principles (GCPs). (Reproduced with permission: Copyright 2023, MDPI [147]).

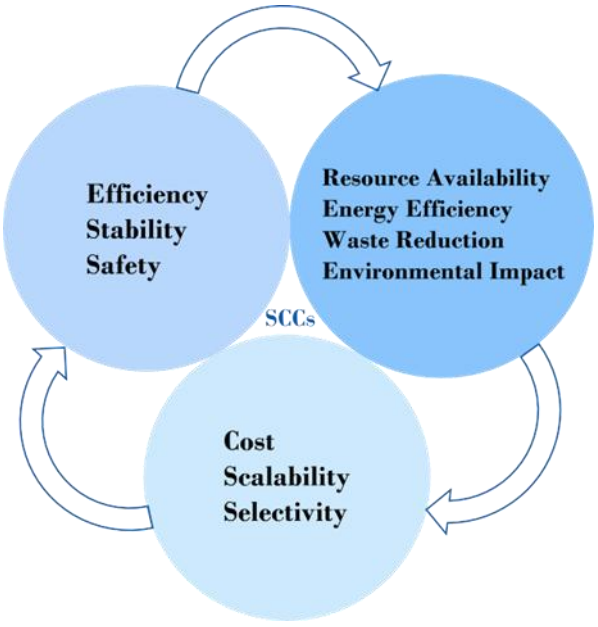


Figure 2. Diagram of Sustainable Catalysis Criteria. (Reproduced with permission: Copyright 2022, Elsevier [148]).

Safety is a crucial consideration, meaning sustainable catalysis should not involve potentially hazardous substances like heavy metals or dangerous solvents, with a focus on preventing accidents and mishaps during reactions [60]. Resource

availability emphasizes the use of readily available and reasonably priced catalysts, and whenever possible, the incorporation of renewable materials [61]. Energy efficiency is a key goal, with a focus on reducing energy consumption and utilizing renewable energy sources [62]. Waste reduction strategies involve recyclable catalysts and conditions that minimize waste production and byproducts [63]. Low environmental impact entails minimizing waste generation, energy consumption, and resource usage while preventing the release of harmful pollutants like greenhouse gases [64]. Cost-effectiveness aims to use affordable and readily available materials, reduce the reliance on expensive catalysts, and keep operational costs low, with an eye on competitive manufacturing costs [65]. Scalability is crucial, making sustainable catalysis suitable for large-scale industrial applications and adaptable to various reaction conditions [66]. Lastly, selectivity is vital, ensuring that the catalysis is highly selective, catalyzing only the intended reactions and minimizing waste and the need for additional reagents [67].

2.3 Examples of sustainable catalytic reactions

Several standard environmentally friendly catalytic processes may create chemicals and fuels.

2.3.1 Conversion of CO_2 to methanol

The increasing concern over environmental change and the exhaustion of fossil fuels has spurred the examination of substitute carbon sources to produce energy and chemicals. CO_2 is widely considered the main contributor to global warming. However, it holds tremendous potential as a primal matter for manufacturing fine chemicals [68]. Acetic acid, formaldehyde, and other important chemical intermediates can all be produced with the help of methanol, an essential raw material. Industrially, it is produced from mixtures of H_2, CO_2, and CO using a $Cu/ZnO/Al_2O_3$ catalyst in at high pressures (50-100atm) and temperatures (450K-600K). This reaction, represented as follows (Equation 1), holds great promise for reducing greenhouse gas emissions [69].

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \quad (1)$$

2.3.2 Dehydrogenation of alcohols

The transformation of alcohols into ketones or aldehydes is a crucial step in organic synthesis, performed on a large scale in industries and laboratory research [70].

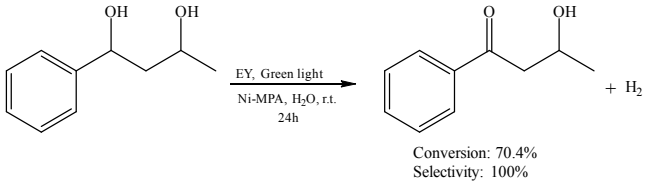


Figure 3. The process of converting 1-methyl-3-phenyl-propylene glycol into its oxidized form. (Reproduced with permission: Copyright 2018, MDPI [149]).

In the photocatalytic conversion of benzylic alcohols, the organic dye eosin Y (EY) is employed as the photocatalyst to instigate the reaction. Under room temperature and Argon atmosphere, Ni-MPA can create EY^+ in oxygen-free aqueous or organo-aqueous solutions. This EY^+ can be used to oxidize benzylic alcohol, arising in the appearance of alcohol cation radicals and the regeneration of EY. Hydrogenation comprises several steps of electron and proton transfer, in which Ni-MPA plays a crucial function in producing hydrogen. The photocatalytic dehydrogenation of 1-methyl-3-phenyl-propylene glycol was accomplished in a homogeneous solution, with 100% selectivity towards the product of benzyl alcohol dehydrogenation [71]. Figure 3 depicts the process of converting 1-methyl-3-phenyl-propylene glycol into its oxidized form.

2.3.3 Oxidation of alkenes

In industrial organic synthesis, alkene epoxidation is a precious process. Epoxides produced as a result are crucial building blocks in producing several significant chemicals, including epoxy resins, fragrances, and plasticizers [72]. Molybdenum-VI (Mo-IV) modified Zr-based metal-organic framework (Zr-MOF) catalysts are effective promoters of olefin epoxidation. The post-synthesis modification (PSM) technique was employed to modify a stable and porous Zr-based metal-organic framework ($UiO-66(NH_2)$) with salicylaldehyde, 2-pyridine chloride or pyridine-2-aldehyde. The resulting framework was then combined with a Mo-based catalyst using a chelating approach. Despite acting as carriers for the Mo-IV catalyst, the MOFs enhance the interaction between the substrate and the active center of the Mo-IV

mixture. The efficient epoxidation of olefins is enabled by the MOF's large pore magnitude and the Mo catalyst's excellent distribution on Zr-MOF, which facilitates the proper connection between the substrate and the catalytically active center. This increases the process's pace and improves the catalyst's efficiency. The Zr-MOF catalyst demonstrated excellent performance in the epoxidation of olefins using either 70% tertiary butyl hydroperoxide (TBHP) or 30% H_2O_2 as the source of oxygen. The catalysts used for the epoxidation of olefins were the Mo-Zr-MOFs. For improved catalytic performance in the epoxidation of olefins, MoO_2 $(acac)_2$ was also deposited on Zr-MOF [73]. The process of using Zr (IV)-based metal-organic frameworks (MOFs) to epoxidize cis-cyclooctene is shown in figure 4.

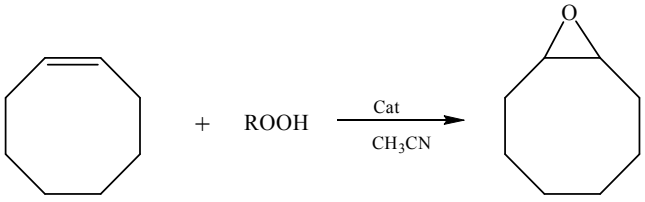


Figure 4: The process of using Zr(IV)-based metal-organic frameworks (MOFs) to epoxidize cis-cyclooctene. (Reproduced with permission: Copyright 2022, Elsevier [150]).

2.3.4 Conversion of biomass to biofuels using zeolites

Zeolites, unique crystalline alum inosilicates with distinct cavities or channels, contain Lewis and Bronsted acid sites [74]. Zeolites have been used successfully to dehydrate glucose in water due to their adjustable outstanding shape selectivities, improved thermostabilities, and acidities [75]. Several types of zeolites, such as HY-zeolite, H-mordenite, Hβ-zeolite, and HZSM-5, were reported to enhance the dehydration of glucose to 5-hydroxymethylfurfural (HMF) in [Bmim]Cl [76]. The maximum catalytic activity was found in Hβ-zeolite, which produced an HMF outcome of 50.3% and 80.6% glucose transformation in under 50 min at a reaction temperature of 423 K using a distinctive BEA pattern and a modest Si/Al distribution of 25 [77].

The Hβ-zeolite/ [Bmim]Cl system's vigorous catalytic activity was due to four factors. Firstly, the complete dissolution of glucose in [Bmim]Cl led to increased glucose availability to the catalyst. Secondly, the presence of Cl^- in [Bmim]Cl provided significant advantages for the isomerization of glucose to fructose through the Lewis acid sites of Hβ-zeolite. The third factor contributing to the enhancement of glucose dehydration to HMF was the interaction between [Bmim]Cl and the Bronsted acid sites of Hβ-zeolite, which facilitated the release of H^+ ions that effectively catalyzed the dehydration of fructose to HMF [78].

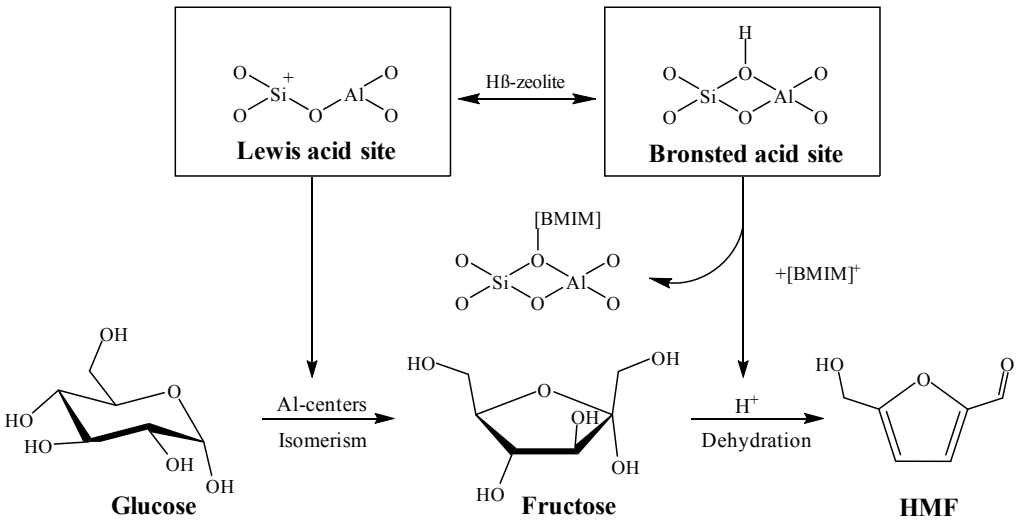


Figure 5. The process of converting glucose to HMF was carried out in the presence of Hβ-zeolite and [Bmim] Cl. (Reproduced with permission: Copyright 2017, Elsevier [151]).

In conclusion, the presence of $[Bmim]^+$ in [Bmim]Cl solution could potentially stabilize HMF and prevent its further breakdown. Moreover, the HMF production efficiency of Hβ-zeolite (Si/Al = 25) decreased to 35.6% after being used three times, which was caused by the deposition of humans on the material's surface [77]. Figure 5 depicts the process of converting glucose to HMF in the presence of Hβ-zeolite and [Bmim]Cl.

3. Challenges in Sustainable Catalysis

The challenges to global energy systems are discussed, including those posed by rising populations and economies, as well as environmental concerns and a rise in energy use. To meet their energy needs, many Asian countries rely significantly on fossil fuels, has led to an undramatic increase in CO_2 emissions. Between 2010 and 2030, analysts predict that Asian demand for both natural gas and coal will rise by 114% and 50%, respectively. As a result, decreasing emissions and improving energy efficiency are crucial to finding solutions to these problems. Significant environmental damage, including climate change, is caused by the increasing concentration of greenhouse gases, mainly CO_2. This is because burning fossil fuels releases harmful pollutants in addition to carbon dioxide. Reducing emissions of greenhouse gases is essential for mitigating climate change concerns. As global energy consumption is expected to expand dramatically in the following years, leading to further increases in CO_2 emissions, energy efficiency is vital to accomplishing this aim. The carbon footprint of industrial processes can be significantly diminished, and energy efficiency improved using sustainable catalysis [78].

Energy efficiency and carbon footprint can be improved by switching to a CO_2 capture and usage (CCU) method rather than conventional carbon capture and storage (CCS). CCU entails capturing CO_2 and using it as a feedstock to produce valuable products, such as energy-related fuels and chemicals, instead of merely storing CO_2. This tactic can be beneficial when working with low concentrations and at room temperature to reduce energy consumption. Superbase and polyethylene glycol are just two examples of chemical absorbents that research has shown can effectively catch and activate CO_2 for use in making chemicals with economic value. The carbon absorbent polyethyleneimine (PEI) has also been demonstrated to be helpful in situ hydrogenation of collected CO_2 into energy-related compounds. Generally, CCU is an appealing strategy for lowering GHG emissions and fostering a more sustainable economy. CCU can help mitigate climate change by reducing the need for irreversible use of stored carbon through carbon recycling and as a feedstock for valuable products [79]. A hybrid solid acid catalyst (SO_4^{2-}/ZIF-67-C@TiO_2) created from metal-organic frameworks can increase energy use efficiency in CO_2 capture by regenerating amines. The catalyst's active components provide a shield by a layer of TiO_2, extending its useful life. Increased CO_2 desorption rates and yields from new Co-Nx sites and protonated groups on the TiO_2 surface reduce power requirements by 36%. Proton transfer and the rupturing of N-C bonds via catalysis are among the potential mechanisms [80]. This paper revealed a method for efficient acid catalysis in CO_2 capture that requires less energy than previous methods. Using a catalytic drive, lignocellulosic biomass can be converted into bio-natural gas. Using a catalyst containing a Ni_2Al_3 alloy phase, the scientists may achieve nearly 100% bio-natural gas conversion from agricultural and forestry residues. After several hours at a moderate 300 degrees Celsius, the overall carbon output of gas products reached as high as 93%. Thirty production cycles demonstrated the catalyst's effectiveness. The technical, economic analysis predicted the process would be competitive with other production methods, and the estimated carbon impact was negligible. Compared to nickel-based alloy catalysts, the Ni_2Al_3 phase exhibits superior catalytic performance in terms of reaction pathways and cleaving C-O and C-C bonds in ethanol. The chemical pathways were further analyzed with density functional theory (DFT) computations [81].

3.1 Catalyst Stability leads to sustainable catalysis

Precious metals are frequently used as catalysts because of their stability, selectivity, and capacity to undergo two-electron oxidation-state transitions. Since they are so simple to define

with standard methods, these catalysts find widespread application in catalytic reactions. However, there is a need for sustainable alternatives due to their scarcity, high cost, and environmental impact. As a result, scientists are working to create sustainable catalysis by discovering new catalysts that do not rely on expensive metals. Sustainable development is defined as growth that satisfies the requirements of the present without jeopardizing the potential of future generations to do the same. Due to their low cost, global availability, and few safety issues, base metals with high crustal abundance are employed as an alternative to precious metals to build more sustainable catalysis. However, the stability, selectivity, and scope of base metal catalysts provide difficulties in their implementation. Since they preferred single-electron transfer processes and needed an inert atmosphere during their synthesis, low-valent base-metal complexes are not helpful in various catalytic transformations. For base metals, free radicals can be generated during single-electron transfer events; these radicals are difficult to regulate and can restrict the usefulness of the substrate. Weak ligand fields in base-metal catalysts make them elusive to separate and describe. Due to their intrinsic reactivity, base metals are more difficult to predict and regulate than precious metals in catalytic reactions. Recent studies have led to effective methods for manipulating the reactivity of base metals, which could have positive societal and environmental effects if used as catalysts. The intrinsic reactivity of base metals, the metal-metal cooperativity of ligands, and the redox activity of redox-active and non-innocent ligands all present exciting possibilities for developing new catalytic processes and fine-tuning Lewis acidities. More studies should yield more refined and long-lasting options for precious metal complexes [82].

Sustainable growth and less reliance on potentially harmful chemical processes are two of the main goals of bio-catalysis, also known as green catalysts. Biocatalysts are a promising alternative to conventional chemistry since they are produced using renewable resources and can catalyze various chemical reactions. Thanks to developments in green chemistry, metagenomics, and computational techniques, novel enzymes with enhanced properties for the pharmaceutical, agricultural, healthcare, and chemical industries have been discovered. Nonetheless, further work is required before these enzymes can be widely used in industry [83]. Heterogeneous catalysis is at the heart of the chemical and energy sectors, making developing selective and efficient active processes crucial. The world could benefit significantly from developing efficient and selective heterogeneous catalytic processes using knowledge gained from basic research [84].

3.2 Synthesis and design of catalysts

Heterogeneous catalysis is evolving to focus on the atomically precise design of active and selective catalysts. Catalyst sintering can only be addressed with a thorough comprehension of the underlying transitory event; therefore, in-situ/operando observation of sintering occurrences is essential. Although chemical and physical methods have been developed to reduce sintering, no silver bullet will work for all materials in all environments. Predictably effective and generally successful anti-sintering solutions require ongoing collaboration between fundamental understanding and innovative material creation [85]. In situ, co-precipitation of Fe^{2+} and Fe^{3+} under primary conditions was used to create the Fe_3O_4 CS nanocomposite catalyst. Carbon disulfide was used as a post-modification, and NH_2-Fe^{3+} functions were added. The magnetically separated multifunctional catalyst displayed high catalytic activity in the aqueous oxidation of benzylic alcohols at room temperature in H_2O_2. Under mild reaction conditions and short reaction durations (usually 1-2 h), the catalyst showed high product yields (>90%), and it could be quickly recovered and reused at least 8 times without significantly decreasing product yields [86].

A novel electrocatalyst was developed using a host-guest technique, featuring Fe-Co dual active sites supported on N-doped porous carbon. This catalyst was specifically designed for the oxygen reduction reaction (ORR) in an acidic electrolyte. Notably, in comparison to the commercial Pt/C catalyst, the newly developed catalyst exhibited superior ORR performance, showcasing an onset potential (Eonset) of 1.06 V and a half-wave potential (E1/2) of 0.863 V. In practical tests

using fuel cells with H_2/O_2 and H_2/air, this catalyst outperformed most reported Pt-free catalysts, underscoring its exceptional efficiency. Moreover, the catalyst demonstrated remarkable long-term stability, withstanding 50,000 electrode measurement cycles and operating continuously for 100 hours (approximately 4 days) in a single-cell setup with H_2/air. This performance indicates the catalyst's promising potential for sustainable and enduring use in electrochemical applications [87].

Activation of O-O is essential for the four-electron oxygen reduction process, and density functional theory studies showed that the dual sites were favored for this purpose. Predicted chirality in horizontal arrays of single-walled carbon nanotubes (SWNTs) can be generated by manipulating the symmetry of the active catalyst surface. Thermodynamic matching was employed to nucleate the SWNTs, selectively, and the nanotubes were produced using uniform-size Mo_2C and WC solid catalysts. Possible applications in sustainable catalysis include predicting growth conditions for desired chirality's using this approach, which provides more degrees of freedom [88].

3.3 Catalyst recovery and reuse

Designing stable catalysts and easily recoverable, creating efficient separation and purification processes, and optimizing reaction conditions to limit catalyst deactivation are all potential jumping-off sites for promoting sustainable catalysis through catalyst recovery and reuse. Using cobalt (II) phthalocyanine-tetra-sodium sulfonate as a catalyst and O_2 as an oxidant in water, the research team established a practical and adaptable technique for forming S-N/S-S bonds. Up to 20 recirculations of the mother liquor are possible with minimal loss of activity and product yield thanks to the catalyst's ease of recovery by filtration and subsequent reuse without treatment. As a result, there is no hope for the environmentally friendly and cost-effective industrial production of disulfides and sulfonamides [89]. Figure 6 shows the mother liquor circulation flowchart diagram.

Although heterogeneous catalysts can be recycled, they typically perform worse than their homogeneous counterparts. Homogeneous catalysts are unstable and may leach the active metal, making recovery difficult and expensive. High surface area, minimal toxicity, and simple separation by external magnetic fields are all advantages of metal complexes supported on [90] catalysts in solution, making heterogeneous catalysis a greener and more cost-effective option. [91]. CuO nanoparticles (NPs) were synthesized by encapsulating them in a biomaterial that served as both a reducing and stabilizing agent, utilizing a photogenic technique. The biosynthesized CuO NPs underwent various characterization methods to ensure their quality. Notably, in the presence of sodium borohydride at room temperature, these CuO NPs exhibited impressive catalytic activity. They efficiently reduced substances like Congo red, methylene blue, and 4-nitrophenol. Importantly, even after six use cycles and the collection of the CuO NPs catalyst via centrifugation, more than 90% conversion efficiency was maintained. This highlights the robust and sustainable catalytic potential of the CuO NPs.

Figure 6. Mother liquor circulation flowchart diagram. (Reproduced with permission: Copyright 2018, Springer Nature [152]).

CuO NPs have considerable potential in reducing poisonous dyes and nitro organic contaminants in water, and ICPAES was used to study their leaching after catalytic application. [92]. The immobilized cobalt complex on chitosan microspheres was employed as a green catalyst for Heck and Sonogashira cross-coupling reactions, marking another critical step forward in the field. Under reaction circumstances, the catalyst was stable and could be recovered with a magnet. It has been successfully recycled at least five times with no discernible loss of catalytic efficiency. This demonstrates the

cobalt catalyst's efficacy, low cost, and long-term viability based on chitosan for various reactions [93]. Figure 7 depicts the Schematic diagram of MNP splitting.

3.4 Scale-up and Commercialization

The Optimal composition of nickel-iron (Ni_3Fe) alloy catalysts depends on the support and metal loading. However, this rational design method has shown promise in replacing noble-metal catalysts for CO_2 metalation. These results show that sustainable catalysis employing Ni3Fe catalysts can be commercialized and scaled up. The physicochemical characteristics and catalytic performance of the NieFe/ (Mg, Al)Ox HT-derived catalysts were consistent and reliable. Keeping the same catalytic activity level, increasing the total metal concentration produced more catalyst mass per batch. Under relevant industrial circumstances, the scaled-up catalysts demonstrated significant CO_2 conversion (up to 79%) and CH_4 selectivity (up to 95%), making them promise for the commercialization of CO_2 methanation for the manufacture of SNG from renewable H_2 and CO_2 [94].

Photoelectrochemical (PEC) water splitting using $BiVO_4$-based photoanodes is a sustainable method of transforming solar energy into chemical energy. Although $BiVO_4$'s absorption of a large proportion of the solar spectrum bodes well for its use as a semiconducting photocatalyst, the material is also linked to limited electron mobility and sluggish water oxidation kinetics. Recent studies have overcome these issues by enhancing the performance of $BiVO_4$-based photoanodes. However, specific issues must be addressed before PEC can be used commercially. These issues concern the long-term stability of the photoanode and scalability of the PEC device. However, the production of clean fuels and chemicals using artificial photosynthesis is still possible, thanks to the advancement of sustainable catalytic processes such as PEC water splitting [95].

High-quality bio-oils from sawdust were produced using catalytic fast pyrolysis (CFP) using three commercially available catalysts. The goal was to find the best catalysts and the proper loading levels before they could be taken to the next level of commercialization and improvement. According to the findings, the H/Ceff ratio, the relative area percentage of hydrocarbons, and the number of distillates in the diesel range were higher in catalytic cases than in non-catalytic bio-oils. The same behavior was seen regardless of the amount of catalyst loading. Oils with H/Ceff ratios greater than 0.6 are promising candidates for hydride oxygenation, and this was the case for all bio-oil products derived from catalytic instances. It was shown, however, that while bio-oil product quality improved, the yield decreased. These results indicate that CFP, when combined with suitable catalysts, may be an effective method for creating high-quality bio-oils that can be commercialized and upgraded to replace conventional fuels, aiding the global economy's decarbonization [96].

4. Opportunities for Sustainable Catalysis

4.1 Bio-inspired Catalyst

Bioinspired catalysts are artificial catalysts that work analogously to naturally occurring enzymes. Methods such as rational design, guided evolution, and combinatorial chemistry are used to develop these catalysts so that chemical reactions can be carried out more effectively and selectively. This research aims to improve the Pd catalyst's activity, efficiency, and selectivity in CO_2 reduction, fuel cell performance, and ethanol oxidation by synthesizing a bio-inspired metal oxide-support catalyst. Pd nanoparticles were supported on NiO/C in a single, environmentally friendly step by employing pomegranate peel extracts as a reducing agent. The resulting Pd-NiO/C mono-catalysts were more active and resistant to poisoning by intermediate oxidation species, making them ideal for oxidizing ethanol. The Nano-catalyst’s improved current efficiency of 45% and cell output of 117m (about 383.86 ft) W demonstrated its selectivity for HCOOH. The synthesis process is cheap, quick, and safe because it uses no dangerous ingredients. The catalyst promotes alternative methods for producing various high-tech electronics and fuel cell materials [97]. Due to its capacity to emulate nature's efficient and selective catalytic processes, bioinspired catalysts have been gaining traction in sustainable catalysis. These catalysts mimic the structure and function of their biological counterparts, such as enzymes, and can be produced without

negatively impacting the surrounding ecosystem. In the presented work, scaffolds to produce dip catalysts were prepared using the surface topographical features of plant leaves; these catalysts proved very effective for Suzuki-Miyaura cross-coupling reactions. As a renewable and biodegradable raw material, plant leaves make an appealing catalyst design idea for environmentally friendly catalysis. The overall environmental impact of the catalyst synthesis is reduced since the straightforward soft lithography approach employed for creating the catalysts is a low-cost, scalable, and environmentally friendly process.

The new bioinspired dip catalysts also showed remarkable activity in the Suzuki-Miyaura cross-coupling reactions. This reaction is crucial to produce different types of organic molecules. This reaction's success with bioinspired catalysts demonstrates their potential for usage in other organic transformations, ultimately leading to greener and more efficient chemical processes.

Creating bioinspired catalysts is essential for sustainable catalysis, providing a new way to create effective and selective catalysts with little environmental impact. The paper demonstrated that using plant leaves as a design inspiration for catalysts is a novel and environmentally friendly approach to creating new catalysts for various chemical processes [98].

4.2 Renewable Energy Sources

Exploiting new energy supplies based on low-carbon and renewable resources are necessary because of the rising global energy demand and the severe environmental challenges of burning fossil fuels.

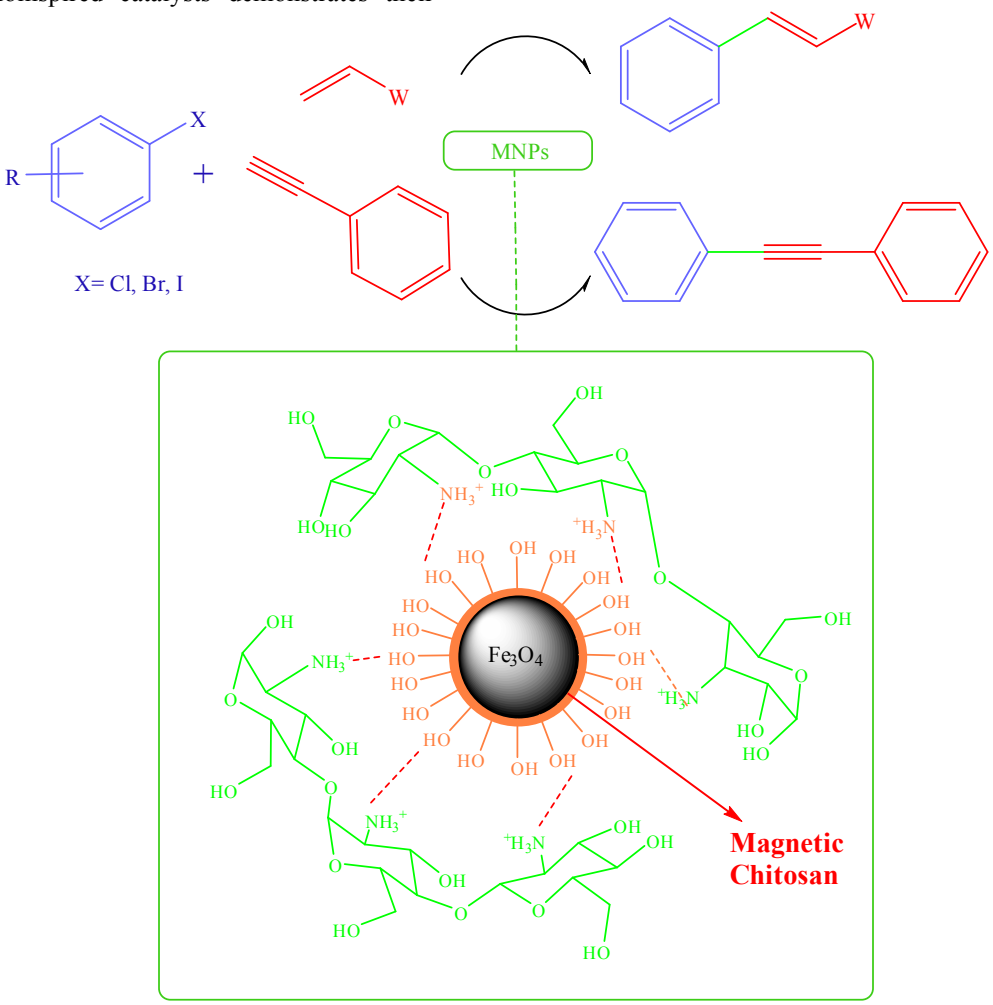


Figure 7. Schematic diagram of MNPs splitting. (Reproduced with permission: Copyright 2012, The American Chemical Society [153].

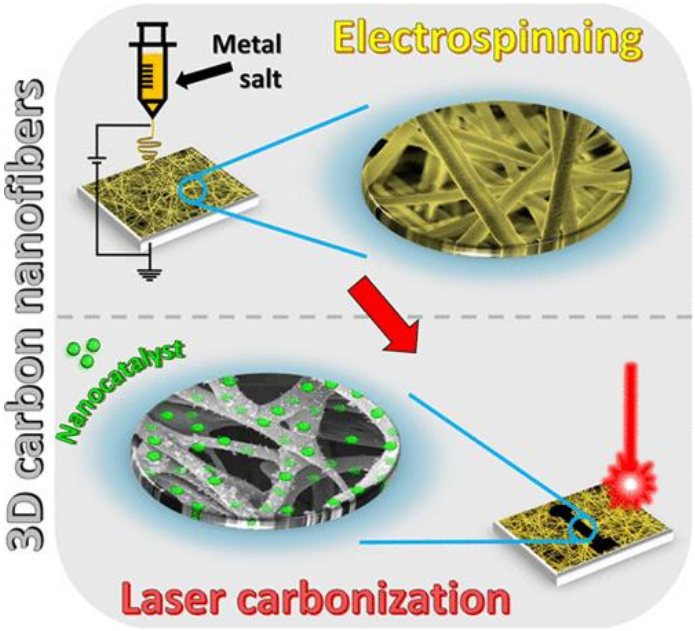


Figure 8. The 3D Carbon Nanofibers for energy storage applications. (Reproduced with permission: Copyright 2023, The American Chemical Society [154]).

The hydrogen evolution reaction (HER) is the preferred method for producing hydrogen from renewable energy sources such as wind and solar. Hydrogen is a clean energy carrier since it produces only water as a byproduct and has a high energy density per unit mass. Due to their high hydrogen content and simple refilling as a liquid, chemical storage materials such as formic acid and ammonia have drawn substantial concerns for H_2 storage. Electrochemical processes powered by renewable energy sources can transform the plentiful H_2O, CO_2, and N_2 in Earth's atmosphere into fuels and chemicals.

However, due to the slow kinetics of the electrochemical reactions, their total energy efficiency still needs to be determined for practical applications. The reactions can be speeded up, and the efficiency is increased with the help of effective catalysts. Research on creating alternative electrocatalysts using cheap and naturally plentiful materials has gained much attention. Hydrogen is produced and stored in the review through numerous clean energy mechanisms, including hydrogen evolution reaction (HER), carbon dioxide reduction, and nitrogen reduction. The correlation between structure/composition and catalytic activity and methods for enhancing performance are focal points of this discussion [99].

Electrochemical and photoelectrochemical water splitting for hydrogen fuel production, fuel cells for clean electricity generation, and batteries for clean energy storage have all been the subject of extensive study and development in response to the rising demand for clean and sustainable energy sources. Crucial chemical reactions in these technologies, such as oxygen reduction, oxygen evolution, and hydrogen evolution, require noble metal catalysts. While noble metals are currently the most effective catalysts for these reactions, their high price and scarcity prevent them from being widely used. Therefore, it is essential to develop catalysts that can effectively convert and store renewable energy at a reasonable cost. The design and synthesis of COF-based catalysts, a new class of molecular frameworks linked by covalent bonds, have recently advanced. Electrocatalysis, photovoltaics, field-effect transistors, light-emitting diodes, selective transport, sensors, and drug delivery systems are all areas in which COFs show promise because of their unique properties, such as their large surface area, high crystallinity, tunable pore size, and unique

molecular architecture. Catalytic activity, long-term stability, and resistance to CO-poisoning have all been demonstrated to be improved upon using COF-based catalysts compared to the best commercial catalyst, Pt. One possible path toward efficient and sustainable energy conversion and storage is using COFs as catalysts for renewable energy sources [100].

Electrochemical conversion of carbon dioxide to usable molecules: the possible use of nanostructured carbon materials as electrocatalysts and supports. Sequestering carbon from the atmosphere, providing energy storage for intermittent renewable sources, and manufacturing fuels and industrial chemicals are ways this technology might help address current concerns about energy security and sustainability. The stability of the CO_2 molecule, the competing hydrogen evolution reaction, and the essential features of efficient catalysts are just a few obstacles this technique must overcome. Future advancement of this technology is anticipated to be facilitated by the application of cutting-edge experimental procedures and theoretical computations. The paragraph also discusses the importance of developing better renewable energy policies and the challenges associated with converting and storing renewable energy. Since CO_2 conversion may be used to make industrial chemicals and fuels, solutions that combine CO_2 reduction systems with renewable energy sources are particularly appealing [101].

4.3 Nano-catalysis

Catalysis has dramatically improved through nanotechnology, which has also reduced its negative impact on the environment. The enhanced catalytic activity and expanded surface area of NPs make them an attractive candidate for environmentally friendly synthesis. Because of their small size and the ability to be quickly recovered and separated, Nano-catalysts combines the best features of homogeneous and heterogeneous catalysis. They are vital to green production, helping pave the way for more efficient and inexpensive manufacturing techniques. Regarding long-term sustainability, Nano-catalysis is quickly becoming a promising new study area. Due to their vast surface area, nanoparticles can improve reaction speeds and selectivity, making them practical and selective catalysts. Nanoparticles' catalytic performance can be optimized by adjusting physical features such as structure, shape, size, and content. By manipulating these features, researchers may build and develop highly active, selective, and long-lasting Nano-catalysis for chemical manufacture, energy conversion, and storage. Compared to their bulk equivalents, Nano-catalysts significantly improve resource efficiency, energy consumption, and waste reduction. Thus, they are an essential instrument for mitigating the adverse effects of chemical processes on the environment. Nanomaterial's atomic coordination and interatomic contacts, among other unique features, are essential to their catalytic efficacy. Catalytic characteristics such as bond relaxation and energy transfer are among the many that researchers can tune. In conclusion, Nano-catalysis presents several prospects for environmentally friendly catalysis, such as enhanced efficiency, selectivity, and longevity performance. Researchers can create highly efficient and long-lasting catalysts for various uses by learning how the physical characteristics of nanoparticles affect catalytic performance [102].

Carbon nanofiber (CNF) Nano-catalysts hybrids for energy storage, synthetic chemistry, and sensors: a new production technique. The existing technologies used to create such hybrids are time-consuming and not conducive to downsizing or mass production. This novel approach uses electrospinning and laser carbonization at room temperature to incorporate Ni NPs into 3D CNFs of arbitrary structure. The result is a dense network of CNFs to which tiny Ni NPs have adhered consistently. This approach is flexible enough to be used with a wide variety of metal precursors, and it opens the door for the use of 3D CNF Nano-catalysts hybrids in point-of-care settings where excellent performance, sustainability, and cost-effective production are of the utmost significance [103]. Figure 8 shows 3D Carbon nanofibers for energy storage applications.

4.4 Computational Methods and Artificial Intelligence

Sustainable energy systems and materials design are only two examples of the many fields that could benefit from the advent of quantum computing (QC). However, QC and quantum artificial intelligence can manage renewable and sustainable energy systems at bigger sizes than traditional approaches, which rely on classical computing techniques that may need to scale more effectively. The authors offered quantum artificial intelligence approaches that can address complicated optimization and machine learning issues emerging in renewable energy systems, and they developed quantum algorithms that improve the computing efficiency of quantum chemistry calculations for sustainable energy materials. Sustainable energy applications that may benefit from QC-based techniques are identified, and the provided quantum algorithms are evaluated based on their performance on current quantum devices [104]. Artificial intelligence (AI) is a field of study and development that create intelligent computers that can do tasks previously requiring human intelligence. Science, mathematics, philosophy, psychology, linguistics, and computer science all serve as foundations for studying AI, which has been studied for over 60 years. There have been three waves of AI research driven by deep learning, resulting in more practical technology uses. The quality of life for citizens and the effectiveness of government could benefit from using AI in various governmental sectors, including education, infrastructure, transportation, healthcare, research, policymaking, the legal and justice systems, etc. AI can automate mundane processes, leading to faster transactions and more precise evaluations of policy effects. Environmental monitoring and management, land use planning, vehicular navigation, and distribution logistics are areas where AI can optimize and anticipate energy use, make choices, and establish policies. AI also has potential in medicine, law enforcement, transportation, defense, and preventative upkeep. An empirical study is necessary to understand the scope and impact of AI-based applications and associated issues holistically. However, technological, organizational, financial, and policy challenges are involved with the possible use of AI in different areas. The most studied areas of government use of AI are public healthcare, ICT, environmental sustainability, transportation, government law and policymaking, economic and financial applications, and other domains, so a theoretical framework is proposed to understand these uses [105]. Figure 9 summarizes the use of AI in different sectors. The pros and cons of engineering proteins with unnatural activities and other new biomolecules with desirable functional characteristics. Understanding molecular mechanisms and creating new technologies in disciplines such as health and materials science can influence the design of such biomolecules. From the basic fold prediction through ab initio structural design, computational approaches have played a pivotal role in the evolution of the protein and enzyme design process. Future progress and prospects in this area are anticipated to be driven by the fusion of hardware, software, and theoretical advancements.

4.5 New Catalysts for Sustainable Chemistry

The manufacturing, distribution, use, and discharge of chemicals have all contributed to adverse environmental and human health effects as human activity has expanded rapidly. Sustainable development, which emerged in the 1980s as a response to these issues, provides for the needs of the present without jeopardizing future generations' ability to do the same. The United Nations and the European Union have created sustainable development goals (SDGs) that call for participating in all sectors and will be evaluated using global, regional, and national indicators. A molecule, substance, reaction, process, or technology can be considered sustainable if it uses resources at a rate at which they can be naturally replaced, and waste is not produced at a quicker rate than it can be cleaned up. Sustainable chemistry is a new focus for chemists and chemical engineers, and it requires the creation of chemicals, reactions, and processes that are safe for the environment, profitable for businesses, and ethical for society [106]. An important topic of sustainable chemistry is the hydrodeoxygenation (HDO) of

vanillin produced from biomass to create liquid biofuel MMP. It's because they necessitate high H2 pressure and temperature; conventional HDO methods are challenging to scale up. New and efficient catalytic systems are required to accomplish HDO in more forgiving environments. With its low cost and ease of availability, polymethylhydrosiloxane (PMHS) has shown promise as a hydrogen donor in catalytic systems. Due to their vast surface area, excellent thermal stability, and outstanding electron conductivity, carbon Nanospheres are a promising catalyst or catalytic support platform. Hydrothermal synthesis was employed to produce a Pd-supported resorcinol-formaldehyde resin carbon spheres catalyst (Pd/CFR) for the HDO of vanillin. Instead of using acid additives, the microstructure of the carbon support was modified to induce new active sites. Without any additional chemicals, the Pd/CFR catalyst can attain high levels of activity and selectivity, showcasing the possibility of efficient and environmentally friendly catalytic systems for HDO processes. The development of efficient and environmentally friendly chemical processes and products has helped the marriage of continuous flow chemistry and microreactor technology. The use of wall-coated and packed-bed microreactors for heterogeneously catalyzed gas-liquid and liquid-liquid reactions is one of the primary areas of research in this subject since it can provide better control over reaction and process parameters, ultimately leading to more consistent product quality [107].

In particular, liquid-phase hydrogenation, oxidation of organic substrates, and synthesis of biofuels are three chemical transformations. Using microreactors with multiphase flow processing and heterogeneous catalysis has shown remarkable promise for enhancing sustainability. Heterogeneous catalysis helps make these processes more environmentally friendly because it streamlines product work-up and facilitates catalyst separation and reuse. The specific surface area for catalysis can be increased, and reaction rates can be improved by including active, selective, and stable solid catalysts in microreactors. Using microreactors with heterogeneous catalysis and multiphase flow processing is a promising strategy for achieving efficient and sustainable chemical synthesis, with promising commercial applications in sectors like petrochemicals, fine chemicals, and pharmaceuticals [108].

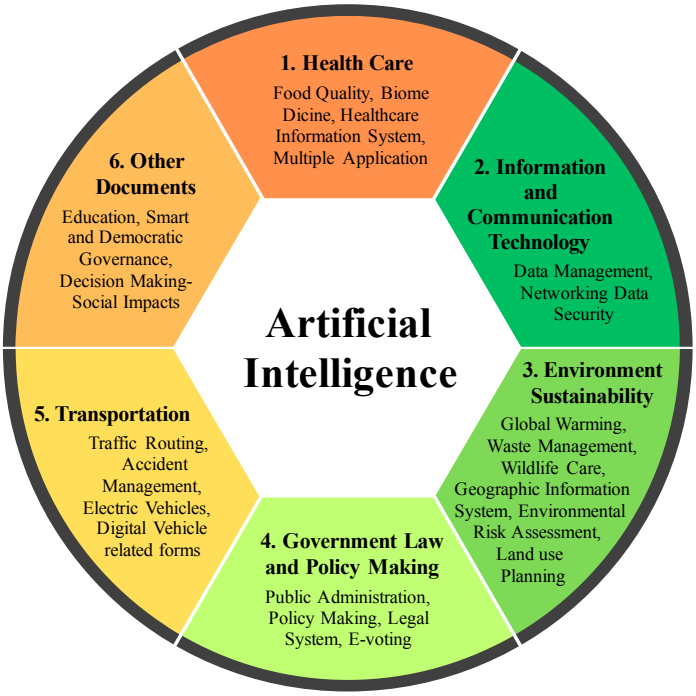


Figure 9. The use of Artificial Intelligence in different sectors. (Reproduced with permission: Copyright 2023, MDPI [155].

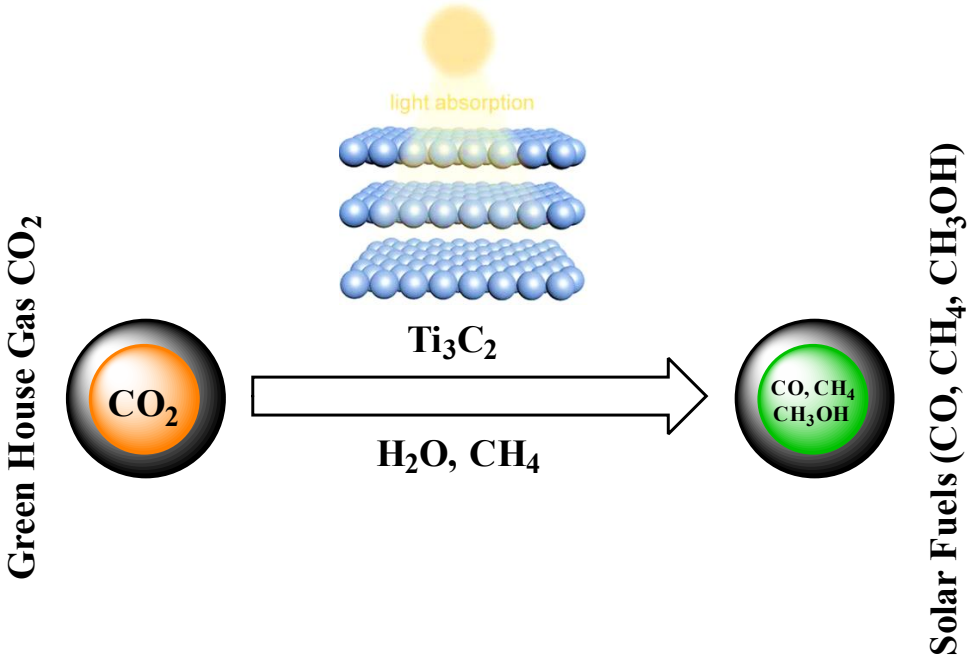


Figure 10. Photocatalytic Conversion of CO_2 to fuels with Ti_3C_2. (Reproduced with permission: Copyright 2021, The American Chemical Society [156].

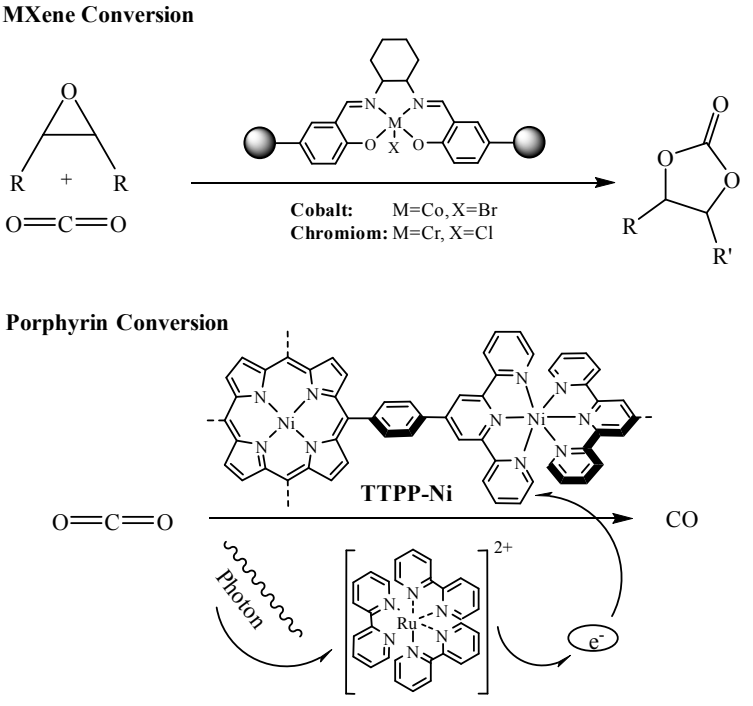


Figure 11. MXene (Reproduced with permission: Copyright 2020, The American Chemical Society [157]; and Porphyrin conversion of CO_2. (Reproduced with permission: Copyright 2022, The American Chemical Society [158].

5. Case Studies in Sustainable Catalysis

5.1 Catalysis for CO_2 conversion

Designing effective catalytic systems for CO_2 conversion involves considerable chemical and practical hurdles. Thermodynamic stability and the significant energy barriers that must frequently be overcome due to their kinetic stability are substantial chemical problems. A key obstacle is the synthesis of novel catalysts for converting CO_2 into value-added compounds [109]. However, research and development may overcome these limitations and pave the path for a more sustainable future.

Furthermore, two strategies for developing effective catalysts for CO_2 transformation were discussed: using size greater porphyrin moieties integrated into porous structures to increase activity and stability and creating mimetic scaffolds by incorporating anion sequential polymeric materials into a highly porous motivator to allow heterogeneous concerted catalysis elaborated in figure 11. Both techniques demonstrated high activity, recyclability, and catalytic efficiency toward bicarbonate products [110].

5.2 Catalysis for biomass conversion

To determine the structure and content of biomass-derived products, sophisticated analytical methods such as Nuclear magnetic resonance (NMR), and Mass spectroscopy (MS) are required. As a sustainable energy source, catalytic pyrolysis and hydrocracking can turn biofuel into desired and fine chemicals [111]. Nevertheless, high oxygen concentration, low target product selectivity, complicated catalytic mechanisms, and catalyst deactivation are significant hurdles in biomass catalytic conversion. Metal including Ni, Cu, Co, Fe, Zn, Ga, Zr, Na, Ca, Pt, Pd, Ru, Ir, La, Ce, Mo, and Ti added to mono-metal or bimetallic catalysts can increase pyrolysis product quality. Improving pyrolytic bio-oil is required for biofuels in the transportation industry [112]. Using metal-organic frameworks (MOFs) to convert biomass into valuable chemicals and biofuels is a potential strategy. The emphasis is on the characteristics of MOF materials and design approaches, such as selecting organic and inorganic construction blocks, particle size control, post-synthesis reconfiguration, and synthesizing MOF-based composite materials. HKUST-1, MIL-101(Cr), UiO-66, and UiO-67 are the most commonly used MOF structures in catalytic reactions for biomass value addition because they have sites with Lewis acidity in their inorganic nodes, which are critical for the catalytic processes involved in biomass conversion processes [117].

5.3 Catalysis for water treatment

In established metropolitan areas, a centralized treatment process has been the primary option, but mounting obstacles need a change to decentralized approaches, such as sophisticated oxidation technologies (AOPs). AOPs, which employ exceptionally reactive free radicals to remove pollutants, have evolved since the Fenton procedure was introduced in the 1890s. To address the limitations of the classic Fenton process, heterogeneous Fenton methods employ nanoscale metal oxide transition catalysts. AOPs can also be improved by light or electricity. Other peroxides compounds, including ozone, have also been investigated for AOPs. Nevertheless, the expense and reliance on externally provided chemicals may restrict the usefulness of AOPs for decentralized architectures [113]. Toxic organic chemicals in industrial effluent, such as chlorinated compounds (CPs), are challenging to eliminate from the environment and pose health concerns. The maximum permitted content of 2-CP in drinkable water is 10 gL^{-1}. As a result, practical methods for treating CP-containing wastewater are required. Photo-degradation, supercritical water oxidation, the Fenton process, zonation, microwave irradiation, ultrasonic irradiation degradation, moist air oxidation (WAO), and hydro dehalogenation have all been explored [114].

BiVO4 (BVO) is being used as a photocatalyst in water purification. When exposed to specific wavelengths of light, BVO creates electron-hole pairs and can destroy organic contaminants in water by oxidizing them to OH radicals. BVO thin films with varying Bi/V ratios are synthesized and assessed for their effectiveness in the photo-reduction of

pollutants [120]. Finally, the use of black BiOCl components with oxygen vacancies, positive interactions with other photocatalysts such as Bi_2O_3, and a carbon material Bi-bridge Z-scheme black $BiOCl/Bi_2O_3$ heterostructures with oxygen-containing functional groups (black $BiOCl-Bi-Bi_2O_3$/rGO) could provide efficient charge detachment and transfer for high photocatalytic dissolution rate in the therapies of natural industrial wastewater [115].

5.4 Catalysis for renewable energy production

Renewable hydrogen generation is vital for creating renewable energy sources, and catalysis is integral to this process. Steam reforming of simulated bio-oil utilizing catalysts such as $Ni/CeO_2-Al_2O_3$ and $Me-Ni/CeO_2-Al_2O_3$ (Me = Rh, Ru) may create hydrogen from renewable biomass feedstocks. Preparing the catalysts and simulated bio-oil is the first step, followed by putting the simulation bio-oil into a hydroformylation reactor containing a catalyst. The hydrogen and carbon monoxide produced are then passed on to a water-gas shift reactor, which produces more hydrogen and carbon dioxide. After that, the hydrogen gas is filtered and deposited in high-pressure tanks. Overall, this method of creating hydrogen gas is both efficient and renewable [122]. Aqueous phase reformation (APR) can create hydrogen utilizing ethylene glycol (EG) as a modeling molecule. This method treats EG in an aqueous phase with a bimetal catalyst, including Group VIII metals such as Ni and Pt. The catalyst facilitates the oxygenated compound's reforming process, which results in the production of hydrogen, carbon dioxide, as well as other contaminants. Introducing Pt to the Ni catalyst can improve its catalytic efficacy [116].

Butanol reformation is a viable approach for creating renewable hydrogen via catalysis. This approach comprises steam reforming sustainable bio-butanol utilizing Ni and Co catalysts based on carbon nanotubes (CNT). Butanol is vaporized and transported over the catalyst bed, combining with steam to create hydrogen, carbon monoxide, and carbon dioxide. The hydrogen is extracted from the gaseous phase and stored for later use. This process has various advantages, including being fuel and having an excellent hydrogen yield. Moreover, utilizing Ni and Co catalysts based on CNTs provides a very efficient and stable catalytic system for this procedure. Butanol reformation is an effective and sustainable way of manufacturing sustainable hydrogen to help establish a clean energy future [112].

6. Future Directions in Sustainable Catalysis

6.1 Metal-free catalysis and sustainability

Catalysis is essential in chemical industrial applications, accounting for approximately 80% of these processes. However, the use of noble and critical metals in catalysis has restrictions due to their scarcity. As a result, research has concentrated on identifying alternatives to these metals, such as creating more efficient catalysts that minimize metal consumption by enhancing activity per site. One method is to minimize the size of metallic particles, even to the level of single-atom site catalysts, and to improve their stability and reactivated methods. Another option is replacing noble and crucial metals with plentiful base metallic elements or metal-free catalysts, such as carbon-based compounds. Carbon-based catalysis with active carbons has been widely recognized for decades. However, their potential has been restricted due to the poor geometry of active carbons and the intricacy of functional group distribution. In addition, using carbon-based catalysts generated from biomass, particularly biomass wastes, provides a sustainable and cost-effective approach to Carbo catalysis.

Carbon allotropes show remarkable results in the field of catalysis i.e., graphene shows excellent catalytic properties due to its sheet-like structure having more catalytic sites. Carbon-based catalysis has garnered fresh attention because of its established structure and easy characterization. Diamond NPs are potent metal-free catalysts for the oxidative dehydrogenation of alkanes to alkenes, but they can only form covalent solid bonds or van der Waals forces with substrates. Due to graphene walls, carbon nanotubes (CNTs) are suited for adsorption and contact with substrates and can induce a variety of processes such as oxidative dehydrogenation of hydrocarbons and elimination of C-C multiple bonds. However, the availability and adaptability of graphene open new avenues and capabilities for carbon-based catalysis. Several methods

for producing doped graphene include adding the dopant element during synthesis or grafting the doping agent element on graphene oxide during reductions to reduce graphene oxide. Graphene provides metal-free heterogeneous catalysis for various processes, and there is considerable interest in investigating its potential for sustainable, metal-free catalysis.

Metals are commonly used as catalysts, but there is an increasing demand to replace them with more sustainable options, making graphene appealing due to its distinctive characteristics. Graphene helps boost specific aerobic oxidations, yet more information on other reactions needs to be provided. The goal is to show that graphene may be employed as catalysts for reactions generally catalyzed by metals, such as reduction, oxidation, Lewis hydrochloric-promoted processes, and corrosive, homo, and cross pairings. The active sites and their interactions with Organo-catalysis must also be studied. The ultimate objective is to employ graphene as a metal-free catalyst in large-scale industrial operations, where their characteristics and availability would make them the ideal catalyst [117].

The conversion of carbonyl compounds to their equivalent alcohols is a crucial step in chemical synthesis. However, direct hydrogenation with hydrogen is a risky and complicated process that demands exceptionally high temperatures and pressure. That is why other techniques for hydrogen transfer processes have gained popularity. Catalytic transferring hydrogenation is efficient as it offers various benefits over other reduction methods. The transition metals Rh, Ir, Ni, Pt, and Ru have been used extensively in the catalytic transferring hydrogenation of carbonyl compounds. However, these metals have several drawbacks in terms of sustainability. As a result, there is a need to develop and design a metal-free catalytic system capable of executing transfer hydrogenation processes that are also green, safe, and low-cost. Because of their stability, eco-friendliness, and low cost, carbon-based materials have recently emerged as an excellent catalyst for a wide range of applications. Because of its distinctive tri-s-triazine structure, graphitic carbon nitride (GCN) is ideal for operating as a metal-free catalyst or catalyst applicable for industrially important heterogeneous catalytic hydrogenation. According to multiple papers, GCN has been employed as a support for catalysts for noble metals such as Ru and Pd in catalytic hydrogenation processes. GCN has many catalytic sites because of its vast surface area and sheet-like shape. The heterogeneous catalyst name, O-GCNo-sheets, is a sustainable and efficient technique for the hydrogen transport reaction of carbonyl compounds. Using 2-propanol as a hydrogen source, the reaction produces high yields of the intended item in a shorter time. The reaction rate and product yields can be increased by adjusting reaction parameters, such as using a catalytic base quantity. With a high changeover number, strong stability, and recyclability, the O-GCN catalyst is promising for large-scale applications. This hydrogen transfer process is environmentally friendly and sustainable [118].

Due to industrialization and civilization, the human species are facing natural resource problems and environmental destruction. To solve this, sophisticated oxidation (AOPs) methods have been created to generate highly reactive oxygen species (ROS) from various chemicals, which can break down hazardous organic pollutants into non-toxic minerals like carbon dioxide and water. To create sulfate radicals, hydroxyl radicals, and superoxide radicals, transition metals and oxides of Fe, Co, or Mn have been employed as activators of peroxymonosulfate (PMS), peroxydisulfate (PDS), hydrogen peroxide (H_2O_2), and ozone. Carbonaceous materials have recently been employed as heterogeneous catalysts due to their metal-free nature, availability, and other benefits. Research shows that superoxide systems include various reactive compounds and reaction paths. This article focused on current materials design advances, such as discovering catalytically active locations and investigating reactive species and reaction pathways utilizing experimental and theoretical studies. Finally, the research gaps of metal-free AOPs are identified, and the potential for additional mechanistic investigations using improved methods and carbo catalysis in catalytic oxidation was presented.

Granular carbonaceous materials such as activated carbon, carbon fiber, and biochar have been used in AOPs, but their

performance and stability are subpar. Because of their structural flaws and oxygen features, such as ketone (C=O) and Quinone groups, reduced graphene oxide (rGO) and other hydrochloric-dimensional carbons have shown promising results as carbon catalysts. These groups react with persulfate (PMS) to weaken the peroxide O-O link and generate sulfate radicals that damage organic molecules. The activated PMS complex can assault the electron-rich organic molecule via nonradical electron abstraction. Carbon nanotubes (CNTs) and mesoporous carbon, on the other hand, exhibit more complicated behavior, with both sulfate radicals and singlet oxygen discovered to be reactive species catalyzed by the Quinone groups (CNT-C=O). Carbon arrangement and size are also critical in carbo catalysis. Carbonaceous materials' adsorption and catalytic activity were closely connected to their molecular organization, with Nano carbons outperforming granular carbonaceous materials in adsorptive capacity and catalytic activity [119].

6.2 Integration of catalysis with other sustainable technologies for fuel cell

The world is facing a catastrophic crisis due to the enormous energy use, dwindling fossil resources, and its effect on the environment and climate. We must create efficient conversion and storage techniques for sustainable and clean energy to minimize reliance on fossil fuels and address these concerns. Fuel cells, particularly low-temperature proton exchange membrane fuel cells, are a potential energy technology that has grown in popularity because of their safe and low-temperature operation, high energy conversion efficiency, durability, and ecologically sustainable regeneration. Because of these benefits, they are a viable choice for improving industrial transformation and attaining a sustainable human civilization.

Due to their excellent efficiency and continuous supply of electricity with just water as waste, fuel cells are a viable power source for a variety of applications. The sluggish kinetics of the oxygen reduction reaction (ORR) at the cathode, on the other hand, restricts the general effectiveness of fuel cells, and platinum (Pt) is the ideal catalyst choice to increase reaction kinetics and efficiency. Pt/C catalysts are now widely utilized; however, their low activity and poor stability make them unsuitable for high-service needs. Researchers have devised various techniques to circumvent these constraints, such as enhancing the surface and morphology of Pt-based catalysts, incorporating transition metals to make alloys, and increasing the graphitization degree of Nano carbon supports. However, creating practical, low-cost, and long-lasting Pt-based catalysts as ORR in fuel cells remains a significant issue. As a result, researchers are working on large-scale production of high-performance, low-cost ORR catalysts for use in fuel cells [114].

Fuel cell technology is a potential approach for zero-emission automobiles. However, the high cost of fuel cell stacks and restricted accessibility to platinum group metals (PGMs) are significant barriers to broader use. The application of PGM-free electrocatalysts, such as transition metal-nitrogen-carbon (Fe-N-C) catalysts, is a potential way to lower the cost of fuel cell stacks, however, integrating PGM-free catalysts into the catalytic layer offers issues. For improved water management, the increasing layer thickness of PGM-free electrodes demands adjusting the electrode structure to consider key transport parameters, increase hydrophobicity, and decrease ionomer tortuosity. Despite the commercialization of fuel cell vehicles such as the Toyota Mirai, their high cost compared to traditional internal combustion engine vehicles restricts their market viability [114].

6.3 Implementation of sustainable green chemistry in the industry

The global economy's expansion and the decrement in the supply of natural resources have generated a critical need for sustainability. Green chemistry is a concept that emphasizes the reduction or removal of hazardous compounds. Green chemistry's instruments include alternate feedstock, solvents and reagents, and catalytic processes. The phrase "hazardous" encompasses physical, toxicological, and environmental elements. Green chemistry attempts to provide customers a safe and healthy environment while minimizing energy consumption and waste creation. Green chemistry is a

theoretical notion and a natural method increasingly implemented by industries to build a more sustainable future. Businesses are developing and commercializing green techniques to reduce harmful chemicals and increase efficiency. The chemical industry is embracing less hazardous technologies, bio-based synthesis, and renewable feedstocks as part of its commitment to sustainability. Between 2004 and 2013, the US pharmaceutical sector, for example, reduced VOC consumption by 50%, resulting in a 7% reduction in chemical waste emitted into the environment.

Due to pollution, industrial facilities in India and China have encountered regulatory action, stressing the importance of green practices. Bioplastics have already been used by companies such as Wal-Mart and Nokia, while Procter & Gamble is replacing PVC with green alternatives. Badische Anilin and Soda Fabrik (BASF) has devised a non-toxic hair color, while the Warner Babcock Institute developed a green synthesis for Ibuprofen. Merck & Co. used green chemistry principles to create the antiviral medicine Litemor, which resulted in greater yields, lower prices, less waste, and water use. In 2017, the EPA awarded green synthesis a Presidential Green Chemistry Award. These examples show that green chemistry is both ecologically and economically favorable. Enzymes are renewable, biodegradable, and potent catalysts; hence biocatalysts are significant in green chemistry. Enzymes catalyze many processes in biological systems, but corporations are creating and exploiting enzymes as biocatalysts to meet sustainability goals. Biocatalysts have found use in medicine synthesis and plastic manufacture, particularly biodegradable polymers generated from renewable resources. Pfizer's greener synthesis of Pregabalin, a key component in the neuropathic pain medication Lyrica®, is one example of the influence of biocatalysts on pharmaceutical production. Pfizer lowered solvent usage by 90%, raw material needs by 50%, and energy consumption by 50% by using biocatalysts as a critical step in the synthesis. The utilization of biocatalysts has also resulted in the creation of air carbon™, a thermoplastic manufactured by New Light Technologies that blends air with methane emissions to create a carbon-negative product [120].

Green chemistry is also being used to improve society, industry, and the environment in the pharmaceutical business. A two-tiered technique is recommended to accomplish this. The first step entails integrating metric-based techniques and translating them into concrete and straightforward goals. The Green Aspiration Level (GAL) measures the environmental effect of generating any pharmacological agent according to the complexity of its hydrochloric-adjusted synthesis process. The GAL evaluates and process waste. The consensus analysis starting points help simplify any Life Cycle Analysis (LCA) methodology. The second level of the strategy entails demonstrating the GAL to assess green drug manufacturing and aligning industry through industry consortia such as the International Organization for Innovation and Quality in Pharmaceutical Growth (IQ) and the ACS Green Chemistry Institute Pharmaceutical Roundtable (ACS et al.). The GAL is a helpful tool for assessing the best green chemistry options, and the approach has been standardized for consistency [98].

Plastics are widely utilized because of their unique qualities, but they also offer a substantial environmental risk by contributing to pollution, particularly single-use plastics utilized in packaging. Plastic pollution results from a systemic failure involving several stakeholders along the plastics value chain, from the chemical industry to recycling and disposal. To solve these issues, green chemistry can play an essential role in replacing plastics generated from fossil resources with bio-based alternatives obtained from renewable resources that are easier to recycle and biodegrade at the end of their useful life. This looks at the underlying chemo and biocatalytic technologies for the manufacture of plastics and recycling identifies priorities for future development, and recommends a redesign of the regulations and incentives that apply to the plastics value chain to achieve a circular plastics economy with optimized resource efficiency and minimal environmental pollution [99].

6.4 Impact of sustainable catalysis on the Environment and Society

Sustainable catalysis is a burgeoning topic with the potential to

Table 2: Levels of endocrine-disrupting chemicals detected in both wastewater.

EDC	Use	Wastewater Concentration (ng/L)	Limit Detection (Ng/L)	Ref
Estrone (E1)	Medication	(13.1 - 104)	01.8	[124]
17β-Estradiol (E2)		(24.7 - 66.9)	24.23	
17α-ethinylestradiol (EE2)		(0.5 - 5.7)	0.5	
Phenol	Food purposes	ND	-	[125]
Bisphenol A (BPA)		(2.2 - 1030)	0.7	
Parabens	Cosmetic and Personal care	(72 - 91)	0.5	[126]
Triclosan (TCS)		39.8 (2 -118)	-	[127]

*ND; not detected

minimize chemical processes' environmental effects while benefiting society dramatically. Catalysts enable more effective and selective chemical processes, reducing energy consumption and waste creation. We can cut emissions of greenhouse gases, conserve natural resources, and limit the release of dangerous compounds into the environment by inventing and implementing sustainable catalytic processes. This, in turn, may benefit public health, environmental sustainability, and economic prosperity. The environmental and societal effect of sustainable catalysis is considerable, and it is increasingly seen as a crucial driver of development toward a more sustainable future.

6.5 Different types of catalysis have an impact on the environment and society

6.5.1 Photocatalysis

Trace pollutants or micro-pollutants are artificial compounds found in the aquatic environment that are of concern owing to their negative impact on human health and living species Endocrine-disrupting chemicals (EDCs) can cause genetic defects, infertility, feminization, higher cancer rates, Alzheimer's disease, and other health difficulties by interacting with the endocrine system of living creatures. Lauretta et al. 2019 explores the effects of EDCs on various endocrine glands, including the thyroid, adrenal, pituitary, and reproductive glands. For each gland, the authors meticulously dissect the mechanisms through which EDCs interfere with hormonal signaling, disrupt hormone production, and induce detrimental effects on glandular structure and function. The work also underscores the vulnerability of certain population groups, such as pregnant women and developing fetuses, to the adverse effects of EDCs. It elucidates how early-life exposure to EDCs can have enduring repercussions on endocrine health and overall well-being [121]. In a study conducted by Chang et al. [122], it was revealed that over 60% of hormones, predominantly Estrone (E1), 17β-Estradiol (E2), and 17α-ethinylestradiol (EE2), detected in 45 urban rivers in China originate from untreated sewage that is freshly discharged. This detection pattern is attributed to the excretion of both natural and synthetic hormones, which are not entirely metabolized by the body, and are consequently excreted through urine and feces [123].EDCs can be found in medications, surfactants, cosmetics, and other personal care goods [128], as mentioned in Table 2 that end up in the sewage system and still must be successfully removed by standard biological wastewater treatment facilities [129]. The table underscores the presence of these EDCs in wastewater, with concentrations varying widely depending on the compound. Monitoring and regulating these chemicals in wastewater is vital to mitigate their potential environmental and health impacts. It is noteworthy that some of these compounds, like estrone and bisphenol A, are detected at relatively high levels, underscoring the importance of water quality management and treatment strategies to address EDC contamination..

Table 3: Advanced oxidation processes for the degradation of endocrine disruptors in water.

Process	Compound	Class	Degradation (%)	Ref
Photolysis	Estrone (E1) 17β-Estradiol (E2) 17α-ethinylestradiol (EE2)	Hormones	51.0-46.0 (E2, EE2) >93 (E1)	[134]
	4-nonylphenol (NP)	Phenol	-	[135]
	Bisphenol A (BPA)	Alkylphenol	58.0 (BPA)|HA	[136]
	Triclosan (TCS)	Alkylphenol	75.0 (TCS)|HA	
	Nonylphenol diethoxylate (NP2EO)	Phenol	95.0	[137]
Photocatalysis	Bisphenol A (BPA)	Diphenol	until 92.0	[138]
	Methylparaben (MPB)	Parabens	88–98%	[139]
	Triclosan (TCS)	Antimicrobial	90.0	[140]

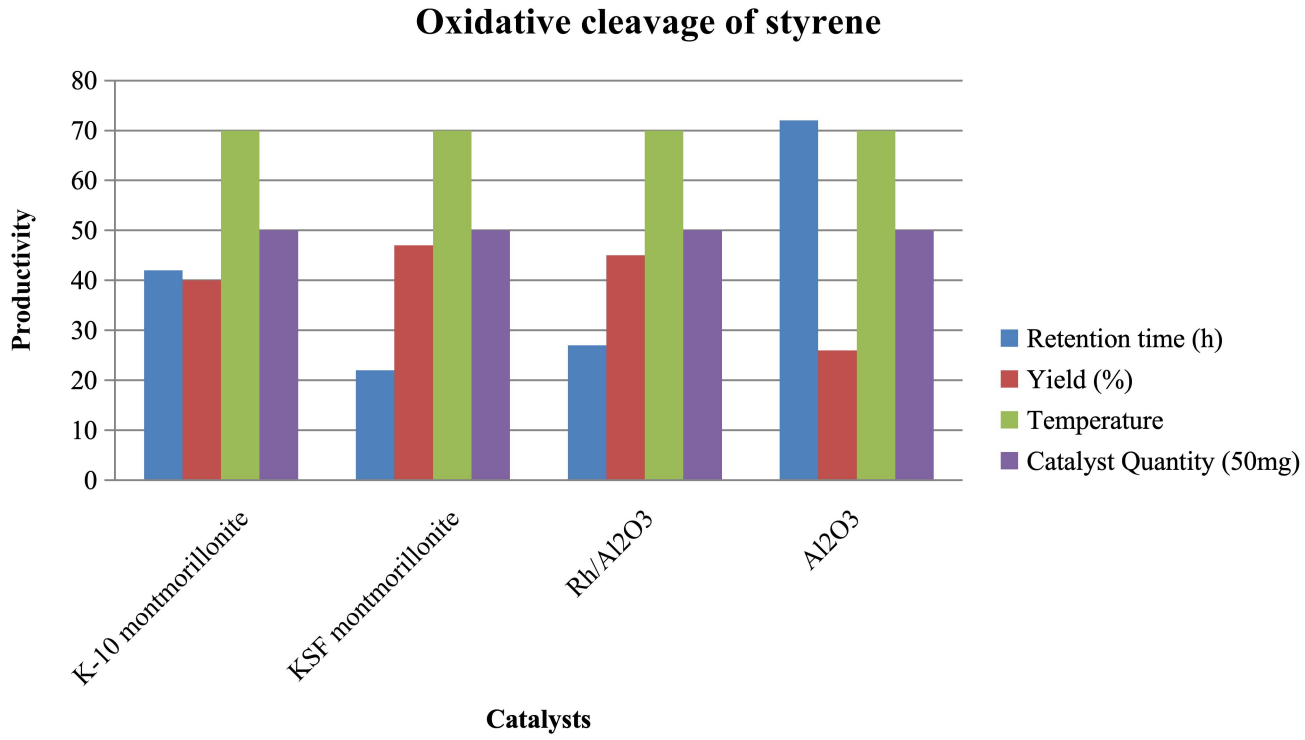


Figure 12. Catalytic Oxidation for the Cleavage of Styrenes into Benzaldehydes. (Reproduced with permission: Copyright 2014, Elsevier [159].

For the removal of these materials from wastewater photolysis and photocatalysis are the essential processes. Photolysis relies on the degradation of compounds through exposure to light, and it is particularly effective for the removal of hormones like E1, E2, and EE2 and photocatalysis employs catalysts to accelerate the degradation of contaminants, achieving substantial removal rates for various compounds, including phenols, parabens, and antimicrobial agents. The table 3

presents a comprehensive overview of the effectiveness of different removal methods in reducing the concentration of various compounds in wastewater. Both photolysis and photocatalysis stand out as promising techniques for mitigating the presence of contaminants in water sources. Photolysis, notably, proves highly efficient in breaking down hormones such as Estrone (E1) [130], while photocatalysis, often with the addition of catalysts like humic acid, demonstrates substantial removal rates for a diverse range of compounds, including phenols, parabens, and antimicrobial agents [131]. These processes play a crucial role in wastewater treatment, holding the potential to significantly diminish the levels of harmful and persistent substances, ultimately enhancing water quality and safety. It is imperative to ensure the proper implementation of these methods and continue research efforts to optimize them, fostering sustainable water management and environmental preservation [132]. Tertiary solid treatment technologies, such as light-driven advanced oxidation processes (AOPs), must be added to existing WWTPs. Solar, UV-A, and UV-C photolysis and photocatalysis utilize reactive oxygen species to oxidize the organic content of water samples and can be enhanced by adding titania (TiO_2) or other chemicals [133].AOPs are energy-intensive, have significant running costs, and produce residual fluxes with negative environmental consequences, such as metal-ion-contaminated sludge, exhausted solid catalysts, and so on. The environmental sustainability of each AOP should be studied at the bench or pilot size to identify benefits and downsides, significant environmental impact hotspots, and explore approaches to reduce the total environmental footprint using scenario and sensitivity studies. The technique might be efficiently scaled up to sustainable, large-scale applications by calculating the best environmental performance of AOPs [141].

6.5.2 Heterogeneous catalysis

As alkenes or alkynes are used to synthesize many compounds, their preparation and conversion are essential areas of study. Traditional procedures, such as dihydroxylation and ozonolysis, have environmental effects and safety drawbacks. Recent advances in flow systems and catalytic techniques using oxygen, air, organic peroxides, or hydrogen peroxide are promising. The optimal procedure for this reaction would entail using a commercially available, toxic-metal-free catalyst that uses the natural oxygen content of air as an oxidant, potentially at atmospheric pressure and with water as a medium. In a study led by Qian L. and colleagues, a novel approach to enhancing the catalytic properties of Pd catalysts for selective alkyne hydrogenation is explored. The researchers developed a modified Pd catalyst (referred to as Pd/NHPC-DETA) by grafting diethylenetriamine (DETA) onto a nitrogen-doped hierarchical porous carbon (NHPC) support. This modification created dynamic metal-support interactions (DMSI) and significantly improved the catalytic performance of the optimal Pd/NHPC-DETA-50 catalyst. This enhanced catalyst exhibited exceptional performance in the selective hydrogenation of alkynes to alkenes under mild conditions, surpassing the capabilities of the commercial Lindlar catalyst. These findings open new avenues for the rational design of heterogeneous catalysts by harnessing DMSI, providing a valuable approach for catalyst development [142]. Christian S. et al., 2018 provides valuable insights for conversion of styrene to benaldehyde. The figure 12 indicates comprehensive evaluation of various catalysts with respect to retention time, yield, temperature, and a standardized catalyst quantity of 50 mg. Among the assessed catalysts, KSF montmorillonite emerges as a particularly promising candidate. Notably, it exhibits a notably abbreviated retention time of 22 hours, indicative of its exceptional proficiency in expediting reaction kinetics. Additionally, KSF montmorillonite achieves an impressive yield of 47%, underscoring its efficacy in promoting the desired reaction. The relatively low operating temperature of 70°C further highlights its efficiency. In essence, these findings collectively signify that KSF montmorillonite holds considerable potential as a catalyst for the specified reaction, showcasing both elevated catalytic activity and cost-effectiveness [143].The Montmorillonite KSF catalyst has shown promise in the oxidative coupling of amines and the aromatization of different heterocycles. This is a sustainable

alternative to standard ozonolysis for the cleavage of styrene derivatives to substitution benzaldehydes has been discovered, with the potential to have a significant favorable influence on the environment [111].

6.5.3 Electrocatalysis

The increase in greenhouse gas emissions has emerged as a critical problem for long-term sustainability. CO_2 is the most prominent greenhouse gas, and its amount in the atmosphere has globally risen from 278 ppm at the start of the industrial revolution to more than 419.51 ppm in 2023. Converting CO_2 into high-value goods is a viable option to combat global warming. CO_2 conversion, on the other hand, presents several problems, such as a high free Gibbs energy and the need for a considerable quantity of energy, optimized reaction conditions, and robust catalysts. Stoichiometric, biochemical, photocatalytic, photoelectrochemical, electrochemical, and thermochemical processes are among those used to generate added-value products from CO_2 conversion. Sabatier and Fisher-Tropsch thermochemical methods are currently being studied to produce fuels or chemicals today. Zahedian and co-workers introduce an innovative system design aimed at gasifying heavy fuel oil and producing lighter hydrocarbons. The gasification process involves heavy oil introduced into the gasifier under specific conditions, including an outlet temperature of 430.6 °C and a pressure of 4.46 bar. Notably, the gasification process yields hydrogen and carbon monoxide as the predominant products, comprising 40.29% and 40.59% of the output, respectively. Of significance is the close-to-stoichiometric ratio of hydrogen to carbon monoxide, approximately 0.99, which has implications for subsequent processes. Within this system, the Fisher-Tropsch process assumes a pivotal role. Renowned for its capacity to convert synthesis gas, a blend of carbon monoxide and hydrogen, into valuable hydrocarbons, particularly liquid fuels, it plays a crucial part in transforming the gases generated during gasification. This process is instrumental in the conversion of these gases into lighter hydrocarbons and useful fuels. Additionally, the study highlights the significance of the Sabatier reaction in the context of environmental sustainability. This reaction involves the catalytic reduction of carbon dioxide (CO_2) using hydrogen to yield methane (CH_4).

Table 4: Comparing various pathways for the conversion of CO_2 into CH_3OH [144].

Process	Reductant	Catalysts	Maximum selectivity (%)	Stability	T (°C)	Productivity ($mmolg_{cat}^{-1}h^{-1}$)
Heterogeneous catalysis	H_2	Pd, Au,Cu–ZnO, ZnO,M–ZrO_x, In_2O_3	>3000h	2-20	220-300	2-20
Photocatalysis	H_2O	Cu, Zn, Ag, Bi, In, semiconductors	>40h or 4-10 cycles	0.02-0.5	RT	0.02-0.5
Electrocatalysis	H_2O	CuPd,CuSe alloys,Co phthalocyanines	>4-120h	>22 >30 $\mu molm^{-2} s^{-1}$	>50	>22 >30 $\mu molm^{-2} s^{-1}$

Its environmental importance is derived from its ability to convert CO_2, a greenhouse gas, into a valuable fuel resource, methane. By incorporating the Sabatier reaction into the system configuration, the research aligns with sustainable practices by actively participating in CO_2 emissions mitigation and the generation of valuable fuels [145].

However, the classic thermochemical process has significant drawbacks, including low support stability in the presence of steam, poorer thermodynamic favorability than the existing syngas method, and high energy demand. Furthermore, the hydrogen necessary for the process continues to be generated mainly by steam methane reforming, which could be more cost-effective and environmentally friendly. Yu and co-workers explore the catalytic role of electrolyte cations in electrochemical CO_2 reduction. Cations, known for their influence on key intermediate species, particularly in CO_2-to-CO conversion, have attracted significant research attention.

Using a cobalt single-site catalyst (Co-N_4), the study achieves approximately 25% methanol selectivity at -0.78 V vs. RHE. Isotope labeling confirms methanol production from CO_2 reduction. The researchers delve into the kinetic isotope effect using deuterated electrolytes and propose a comprehensive reaction pathway for CO_2-to-methanol conversion on the cobalt single site.

These findings extend our understanding of cations' multifaceted role in electrochemical CO_2 reduction beyond stabilizing intermediates, offering potential enhancements in CO_2 conversion [146]. The electrochemical conversion of CO_2 to methanol offers several benefits over existing thermochemical procedures, i.e., the use of renewable energy sources, the r for in-situ proton production, and the rate reaction conditions as mentioned in the Table 4.

The table compares three methods for converting CO_2 into CH_3OH, considering reductants, catalysts, and key indicators. Heterogeneous catalysis, with H_2 as the reductant and catalysts like Pd and Cu–ZnO, exhibits high selectivity and stability, operating at 220-300°C. Photocatalysis, utilizing H_2O and catalysts such as Cu and semiconductors, operates at RT, with moderate selectivity but lower productivity. Electrocatalysis, with H_2O as the reductant and catalysts like CuPd, excels in productivity and stability, operating at temperatures exceeding 50°C. The choice depends on specific requirements, balancing selectivity, environmental aspects, and productivity. Electrocatalysis appears as the most promising method, offering a balance between high productivity and stability [144]. To decrease CO_2 electrochemically, significant over potentials are necessary, and the low productivity and specificity of state-of-the-art electrochemical procedures are obstacles. Nonetheless, electro-synthetic techniques have a bright future. The chemical sector is on pace to meet the needed emissions reductions by 2050, and the International Energy Agency promotes chemistry and engineering research programs that will reduce energy usage and the GHG footprint [141].

7. Conclusion

This review explores the recent advancements and use of the catalysis process in different fields. There is an urgent need for society to move toward a greener and more sustainable future presents a very exciting opportunity for catalytic chemists. This short excursus about future directions and challenges for catalysis evidences well how catalysis will play a key role for a transformative society, energy and chemistry. The authors offered quantum artificial intelligence approaches that can address complicated optimization and machine learning issues emerging in sustainable future for catalysis. Sustainable chemistry is the HDO of vanillin produced from biomass to create liquid biofuel MMP. New and efficient catalytic system with its low cost and ease of availability, polymethylhydrosiloxane (PMHS) has shown promise as a hydrogen donor in catalytic system. Carbon nano-spheres are a promising catalyst with huge surface area, great thermal stability, and outstanding electron conductivity. Metal-free catalysts (Graphene, CNTs) are also used in order to control the contamination or pollution caused by metals. Case studies presented that MXene, a class of 2D transformation carbides and nitrides are propitious to tackle the challenges in CO_2 conversion. MOFs are a potential strategy for turning biomass conversion into valuable chemicals and biofuels. BVO proved

as an optimistic photocatalyst in water purification. CTN-based bio-butanol is a viable approach for creating renewable hydrogen via catalysis. These studies point to the possibility of green catalytic routes toward the production of fuels and useful chemicals from the utilization of the green-house gas carbon dioxide; as well as the potential for these materials to be used as catalysts in hydrogen fuel cells. In the realm of materials science, catalysts are instrumental in the production of cutting-edge materials like carbon nanotubes and graphene, with wide-ranging applications in electronics and energy storage. They enable the chemical and pharmaceutical industries to streamline their processes, reducing waste and energy consumption. Catalysts also find their place in clean water technologies, ensuring efficient removal of contaminants to provide safe drinking water. Moreover, in the pursuit of better energy storage solutions, catalysts are essential for high-performance batteries, improving energy density and efficiency. They contribute significantly to the electronics industry by aiding in the fabrication of advanced semiconductor materials and nanoelectronic devices, ultimately leading to more energy-efficient electronics. Catalysis underpins the development of sustainable and innovative solutions across multiple sectors, making it an indispensable force in our journey towards a more technologically advanced and environmentally conscious future.

Authors Contribution

Umair Habib: Supervision, Conceptualization, Investigation, Validation, Formal analysis, Writing - original draft, Visualization. Farooq Ahmad: Conceptualization, Project administration, Supervision, writing-review and editing. Muhammad Awais: Writing & review. Namisa Naz: Formal analysis & software. Maira Aslam, Formal analysis & software. Malka Urooj: Methodology, Hira Tahseen: Formal analysis & software, Writing. Anam Moqeem: Formal analysis & software, Writing: Aimen Waqar: Formal analysis and investigation. Muhammad Sajid: Formal analysis. Muhammad Jamshaid Shabbir: Formal analysis and investigation

Conflicts of Interest

There are no conflicts of interest reported by the writers.

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Data Availability statement

The data presented in this study are available on request from the corresponding author.

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