Journal homepage: www.scienceletters.researchfloor.org

Contents list available at Journal of e-Science Letters

Journal of e-Science Letters

Review Article | ISSN :3041-5454

Sustainable Catalysis: A Review of Green Catalysts and Their Applications

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ABSTRACT

The effective conversion of raw materials into valuable products is made possible by catalysis, which is essential to many industrial processes. However, classic catalytic procedures have a major impact on the environment since they frequently rely on hazardous chemicals, severe temperatures, and valuable metals. Green catalysts, which minimize waste, reduce energy consumption, and promote environmentally benign chemical reactions, are being developed in response to the growing need for sustainable and eco-friendly methods. A viable substitute for traditional catalysts are green catalysts, which are made from plentiful and renewable resources. The environmental impact of these catalysts can be reduced while maintaining excellent activity, selectivity, and stability. Sustainable catalysis has applications in a number of industries, such as pollution remediation, chemical synthesis, and energy production. This review explored green catalysis and their application. Findings from this study revealed that the development of green catalysts, such as metal-organic frameworks (MOFs), enzyme catalysts, and nanocatalysts, which enable efficient and environmentally friendly chemical processes. These catalysts have shown promising results in various applications, including biomass conversion, renewable energy production, pollution abatement, and organic synthesis. Findings from this study also indicate that green catalysts can significantly reduce waste, energy consumption, and hazardous substances. Overall, sustainable catalysis offers a promising approach to developing low-carbon industrial processes, reducing carbon footprints, and promoting environmentally friendly technologies. Future research directions include scaling up sustainable catalytic processes and integrating them with renewable energy sources. Sustainable catalysis offers a promising approach to developing environmentally friendly chemical processes. Green catalysts like MOFs, enzyme catalysts, and nanocatalysts show potential in reducing waste, energy consumption, and hazardous substances. Future research should focus on scaling up these processes and integrating them with renewable energy sources.

Keywords: *Green catalysis, Sustainable chemistry, Biocatalysts, Nanocatalysts, and Renewable resources.*

Citation: Moses Adondua Abah, Sulaiman Luqman Olaitan, Micheal Abimbola Oladosu, Adeyinka Ademilua, Adewoyin Marvellous Oluwarotimi, Bankole Olayinka Afeez, Joshua Olasunkanmi and Ibrahim Aisha Talatu (2025). Sustainable Catalysis: A Review of Green Catalysts and Their Applications.
Journal of e-Science Letters.
DOI: https://doi.org/10.51470/eSL.2025.6.4.37

Received: 27 August 2025
Revised: 30 September 2025
Accepted: 04 November 2025
Available: November 29 2025

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Introduction

The design and use of catalysts in chemical processes to maximise resource efficiency and minimise environmental impact is known as sustainable catalysis. At the core of green chemistry, it seeks to substitute cleaner methods for traditional, high-energy, wasteful processes [1, 2]. While conventional catalysis frequently uses hazardous heavy metals and produces a lot of waste and byproducts, sustainable catalysis prioritises atom economy and renewable inputs to prevent pollution [3]. These strategies preserve the vital role that the chemical sector plays in promoting contemporary society while reducing negative effects on the environment [4, 5]. For instance, waste reduction was emphasised in the 1990s with the introduction of the E-factor and the atom economy; these metrics underline the critical role of catalysis in waste minimisation [6]. In recent decades, the area has broadened to encompass catalysts based on earth-abundant materials, bio-inspired catalysts, and nanoparticle catalysts, reflecting a larger endeavour to make

catalysis more environmentally friendly [7].
The synthesis of polymers, medicines, and specialised chemicals, as well as the manufacturing of fertilisers and petroleum refinement, have all been made possible by traditional catalysis, which includes both homogeneous and heterogeneous systems. Strong, metal-based acid/base catalysts are essential to traditional industrial catalysis [8]. For instance, cracking, hydrogenation, and reforming reactions are carried out in petroleum refining using solid acids (such as sulfuric acid or HF in alkylation) and transition-metal catalysts. For hydrogenation and cross-coupling processes, fine chemicals and pharmaceuticals frequently use noble-metal catalysts (Pd, Pt, and Rh). High activity and selectivity are generally made possible by these catalysts, but they come with a hefty environmental cost [9, 10]. Refinery alkylation uses concentrated H_2SO_4, which produces a lot of wasted acid waste that is full of organic pollutants. This is only one example of how acid-base catalysts are important [11].
Conventional catalysis, however, has significant environmental problems. Toxic or valuable metals found in many conventional catalysts cause resource and environmental issues. Because of their toxic metal content, spent hydroprocessing catalysts, such as Ni-Mo on alumina, are categorized as hazardous waste and accumulate heavy metals [12]. Similarly, soluble Pd or Rh complexes, which are homogeneous catalysts, can contaminate goods and result in waste streams that are heavy in metals and are challenging to recover. Metal-catalyzed processes frequently produce hazardous byproducts and call for large amounts of organic solvents in the pharmaceutical industry. According to [13], Pd-catalyzed Suzuki couplings utilized in drug synthesis "rely on harsh reaction conditions, toxic reagents, and copious amounts of solvents," raising issues related to both health and the environment. Spent solvents or tainted mother liquors make up a significant portion of chemical plant waste because flammable and poisonous solvents (such as dichloromethane and benzene) are used as reaction media in many traditional syntheses [14]. High temperatures and pressures are frequently needed for traditional processes, which results in high energy consumption and related CO_2 emissions. Even the Fe-catalyzed Haber-Bosch process, as previously said, "sucks up about 1% of the world's total energy" and contributes to the emission of approximately 1% of global CO_2 [15].
Anastas and Warner developed the twelve principles of green chemistry in the 1990s, which served as the foundation for the larger green chemistry movement from which green catalysis grew. According to these ideas, catalysis is specifically required to boost productivity and decrease hazardous waste [16]. By reducing waste, creating recyclable catalysts, and using renewable raw materials, the early attempts at green catalysis aimed to enhance conventional systems. The late 20th century saw the development of biocatalysis as a significant advancement in green chemistry. According to [17], enzymes and whole-cell catalysts have shown the capacity to carry out extremely selective transformations in moderate settings, frequently in aqueous environments, negating the need for harsh reagents and organic solvents. Since then, biocatalysis has been extended to industrially relevant processes, including pharmaceutical intermediate synthesis and biofuel production, thanks to parallel developments in immobilisation methods and protein engineering [18]. The enzymatic production of sitagliptin, a medication used to treat diabetes, is a notable example. Merck and Codexis eliminated hazardous metals and reduced waste by 19% by using an engineered transaminase for a high-pressure Rh-catalysed hydrogenation [19].
More recently, international demands to address resource depletion and climate change have influenced green catalysis research. For example, according to Bouderbala et al., "green catalysis is a cornerstone of sustainable chemistry, addressing global challenges related to resource conservation, environmental protection, and energy efficiency" in 2025 [20].
In this review, the principles and uses of green (sustainable) catalysis are covered. The atom economy, waste reduction, selection and efficiency, use of renewable inputs, and catalyst recyclability all foundational elements of green chemistry in catalysis were described. Biocatalysts, nanocatalysts, catalysts made from earth-abundant metals, and heterogeneous catalysts are some of the primary types of green catalysts that we look at. We talked about the employment of green catalysts in environmental remediation (purifying air and water), fine-chemical and pharmaceutical synthesis, biomass conversion to biofuels and biochemicals, and clean energy (producing hydrogen, fuel cells). We conclude by talking about challenges and possible future directions, including scalability, catalyst stability, and new research directions. The review aims to provide a comprehensive overview of how green catalysts could drive future innovation and advance sustainable chemical industry.

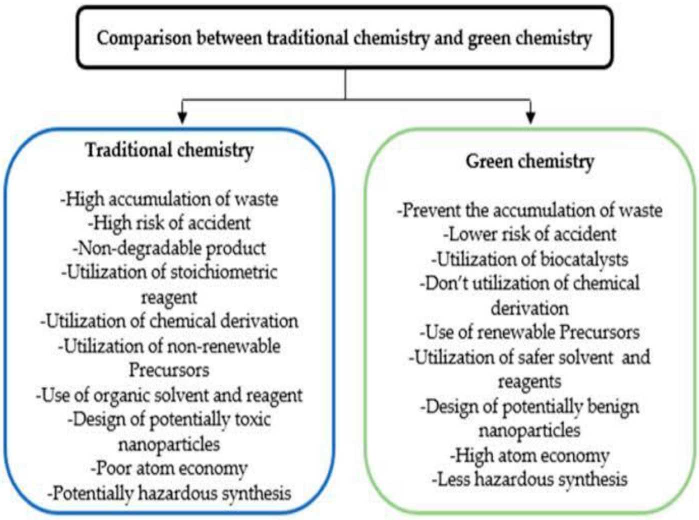

Figure 1. Comparison of green synthesis and traditional synthesis methods
Source: *[21, 22]*

Principles of Green Catalysis

Fundamental ideas drawn from the framework of green chemistry serve as a guide for the creation of green catalysts. The efficiency, sustainability, and industrial potential of catalytic systems are assessed using these principles, which also act as recommendations for their design. These ideas work together to provide the framework for assessing existing systems and directing the development of new catalytic technologies. These Principles are discussed below;

Atom Economy and Waste Reduction

Atom economy is one of the most important concepts in green chemistry, and consequently in green catalysis. Atom economics, first proposed by Barry Trost in 1991, promotes the idea that a chemical transformation's effectiveness should be evaluated not only by yield but also by how well each atom from the reactants is integrated into the finished product. The stoichiometric reagents used in many transformations in classical catalysis, particularly in organic synthesis, produce a lot of waste in the form of solvents, salts, and by-products [23].

For instance, conventional halogenation, oxidation, or reduction procedures frequently call for an excess of chemicals, leaving behind residues that are hazardous to the environment and require energy-intensive separation and disposal. Maximising the integration of every reactant atom into the intended products is the top priority in green catalysis. This efficiency was measured with the introduction of the idea of atom economy [24]. Inherently, catalytic processes increase atom economy by substituting benign oxidants (such as O_2 or H_2O_2) for huge amounts of sacrificial chemicals in processes like catalytic oxidations or carbonylations. Since catalysts allow for one-pot or cascade reactions that limit needless byproducts, Sheldon highlights that catalysis is essential to reducing or eliminating waste [25].

According to green chemistry objectives, planning for high atom economy in practice entails selecting reaction routes (and catalysts) that generate few byproducts. Low atom economy processes usually have high E-factors, which indicate a higher environmental cost. E-factors in the pharmaceutical industry, for example, can reach 100 because of multistep synthesis, the use of solvents, and the dependence on protective groups [26]. In contrast, bulk petrochemical processes and commodity chemicals, which are frequently catalysed by heterogeneous metal oxides or zeolites, attain significantly lower E-factors due to their large-scale throughput and efficiency optimisation. Atom economy is now used as a guiding metric in industrial practice in addition to academic study. Chemical industries are increasingly using process sustainability measures and life cycle assessments (LCA) to assess synthetic processes holistically [27]. Catalytic transformations are not only successful in the lab but also scalable and sustainable on an industrial scale because to the atom economy and associated waste-reduction criteria, which connect economic efficiency with environmental responsibility. The theoretical and practical underpinnings of green catalysis are thus provided by this idea [28].

Use of Renewable Resources and Abundant Materials

The significance of creating catalytic processes that use earth-abundant materials and sustainable feedstocks is emphasized by the second green catalysis principle. Using abundant and renewable feedstocks and resources is encouraged by sustainable catalysis. Platinum, palladium, rhodium, and iridium are among the precious and rare metals that have historically been used in conventional catalysis. Despite their high activity, these metals are restricted in supply, have geopolitical supply risks, and are extracted using environmentally harmful methods [29]. According to [30], biocatalysts and biomass-derived catalysts originate from biological sources, preventing the depletion of limited resources. Earth-abundant elements (such Fe, Cu, Zn, and Ni) are preferred over rare or dangerous metals (like Pt, Pd, and Hg). First-row transition metals, for instance, are inexpensive and safe for the environment; using them can lessen dependency on precious metals [31, 32].

According to [33], "biocatalysts are green catalysts derived from renewable resources, biodegradable and essentially non-hazardous," meeting sustainability standards. Therefore, earth-abundant minerals or biomass (such as cellulose and triglycerides)-derived catalysts and substrates promote resource sustainability [1]. These catalysts are becoming more and more feasible for industrial usage thanks to developments in ligand design and mechanistic knowledge, which have allowed researchers to overcome obstacles like decreased activity or stability. Sustainable catalysis also heavily relies on renewable carbon sources in addition to metals [2]. Processes like the synthesis of bioethanol and biodiesel, as well as the catalytic conversion of biomass into high-value compounds, already demonstrate the industrial significance of renewable feedstocks. Catalyst Design for Efficiency and Selectivity: The sustainability of chemical processes, waste reduction, and energy input minimisation all depend on the selectivity and efficiency of catalysts [3]. Selectivity whether chemo-, regio-, or stereoselectivity determines how much of the desired products are produced at the expense of the undesirable byproducts. The environmental impact of a process is increased by inadequate selectivity in classical catalysis, which frequently calls for lengthy purification procedures, solvent usage, and energy expenditure [4].

Catalyst Design for Selectivity and Efficiency

Catalysts with higher selectivity can channel reactants into desired products with fewer byproducts and less energy use. To do this, sophisticated catalyst structures and synthetic techniques are employed. According to [5], catalysts with more active sites and less solvent waste can be produced using mechanochemical or microwave-assisted syntheses. Because of their customized surface facets or pores, nanostructured catalysts frequently have increased intrinsic activity. Bouderbala et al. emphasize novel techniques that improve the selectivity and efficiency of catalysts. Green catalysts reduce waste and energy consumption in chemical transformations by focusing on certain bonds and optimizing catalytic activity [6].

Recyclability and Reusability

Another fundamental principle is to create catalysts that are easily retrieved and repurposed. A reusable catalyst lowers waste and material usage overall. As a result, immobilized enzymes that can endure several cycles or strong heterogeneous catalysts are preferred in green catalysis. One of the main issues with sustainable catalysis, according to [7] is catalyst recovery and reuse (as well as stability) [8]. To increase the stability of biocatalysts, cross-linked enzyme aggregates have been produced, and many heterogeneous catalysts are solid materials that may be filtered out and recycled. Durability is crucial, and according to [9], "innovations continue to improve lifetime despite challenges like catalyst durability." In conclusion, the goal of green catalyst design is to reduce the catalyst's environmental impact by prioritizing long-term stability and simple separation.

Table 1. Principles of green catalysis and their Implications

Principles	Definition	Implications for Sustainable Chemistry	Example Catalyst/Application	References
Atom economy	Maximizing incorporation of reactant atoms into the final product	Reduces waste, improves process efficiency	Olefin metathesis using Ru-based Grubbs catalyst	[10]
Renewable resources	Using biomass, water, CO_2, or other renewable feedstocks as inputs	Reduces dependence on fossil fuels, enhances sustainability	Biocatalysts for bioethanol production	[11]
Selectivity and efficiency	Designing catalysts that yield fewer by-products and higher conversion	Improves yield, reduces purification steps	Lipase-catalyzed enantioselective synthesis of drugs	[12]
Recyclability and reusability	Ability to recover and reuse catalysts without major loss of activity	Minimizes waste, lowers costs	Zeolite catalysts in petrochemical cracking	[13]

Types of Green Catalysts

The next step toward sustainable chemical transformations is the creation and application of several kinds of catalysts that represent the ideas of green catalysis. In recent decades, scientists have investigated a wide range of catalytic systems intended to reduce their negative effects on the environment, increase their efficiency, and make use of earth-abundant or renewable resources [14]. Instead of being limited to a single material class, these catalysts cover a wide range of biological systems, including enzymes, earth-abundant transition metals that substitute for costly and scarce precious metals, heterogeneous solids that facilitate recycling, and nanoscale materials with adjustable properties [15]. While each kind of green catalyst has its own set of benefits, they also all face different stability, cost, and scaling issues. Collectively, they constitute a range of tactics promoting sustainable chemistry. The design, characteristics, and uses of the main types of green catalysts biocatalysts, nanocatalysts, earth-abundant metal catalysts, and heterogeneous catalysts across several chemical science domains are reviewed in detail in this section [16]. The thorough comments on the various forms of green catalysis are provided here;

Biocatalysts (Enzymes and Whole Cells)

Purified enzymes and entire microbial cells are examples of biocatalysts, which are among the most well-known types of green catalysis. Their primary benefit is their remarkable chemo-, regio-, and stereoselectivity, which allows for the effective synthesis of complex compounds in mild working conditions [17]. Biocatalysts are biologically derived catalysts, including enzymes or microorganisms that have been designed. Because they are non-toxic, biodegradable, and made from biomass, these are naturally sustainable. For instance, at mild circumstances (neutral pH, ambient temperature, and pressure), enzymes catalyse reactions with remarkable selectivity. This frequently results in less waste and higher-purity goods [18]. According to [19], "enzymes are biocompatible and biodegradable," and their reactions require less energy and produce less waste than traditional chemical processes. Biocatalysts make operations more environmentally friendly by avoiding rare precious metals. Pharmaceutical synthesis catalysed by enzymes, food processing, biofuel generation, and other industrial uses are already in place. Biocatalysis was first used in the pharmaceutical sector.

In drug production, enzyme-catalysed transformations are frequently employed, such as the transamination of prochiral ketones to chiral amines or the asymmetric reduction of ketones to chiral alcohols utilising ketoreductases [20]. By offering a comprehensive metabolic environment that enables multistep transformations without the need for separate enzymes, whole-cell systems significantly broaden the application of biocatalysis. For instance, high-value medicines and artemisinin precursors are produced using modified strains of Escherichia coli [21].

Even with these benefits, there are still drawbacks. Enzymes frequently have limited substrate range, expensive production and purifying costs, and instability in industrial settings. In order to improve enzyme activity, robustness, and recyclability, developments in protein engineering, directed evolution, and immobilisation techniques have been used to address these problems [22]. As such, biocatalysis is a crucial area of sustainable catalysis that bridges the gap between green chemistry and biotechnology. The ability to reuse enzymes in numerous cycles has improved cost-effectiveness due to developments in protein engineering and immobilisation. Overall, because they are renewable, extremely selective, and energy-efficient, biocatalysts provide an excellent illustration of green catalysis [23].

Nanocatalysts (Metal Nanoparticles, Carbon-Based Materials)

High surface-to-volume ratios and nanoscale dimensions make nanocatalysts one of the most adaptable and extensively studied types of green catalysts. Their electrical structures, adjustable surface characteristics, and functionalization capabilities make them extremely efficient in a variety of chemical processes [24]. Utilising materials at the nanoscale, nanocatalysts improve catalytic activity. Because of their extremely high surface-to-volume ratios, metal nanoparticles such as Pt, Au, Pd, or base-metal alloys expose more active sites than bulk catalysts. For instance, nanostructured catalysts in fuel cells significantly increase power output and decrease loading of precious metals [25]. "Nanostructured materials play a critical role" in fuel-cell catalysis, according to [26], because they offer high active surface areas, strong conductivity, and nanoporous features that increase activity. In addition to metals, carbon nanomaterials (such graphene, carbon nanotubes, and carbon nitride) have special qualities and can act as catalysts or supports.

By facilitating electron transport and stabilising nanoparticles, these substances can increase catalytic efficiency. According to [27], advancements in catalyst design have included the use of "nanostructured materials" to improve performance. According to [28], heteroatom-doped carbon nanomaterials, such as N-doped graphene, can also function as metal-free catalysts and show outstanding activity in hydrogen evolution and oxygen reduction processes that are pertinent to clean energy applications. Nanocatalyst scaling is still difficult because of stability issues, possible toxicity, and synthesis costs. However, because of their special qualities and versatility, nanocatalysts will be essential to sustainable catalysis in the future [29]. All things considered, nanocatalysts combine high activity and tunable selectivity to enable gentler conditions and lower energy barriers, hence facilitating greener processes.

Earth-Abundant Metal Catalysts (Fe, Cu, Zn, etc.)

The expense and scarcity of precious metals like platinum, rhodium, and palladium are major obstacles to sustainable catalysis.

Researchers have responded by using catalysts based on transition metals that are found in abundance on Earth, like iron, copper, and zinc. Sustainable catalysis relies heavily on catalysts made of common, low-cost metals. Precious metals are much more expensive and scarcer than first-row transition metals like iron, copper, nickel, and cobalt. Earth-abundant first-row transition metals, which are recognised for their affordability and sustainability, are being studied more and more for catalytic applications, according to [30]. As greener substitutes for palladium or rhodium, iron complexes, for instance, have been created for a variety of transformations [31].

In coupling and oxidation reactions that are often dominated by precious catalysts, zinc and copper catalysts are also employed. Utilising metals such as Fe and Co provides "environmental benefits" and creates new catalytic opportunities, according to RSC evaluations [32]. These naturally occurring catalysts can perform on par with or nearly as well as noble metals while significantly lowering their cost and toxicity. According to [33], they are therefore an important class of green catalysts that link environmental and economic sustainability. Mechanistic optimisation, catalyst immobilisation, and ligand design are necessary to overcome obstacles such as reduced stability, a narrow substrate range, and conflicting side reactions.

Heterogeneous Catalysts (Metal Oxides, Zeolites)

By acting on reactants in a separate phase, heterogeneous catalyst solids usually make separation simple. Common examples include porous materials like zeolites (crystalline aluminosilicates) and metal oxide catalysts (such as TiO_2, AlO_3, and CeO_2). By recovering and reusing these catalysts, waste can be decreased. According to [1], heterogeneous catalysts offer a revolutionary method with increased selectivity and efficiency and greatly reduce the environmental impact of the chemical industry. An essential component of green heterogeneous catalysis are zeolites, which are crystalline aluminosilicates with distinct microporous topologies. For example, the homogeneous pores and strong acid sites of zeolites allow for selective processes (such cracking and isomerization) with little solvent. They are perfect for biomass conversion, hydrocarbon transformations, and precise chemical synthesis due to their shape-selective qualities and great heat stability [2].

Many metal oxides take part in oxidation or photocatalytic processes in the purification of air or water, and they operate as strong catalysts or supporters. Because of its capacity to store and release oxygen, cerium oxides are used in catalytic converters. These substances frequently function in green media, including water, and don't require a ligand. Because solid catalysts make separation easier and allow for continuous processing, they are in line with green chemistry [3]. Even though they are widely used in industry, heterogeneous catalysts still have problems with regeneration, selectivity, and deactivation. Future innovation could be facilitated by investigating hybrid systems that combine enzymes or nanomaterials with heterogeneous catalysts. In general, heterogeneous catalysts such as completely inorganic or supported noble metal catalysts are a cornerstone of green catalysis because of their stability and reusability.

Applications of Green Catalysts

Green catalysts' broad range of applications in important facets of contemporary society best demonstrates their practical value. The fundamental impact of sustainable catalysts is found in their application in actual chemical transformations, even though their design reflects the concepts of atom economy, resource efficiency, and environmental responsibility [4]. Green catalysts are propelling a paradigm change toward cleaner and more effective industrial methods in a variety of applications, including the production of renewable energy, the valuation of biomass, the synthesis of high-value pharmaceuticals, and environmental remediation. The creation of closed-loop systems that support the larger objectives of a circular economy is made possible by these applications, which also lessen dependency on dangerous chemicals and fossil fuels [5]. Crucially, the distinct constraints presented by every application domain whether related to cost-effectiveness, stability, or scalability continue to influence research priorities. The primary areas of energy production, chemical synthesis, environmental remediation, and biomass conversion all of which have benefited greatly from the use of green catalysts are thoroughly examined in this section. Collectively, these fields demonstrate how sustainable catalysis can help the world's shift to low-carbon economies and more environmentally friendly production methods [6].

Energy Production (Fuel Cells, Hydrogen Production)

Sustainable energy generation is one of the most important fields in which green catalysts are being used. As the world moves toward decarbonization, new catalytic systems that effectively transform renewable resources into clean fuels and energy carriers are needed. Fossil fuels, which release pollutants into the atmosphere in addition to emitting greenhouse gases (GHGs), constitute a major component of traditional energy generation systems [7]. A key component of sustainable energy technology is green catalysts. Examples of this include fuel cells, which at the point of use transform fuels (such as H_2) into electricity with no carbon emissions [8]. Nevertheless, effective catalysts are needed for the hydrogen oxidation and oxygen reduction processes in fuel cells. Nanostructured catalysts can greatly improve fuel-cell performance, according to research. According to [9], for instance, nanocatalysts significantly increase energy density and dependability while reducing cost. Platinum-group-metal-free catalysts (such as FeNC materials) that can match Pts activity in fuel cells are being developed. Additionally, green catalysis makes sustainable hydrogen production possible. In order to split water into H_2 and O_2, a process known as electrolysis, catalysts are needed for the two half-reactions.

Technological developments in catalyst design, frequently utilising earth-abundant metals or nanostructured surfaces, are increasing the efficiency of electrolysis. According to Bouderbala et al., "sustainable hydrogen generation through water splitting" has been made possible by green catalysis [10]. The oxygen evolution process (OER) and hydrogen evolution reaction (HER) have traditionally employed precious metals like iridium and platinum. Scalability is, however, constrained by their high cost and scarcity. Alkaline electrolysis is being optimised in practice using catalysts like nickel or iron phosphides, and new materials are emerging, such as carbon-based catalysts combined with light or electricity. These catalysts increase the accessibility of green hydrogen as a clean energy carrier by lowering the overpotential and energy input required for H_2 generation [11]. The electrocatalytic conversion of CO_2 to syngas, methane, or methanol is one of the energy applications that green catalysts facilitate. These procedures produce value-added fuels and enable carbon recycling. Incorporating catalysts into artificial photosynthetic systems provides the long-term goal of simulating natural photosynthesis in order to produce clean fuels from sunlight, water, and CO^2. In conclusion, green catalysts, which increase efficiency and substitute rare metals, are essential to the development of fuel cells and hydrogen technologies.

Chemical Synthesis (Fine Chemicals, Pharmaceuticals)

The chemical industry is one of the most resource-intensive industries in the world, generating a lot of waste and using a lot of energy. A revolutionary method for the production of fine chemicals and pharmaceuticals is green catalysis [12]. Green catalysts are utilised to create more sustainable and selective syntheses in the production of pharmaceuticals and fine chemicals. With fewer stages and less waste, catalysts allow complex compounds to be precisely constructed. Enzymes, or biocatalysts, are frequently employed in drug synthesis to generate enantiopure molecules in mild circumstances. Green catalytic methods in the pharmaceutical business produce great selectivity and minimum environmental effect, as noted by [13]. In alkene hydrogenations or C–C couplings, supported metal catalysts can take the place of stoichiometric reagents, producing fewer byproducts and making catalyst separation simpler. Heterogeneous catalysts also play a part. These developments reduce the number of synthetic steps and solvent use, which is in line with the 12 principles of green chemistry. Atom economy, which involves incorporating as many atoms from reactants as possible into the final product, is a fundamental concept in green catalysis for synthesis [14].

By increasing reaction selectivity, catalysts like enzymes, organocatalysts, and nanostructured heterogeneous systems are being used to lessen the requirement for several protection/deprotection procedures and thorough purification. This is particularly important in the production of pharmaceuticals, as process intensification directly lowers costs and has a positive environmental impact. In the pharmaceutical sector, biocatalysis has had a particularly significant influence [15]. These days, industrial synthesis makes extensive use of enzymes like lipases, oxidases, and transaminases because of their enantioselectivity and benign operating conditions [16]. The creation of chiral amines and esters, which are crucial intermediates for active pharmaceutical ingredients (APIs), using enzymes is one such example. The ability to perform multi-step cascade reactions in a single system is another way that whole-cell biocatalysts increase catalytic capabilities. All things considered, the fine chemical sector benefits from green catalysts, particularly biocatalysts and recyclable heterogeneous catalysts, which reduce their environmental impact and increase process efficiency [17].

Pollution Remediation (Such as Water Treatment and Air Purification)

Green catalysts are also frequently used in environmental pollution remediation to address issues with waste treatment, air pollution, and water contamination. High energy consumption, harsh chemicals, and inadequate pollutant degradation are common features of conventional remediation techniques, which might result in secondary environmental issues. Green catalysts are essential for pollution reduction. In water treatment, organic pollutants can be broken down into innocuous products using semiconductor photocatalysts, particularly TiO_2 and Co_3O_4, which use solar energy [18]. Water filtration is more environmentally friendly thanks to these catalysts, which oxidise contaminants without the need for extra chemicals.

Vehicles that employ catalytic converters to purify the air oxidise CO and hydrocarbons and lower NOx emissions by using catalysts, usually Pt, Pd, and Rh on solid supports. Greener alternatives, such as perovskite catalysts and non-noble metal catalysts, are being researched even though current converters require precious metals [19].

As two important uses of green catalysis, Bouderbala et al. point to "advanced photocatalytic degradation techniques and automotive emission control" (Bouderbala *et al*., 2025). Pollutants in air and water can be remedied with little secondary waste in practice by using strong photocatalysts and oxidation catalysts. The cleanup of industrial waste streams is another important use case [20]. High-strength wastewater from refineries, petrochemical plants, and chemical plants is treated using catalytic wet air oxidation (CWAO) procedures, which employ heterogeneous catalysts. By adsorption and reduction, nanocatalysts can also help remove heavy metals. To put it briefly, green catalysis for pollution remediation shows how catalytic systems are essential for environmental sustainability since they not only stop pollution at its source but also offer effective solutions to recover and recycle waste [21].

Biomass Conversion (Biofuels, Biochemicals)

Effective catalytic systems are necessary for the transformation of renewable biomass into fuels and chemicals as the economy transitions from a fossil fuel-based to a bio-based one. A massive and sustainable carbon source is biomass, which includes algae, lignocellulosic wastes, and agricultural waste [22]. For effective valorisation, however, sophisticated catalytic techniques are needed due to its intricate structure. By converting biomass (plant matter and trash) into chemicals and fuels, catalysis promotes a bio-based economy. Green catalysts make it possible to convert non-food biomass into liquid fuels with efficiency. For instance, pyrolysis oils made from wood or agricultural waste can be upgraded into high-octane biofuels using zeolite catalysts. Habib et al. provide instances of "converting biomass to biofuel using zeolites". The esterification of fatty acids to produce biodiesel, the hydrogenation of bio-oils, and the enzymatic saccharification of cellulose to produce bioethanol are other catalytic pathways [23].

The catalysts (solid acids, metal oxides, or enzymes) used in these processes are frequently made for renewable feedstocks. Reliance on fossil fuels is decreased, and waste streams can be utilised when biomass is converted using green catalysts. According to [24], "efficient biofuel production" has been made possible by green catalysis [25]. In order to produce bioethanol, lignocellulose is hydrolysed into fermentable sugars by enzymes such as cellulases and hemicellulases, which are then fermented. In order to increase the depolymerisation efficiency and value lignin, which is generally underutilised, nanocatalysts are also being developed. Biomass can be catalytically transformed into platform chemicals such succinic acid, lactic acid, levulinic acid, and 5-hydroxymethylfurfural (HMF) in addition to fuels [26]. These intermediaries function as building blocks for fine chemicals, solvents, and bioplastics. Thus, biomass conversion offers a route toward a chemical industry free of fossil fuels by bridging the fields of green catalysis, sustainable agriculture, renewable energy, and circular materials science.

Table 2. Selected applications of green catalysts

Application Area	Example Catalyst	Key Benefit	Cross Study References
Energy Production	Ni-Fe oxide for OER	High activity, earth-abundant metals	[27]
Chemical Synthesis	Lipase Enzyme	Enantioselectivity, mild conditions	[28]
Pollution Remediation	TiO_2 photocatalyst	Photodegradation of water pollutants	[29]
Biomass conversion	Zeolite catalyst	Conversion of cellulose to HMF	[30]

Challenges and Future Directions

The design and use of green catalysts have advanced significantly, but a number of obstacles still stand in the way of their widespread use and long-term viability. Even though laboratory research has shown remarkable efficiencies, selectivities, and environmental advantages, problems like catalyst stability, robustness in challenging operating environments, and the viability of large-scale production economically frequently limit the application of these systems in industry [31]. Further impediments to implementation are brought about by the intrinsic complexity of real-world reaction settings, such as feedstock unpredictability and process integration. A comprehensive strategy combining materials science, process engineering, and systems-level sustainability assessments is needed to address these constraints. This section identifies prospective future research directions that could define the next generation of sustainable catalytic systems, looks at the main obstacles to scaling and industrial adoption, and investigates methods to improve stability and durability. The majority of these difficulties consist [32].

Scalability and Industrial Applicability: Scaling potential green catalysts from laboratory to industry is a significant hurdle. It could be challenging or costly to generate lab-developed catalysts in large quantities, particularly sophisticated nanomaterials or modified enzymes. It's not easy to make sure a catalyst performs well in big reactors in industrial settings. For instance, "scale-up and commercialisation" are still challenges in sustainable catalysis, according to [33]. Simplifying catalyst synthesis and showcasing practical pilot procedures must be the main goals of future research.

Catalyst Stability and Durability: For green catalysts to be useful, their performance must be sustained across a large number of cycles. Catalysts can, however, deactivate (for example, metal nanoparticles can sinter and enzymes can denature). It is essential to provide stability and toxin resistance over the long term. According to [19], stability is a crucial concern in green catalysis. Likewise, it is difficult to address "catalyst durability," according to [20]. Future studies must create strong catalyst compositions (such as immobilisation methods and protective coatings) that maintain activity under challenging circumstances while also satisfying environmentally friendly standards.

Looking ahead, the creation of new catalytic materials, enhanced recycling and reusability techniques, and sophisticated computational tools for catalyst design are key to the future of sustainable catalysis. The goal of emerging trends is to get beyond existing constraints. To completely prevent metal sourcing, researchers are looking toward metal-free catalysts (such as carbon-based compounds or organic organocatalysts) [21]. Catalysts with desired qualities are being designed using machine learning and computational techniques. As significant future directions, Bouderbala et al. point to "multifunctional catalysts, computational catalysis, and the integration of green catalysis with industrial processes." Additionally, there is an increasing amount of integration with renewable energy sources, such as fuel cell coupling or solar-driven photocatalysis. All things considered, new materials and process intensification techniques will probably be used in future research to further increase the sustainability of catalysis [22].

Conclusion

The aforementioned analysis emphasises how promising green catalysts are for environmentally friendly chemistry. Their design is guided by key principles, including selectivity, recyclability, atom economy, and the use of renewable resources. A variety of catalyst classes, including earth-abundant metals, enzymes, and nanostructures, each offer special benefits. Cleaner methods of producing energy, making chemicals, reducing pollution, and using biomass are made possible by these catalysts. A quick summary of these findings is presented below.

Table 3. Summary of key findings

Aspect	Key Findings
Principles of Green Catalysis	Emphasize atom economy to minimize waste; use renewable/abundant feedstocks; design for high selectivity and efficiency; ensure catalysts are recyclable and stable [22, 23].
Biocatalysts (Enzymes, Cells)	Derived from natural, renewable sources and biodegradable; operate under mild conditions with very high specificity; avoid toxic metals and reduce waste in syntheses [24].
Nanocatalysts	Metal nanoparticles and carbon nanomaterials offer huge surface area and tunable active sites; greatly enhance activity (e.g. in fuel cells) and reduce use of precious metals [25].
Earth-Abundant Metals	Catalysts based on Fe, Cu, Zn, etc., are cost-effective, non-toxic alternatives to precious metals; enabling similar catalytic transformations with lower environmental impact [26].
Heterogeneous Catalysts	Solid catalysts (metal oxides, zeolites, supported metals) provide easy separation and reusability; key for processes like photocatalysis and selective acid catalysis in water/air [27].
Energy Production	Fuel cells and electrolyzers use green catalysts for clean power/H_2; nanostructured catalysts improve fuel-cell performance, while efficient electrocatalysts enable renewable H_2 production [28].
Chemical Synthesis	Green catalysts (e.g. enzymes, reusable metals) enable cleaner fine-chemical and pharmaceutical syntheses, improving selectivity and reducing waste and energy use [29].
Pollution Remediation	Photocatalysts (e.g. TiO_2) and oxidation catalysts decompose pollutants in water and air, allowing degradation of contaminants without harmful byproducts [30].
Biomass Conversion	Catalytic routes convert biomass to biofuels and biochemicals, integrating renewables into fuel/chemical production and supporting a circular economy [31].
Challenges and Future Direction	Major challenges include scalability, catalyst stability and lifecycle. Future directions focus on novel materials (e.g. metal-free catalysts), computational design, and process integration to further green chemistry [32, 33].

Green catalyst adoption has the potential to revolutionise the chemical sector. They contribute to the achievement of sustainability and regulatory objectives by increasing productivity and decreasing waste. As Bouderbala et al. conclude, green catalysis is definitely "a cornerstone of sustainable chemistry". Going forward, attaining sustainable chemical processes on a global scale will require sustained innovation in catalyst design and wider industrial use. These developments will pave the path for a cleaner, more resource-efficient future by enabling companies to create chemicals, fuels, and materials with a significantly reduced environmental impact.

Acknowledgement

We thank all the researchers who contributed to the success of this research work.

Conflict of Interest

The authors declared that there are no conflicts of interest.

Funding

No funding was received for this research work.

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