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Review Article

Recent Progress in Heterogeneous Catalysis for Sustainable Chemical Processes

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ABSTRACT

Recent advances in heterogeneous catalysis have significantly propelled the development of sustainable chemical processes, addressing key challenges in green chemistry. Metal-based catalysts—including nanostructured and single-atom types—have demonstrated remarkable improvements in activity and selectivity, with turnover frequencies (TOFs) reaching up to 250 h^{-1} and product selectivities exceeding 90% in biomass conversion and CO_2 utilization. These capabilities enable efficient transformation of renewable feedstocks into value-added chemicals and fuels. Zeolite and mesoporous catalysts maintain high thermal stability (up to 600 °C) and tunable pore sizes (~2-50 nm), which are crucial for enhancing the catalytic performance in fine chemical synthesis and waste valorization. Emerging materials, such as metal–organic frameworks (MOFs) and carbon-based catalysts, provide high surface areas (often exceeding 1500 m^2/g) and novel active sites, resulting in improved recyclability and catalytic lifetimes of over 50 cycles. Advances in catalyst design, particularly bimetallic and multimetallic systems, have led to synergistic effects, increasing conversion rates by 30–50% compared to their monometallic counterparts. Surface modification techniques have further improved catalyst durability, reducing deactivation rates by up to 40%. Photocatalysis and electrocatalysis are gaining momentum, achieving solar-to-hydrogen efficiencies of 10-15%, especially in water splitting and hydrogen production, thus facilitating the integration of renewable energy into chemical manufacturing. Despite the ongoing challenges in catalyst scale-up, deactivation, and economic feasibility, recent developments in reactor engineering and catalyst regeneration have reduced production costs by 15–20%. Additionally, the incorporation of AI and machine learning in catalyst discovery has accelerated the identification of novel candidates using optimized metrics, such as energy efficiency and reaction specificity. Overall, the integration of innovative catalytic systems with green feedstocks and renewable energy paves the way for sustainable, efficient, and economically viable chemical processes that support long-term global sustainability goals.

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Content

1. Introduction

Rapid industrialization and urbanization have significantly increased the demand for efficient and sustainable chemical processes. Traditional homogeneous catalysis, although highly active and selective, often suffers from drawbacks such as difficult separation, limited reusability, and hazardous solvent use [1]. As global emphasis shifts toward green chemistry and circular economy principles, heterogeneous catalysis has emerged as a cornerstone of sustainable chemical manufacturing. This review highlights recent advances in heterogeneous catalytic systems and their pivotal role in promoting eco-friendly and energy-efficient processes across diverse chemical sectors [2]. Catalysis plays a vital role in over 90% of industrial chemical processes, including petroleum refining, fertilizer production, and pharmaceutical synthesis. In the context of green chemistry, catalysts offer advantages such as reduced energy consumption, minimal by-product formation, and enhanced atom economy [3]. In the last 20 years, researchers have developed several catalytic systems designed for applications such as CO_2 utilization, biomass valorization, and environmentally friendly oxidation processes. These efforts align with several principles of green chemistry, including waste minimization, renewable feedstock usage, and improved reaction efficiency [4]. Recent studies have demonstrated the potential of catalytic processes to transform biomass-derived compounds, such as levulinic acid, furfural, and glycerol, into high-value chemicals using tailored solid catalysts under mild reaction conditions [5]. Similarly, CO_2, traditionally considered a waste gas, is converted into methanol, cyclic carbonates, and other fine chemicals through catalytic hydrogenation or cycloaddition reactions. These catalytic processes underscore the role of catalysis not just as a reaction enabler, but also as a transformative tool for sustainable development [6]. Heterogeneous catalysts, typically solid-phase materials operating in liquid- or gas-phase reactions, offer significant advantages over homogeneous systems. These include easy separation from reaction mixtures, enhanced catalyst recyclability, and compatibility with continuous-flow systems. Moreover, the ability to tune the surface properties, porosity, and active site distribution provides enormous flexibility for catalyst design [7]. In recent years, heterogeneous catalysis has undergone significant advancements in terms of material innovation and structural engineering. For instance, metal nanoparticles supported on high-surface-area oxides such as TiO_2, Al_2O_3, and SiO_2 have demonstrated exceptional performance in hydrogenation and oxidation reactions [8]. Zeolites and mesoporous silica frameworks offer shape-selective catalysis for hydrocarbon processing, while carbon-based materials, such as graphene oxide and carbon nanotubes (CNTs), serve as efficient supports for redox and acid–base catalytic sites [9].

Single-atom catalysts (SACs) have gained considerable attention for their atomic efficiency and unique electronic properties, enabling a high TOF in CO oxidation, ammonia synthesis, and water splitting. Additionally, metal-organic frameworks (MOFs) and covalent organic frameworks (COFs) provide modular platforms with tunable pore environments and functional groups that are suitable for photocatalysis and electrocatalysis. These advances have expanded the application of heterogeneous catalysis to green energy, fine chemical synthesis, and environmental remediation [10,11]. This review comprehensively examines recent progress in heterogeneous catalysis for sustainable chemical transformations, focusing on both fundamental understanding and applied technologies. It categorizes the key types of heterogeneous catalysts, including metal-based systems, zeolites, MOFs, carbon-based materials, and bio-hybrid catalysts, highlighting their synthesis methods, structural features, and reaction mechanisms [12]. Furthermore, this review emphasizes applications in sustainable chemical processes such as biomass conversion to platform chemicals and fuels, CO_2 utilization through catalytic hydrogenation and functionalization, green hydrogen production via water splitting and reforming, selective oxidation, and C–C coupling reactions under mild conditions [13]. Special attention has been given to recent innovations in catalyst design such as bimetallic/alloyed nanoparticles, nanostructured supports, defect engineering, and atomically dispersed metals. The roles of photocatalysis and electrocatalysis in renewable energy integration have also been explored [14]. Additionally, this review addresses industrial perspectives, including challenges in catalyst deactivation, scale-up strategies, reactor integration, and lifecycle analysis. Emerging tools, such as machine learning and high-throughput screening for catalyst optimization, are also discussed in future directions [15]. By synthesizing state-of-the-art developments in both academic and industrial domains, this review aims to provide a comprehensive roadmap for the design and application of heterogeneous catalysts in the green and sustainable chemistry era. The insights presented herein are intended to guide future research, foster interdisciplinary collaboration, and accelerate the transition toward cleaner and more efficient chemical manufacturing technologies [16].

2. Fundamentals of Heterogeneous Catalysis

2.1. Mechanism and surface chemistry

Heterogeneous catalysis involves reactions at the interface between phases, typically between a solid catalyst and gaseous or liquid reactants. Recent research has significantly advanced our understanding of reaction mechanisms, particularly the nature and dynamics of surface intermediates. The Langmuir-Hinshelwood and Eley-Rideal mechanisms remain the foundational models, but real-time studies using in situ spectroscopy and microscopy have revealed that these models often oversimplify the dynamic surface behaviour [17]. For example, studies using ambient-pressure X-ray photoelectron spectroscopy (AP-XPS) have shown that active sites may change oxidation states under reaction conditions, as observed in CO oxidation over Pt and Pd catalysts, indicating that the surface composition is highly dynamic. Moreover, operando techniques have highlighted the role of surface restructuring, lattice oxygen participation, the Mars van Krevelen mechanism, and spillover effects in reactions such as methane reforming and ammonia synthesis [18]. Advancements in density functional theory (DFT) have enabled the precise prediction of adsorption energies and activation barriers, supported experimental data, and helped map out entire reaction pathways [19]. For instance, DFT calculations have been instrumental in understanding the selective oxidation of alcohols over Au/TiO_2 and identifying the role of surface hydroxyl groups and gold nanoparticles in enhancing electron transfer. Similarly, the development of microkinetic models integrating theoretical and experimental findings has provided insight into rate-determining steps and turnover frequencies (TOFs) [20]. The combined influence of electronic effects (such as the d-band center theory) and geometric features (including terraces, steps, and kinks) on catalytic activity has been well established in the literature. In photocatalysis, charge carrier dynamics at semiconductor surfaces such as in TiO_2 or g-C_3N_4 are crucial in dictating performance, and surface modifications using cocatalysts (*e.g.,* Pt and RuO_2) have shown enhanced hydrogen evolution rates [21]. **Figure 1** depicts the fundamental mechanism of heterogeneous catalysis occurring within the porous catalyst pellets. The reactant molecules diffuse through the surrounding medium toward the catalyst pellets. These pellets possess porous structures that allow the reactants to enter the internal pores. Inside these pores, the reactants are adsorbed onto the internal surface, initiating surface reactions. As the reaction proceeds, product molecules are formed and subsequently desorbed from the surface, diffusing back through the pore channels to exit the pellet. Sequence diffusion, adsorption, reaction, and desorption highlight the critical role of internal catalyst surfaces and pore architecture in enhancing the catalytic efficiency and selectivity in sustainable chemical processes [22].

2.2. Catalyst supports and active sites

The nature of the catalyst support is critical for the stability, dispersion, and activity of the catalytic species. Current research focuses on support–metal interactions (SMI) and strong metal-support interactions (SMSI), which influence the electronic environment and catalytic behaviour of active sites [23]. For example, TiO_2, Al_2O_3, SiO_2, and CeO_2 are commonly used oxide supports, and studies have shown that reducible oxides such as CeO_2 can store and release oxygen, making them particularly effective in oxidation reactions. CeO_2-supported Ni and Cu catalysts have demonstrated superior performance in CO_2 methanation and biomass reforming due to oxygen vacancy formation and lattice oxygen mobility [24]. Recent innovations include the design of high-surface-area mesoporous materials (*e.g.,* SBA-15 and MCM-41) and hierarchical porous structures that enhance the mass transport and accessibility of active sites.

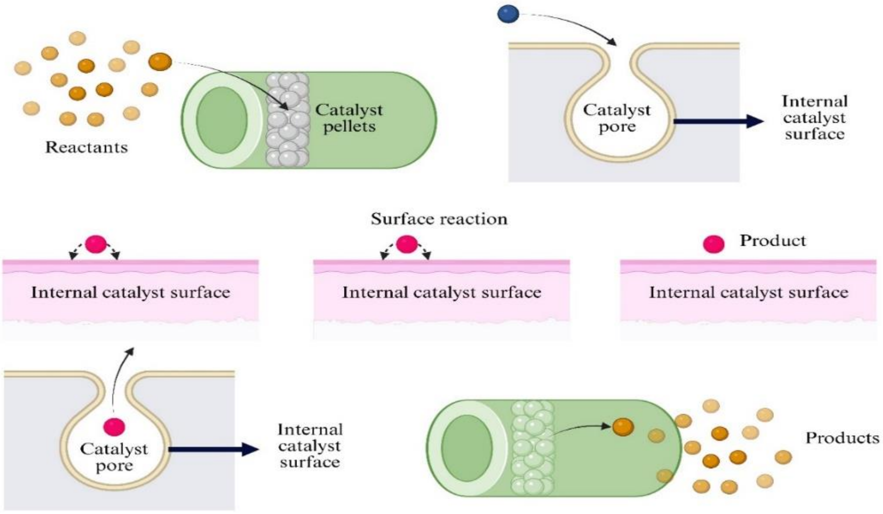


Figure 1. Schematic representation of heterogeneous catalysis on porous catalyst pellets

Carbon-based supports such as graphene, CNTs, and nitrogen-doped carbon have gained attention due to their high electrical conductivity, tunable surface functionalities, and stability under harsh conditions. Metal–organic frameworks (MOFs) and COFs are being explored not only as supports, but also as precursors for heteroatom-doped carbon materials with embedded active metal sites [25,26]. Defining the active sites is a central challenge. For supported metal catalysts, SACs have emerged as a frontier, wherein isolated metal atoms anchored on supports exhibit remarkable selectivity and atom efficiency [27]. For instance, Fe-N-C and Co-N-C catalysts show high activity for oxygen reduction and CO_2 reduction, attributable to the unique coordination environment of the metal centres. Furthermore, dual-atom and bimetallic catalysts have been designed to introduce synergistic effects, which have been proven effective in reactions such as selective hydrogenation and cross-coupling. In acid-base catalysis, the strength and density of Brønsted and Lewis acid sites—quantified through techniques such as NH_3-TPD and pyridine-FTIR are manipulated to optimize performance, as seen in zeolite-catalysed cracking processes [28]. The concept of frustrated Lewis pairs (FLPs) on solid surfaces is gaining traction, particularly for metal-free hydrogenation. In photocatalysis and electrocatalysis, active sites include both metal centres and defect sites oxygen vacancies and sulfur vacancies in semiconductors like MoS_2, $ZnIn_2S_4$, and $BiVO_4$. These defects have been shown to trap electrons or holes, thus improving charge separation and redox capabilities. Research on lattice strain engineering, interfacial charge transfer, and heterojunction formation continues to inform the design of next-generation catalytic systems [29].

2.3. Characterization techniques

Characterizing heterogeneous catalysts at the atomic and molecular levels is critical for understanding their structure-function relationships. Transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM), particularly with aberration correction, have provided atomic-scale images of nanoparticle shapes, lattice fringes, and single-atom dispersion. High-angle annular dark field (HAADF)-STEM has been particularly useful for identifying SACs on various supports [30]. X-ray diffraction (XRD) remains a fundamental tool for determining the crystallinity and phase composition. More advanced techniques, such as synchrotron-based X-ray absorption spectroscopy (XAS), including XANES and EXAFS, are widely used to probe the local environment, oxidation state, and coordination geometry of metal centres, especially under operando conditions. *In situ* XAS studies have revealed changes in the oxidation states and coordination numbers during catalytic reactions, providing insights into reaction intermediates and mechanisms, such as the reversible oxidation of Ni in methane reforming or Cu^+/Cu^{2+} transitions in CO oxidation [31,32]. Fourier-transform infrared spectroscopy (FTIR), especially when combined with probe molecules such as CO or pyridine, provides information on the acid sites, adsorbed species, and intermediate formation. Raman spectroscopy has been extensively applied to carbonaceous supports and metal oxides, revealing the defect structures and graphitization levels. The development of surface-enhanced Raman scattering (SERS) and tip-enhanced Raman spectroscopy (TERS) has expanded the sensitivity and spatial resolution of this technique [33]. Temperature-programmed methods, such as TPD (desorption), TPR (reduction), and TPO (oxidation), offer quantitative information on the strength and number of adsorption sites. For example, NH_3-TPD and CO_2-TPD are routinely employed to evaluate the acid-base properties of catalysts. Solid-state NMR spectroscopy, although less common due to sensitivity issues, has been employed to probe the local structure of zeolites and MOFs [34]. Electron paramagnetic resonance (EPR) spectroscopy and XPS were used to study the electronic structures and oxidation states. In particular, XPS revealed strong correlations between the surface composition and catalytic activity. *In situ* and operando methods, such as DRIFTS (Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS), ambient pressure XPS, and environmental transition electron microscopy (ETEM), have enabled real-time monitoring of surface chemistry under reaction conditions, offering unprecedented insights into transient species and dynamic surface restructuring [35]. Emerging techniques such as time-resolved X-ray spectroscopy, machine learning-assisted spectral analysis, and single-molecule fluorescence spectroscopy have revolutionized catalyst characterization. Coupled with multimodal analysis and data-driven modelling, these tools are now integral to the rational catalyst design [36].

3. Types of Heterogeneous Catalysts

3.1. Metal-based catalysts

Metal-based catalysts remain a cornerstone of heterogeneous catalysis, particularly in redox reactions, hydrogenation, dehydrogenation, and reforming processes. Recent research has shown that noble metals such as Pt, Pd, Ru, and Rh exhibit exceptional activity and selectivity owing to their high surface energies and availability of active sites [37]. The high cost and scarcity of these metals have encouraged the exploration of earth-abundant alternatives, such as Ni, Co, Fe, and Cu. For instance, nickel-based catalysts have demonstrated remarkable efficacy in steam methane reforming and biomass hydrodeoxygenation because of their SMSI and enhanced dispersion on alumina and silica supports [38]. Studies have shown that Fe-based catalysts doped with alkali metals improve the selectivity of Fischer–Tropsch synthesis, yielding long-chain hydrocarbons under mild conditions. Additionally, alloying strategies have garnered significant attention; bimetallic catalysts such as Ni–Cu and Pt–Co exhibit synergistic effects that enhance the reaction kinetics and stability [39]. The use of nanosized metal particles has also improved the TOFs and catalyst recyclability. Notably, SACs supported on oxide surfaces offer high atom efficiency and well-defined active sites, which have proven valuable for CO oxidation and selective hydrogenation. These findings underscore the versatility and tunability of metal-based catalysts for achieving sustainable transformations with enhanced efficiencies [40]. The catalytic properties of individual atoms, nanoclusters, and nanoparticles in many processes. Factors such as particle size, morphology, chemical composition, and metal-support interactions substantially affect the characteristics of these catalysts. Recent improvements in the synthesis procedures and characterization techniques have enabled the correlation of molecular connections. This review examines the electrical and geometric structures of these species and their applicability in diverse reactions, and compares the findings across numerous systems. It seeks to enhance the understanding of the catalytic properties of various metal entities [8].

Gallium-based catalysts are promising for CO_2-assisted propane dehydrogenation, but high acid strength can cause side reactions. This study combines second metal promoters into Ga2O3/Silicalite-1 catalysts to enhance the interaction between Ga species and the S-1 support. The addition of Cu to the Ga_2O_3/S-1 catalyst (7Ga_2O_3-0.5Cu/S-1) improved the acid-base equilibrium and CO2 activation by creating additional basic sites. The 7Ga_2O_3-0.5Cu/S-1 catalyst achieved an initial C3H6 yield of 52.7% and CO_2 conversion of 29.7%, surpassing most documented Ga-based and non-precious-metal catalysts [41]. This study examines the function of metal oxide supports in Ru-based catalysts for ammonia synthesis using Shapley additive explanations. It recognizes the formation energy of supported metal nitrides and supported metal hydrides as essential characteristics for ammonia synthesis. Research indicates that metal oxide supports must possess a certain acidity to mitigate ammonia inhibition and facilitate the formation of metal hydrides to counteract hydrogen inhibition, proposing novel methods that may regulate the reaction [42]. Recent investigations have focused on the development of heterogeneous metal oxide catalysts for transesterification processes, owing to their efficiency and ecological sustainability. An innovative fluorescence-based high-throughput screening technique has been used to evaluate various metal oxides for transesterification. Praseodymium (IV) oxide (PrO_2) exhibited the highest catalytic activity among the synthesized metal oxides. The chosen catalyst was effective in yielding biodiesel at a high rate of 90% from soybean oil, requiring minimal quantities of various substrates and soybean oil [43].

3.2. Zeolite and mesoporous catalysts

Zeolites and mesoporous materials have emerged as vital supports and active catalysts due to their uniform pore sizes, high surface areas, and tunable acidities (**Table 1**). Zeolites such as ZSM-5, Beta, and Y-type zeolites have been widely used in fluid catalytic cracking (FCC), methanol-to-olefins (MTO), and aromatization reactions. Recent research has focused on hierarchical zeolites, which combine micro- and mesoporosity, enhance molecular transport, and reduce the diffusion limitations. These materials exhibit improved catalytic performance in biomass-derived molecule upgrading and hydrocarbon isomerization [44]. Mesoporous silicas, such as MCM-41, SBA-15, and KIT-6, offer a high degree of structural control, allowing for the incorporation of various functional groups and metal species within their frameworks. For example, SBA-15 impregnated with V or Mo has shown high selectivity for oxidative dehydrogenation of propane and glycerol oxidation [25]. Moreover, zeolites exchanged with transition metals, such as Fe-ZSM-5 and Cu-SSZ-13, have shown excellent performance in NOx reduction via selective catalytic reduction (SCR). Studies have also highlighted that mesoporous catalysts doped with acid/base bifunctional sites are effective in cascade reactions, such as the conversion of glucose to lactic acid or levulinic acid. These structural features and compositional tunabilities make zeolite and mesoporous catalysts powerful platforms for tailoring reactions toward green and selective pathways [45].

A variety of hierarchical mesoporous silica core-shell catalysts incorporating beta zeolite were manufactured using a sol-gel method. The influence of the shell thickness, hydrogenating metal, and SiO_2/Al_2O_3 ratio on the conversion of heavy reformate and toluene into xylenes was examined. The resultant catalysts exhibited an increase in the xylene yield relative to that of the virgin zeolite. The catalyst with medium shell thickness exhibited the greatest enhancement, achieving a xylene yield of 25 wt%. The incorporation of a hydrogenation function with 1 wt% nickel metal improved the xylene yield and selectivity. Reducing the SiO_2/Al_2O_3 ratio significantly enhanced the xylene production and selectivity. This indicates the possible use of core-shell composite catalysts for the conversion of heavy reformate into xylene [46]. This study aimed to develop a one-pot GTO process using platinum-based catalysts on HZSM-5 zeolite and hexagonal mesoporous silica (HZ5M). The process uses a bifunctional catalyst to convert glycerol into propanol and acid-catalysed dehydration of C3 alcohols to produce propylene. One-pot GTO yields 20.8% olefins, with the optimal yield achieved by modifying the molar ratio and loading levels of Pt, Ir, and Re in the trimetallic catalysts [47].

A novel technique for synthesizing hierarchical beta zeolites with enhanced molecular transport efficacy in catalysis was delineated. Alkaline etching using a 0.2 mol/L NaOH solution markedly enhanced the n-hexane isomerization activity, elevating the maximum yield of isohexane and dibranched isomers by 6.2% and 38.6%, respectively. This research revealed reduced transport limitations compared to the Pt/Beta-parent, indicating its potential as a catalyst for commercial alkane isomerization [48]. A new encapsulated catalyst (Pt-CeO@meso-S1) with Pt-CeO_2 interfaces was fabricated with a mesoporous zeolite shell for the catalytic oxidation of toluene at low temperatures. The crystalline phase transition technique enhances platinum dispersion, and the zeolite shell and pores stabilize the active components, resulting in exceptional water resistance and high temperature stability. DFT studies show that the presence of Pt-CeO_2 active interfaces reduces the energy required for oxygen vacancy generation and enhances gas-phase oxygen activation [49]. This study illustrates the use of hierarchical ZSM-5 zeolite-supported RuOx catalysts for the catalytic oxidation of vinyl chloride (VC). The incorporation of organic mesoporous porogens, including starch, cellulose, and sucrose, markedly improves the catalytic efficacy of the catalysts.

The 1%RuOx/HZ5-10% sucrose catalyst exhibited superior catalytic activity, stability, and long-term durability. This research identified enol and carboxylate molecules as crucial organic intermediates in the catalytic VC oxidation process [50].

3.3. Metal–organic frameworks (MOFs)

Metal–organic frameworks (MOFs) have gained widespread attention as next-generation catalysts due to their crystalline porosity, modularity, and high surface area. MOFs are composed of metal nodes and organic linkers, enabling precise control over pore size, geometry, and active site incorporation. Recent advances have demonstrated their application in catalysis of CO_2 conversion, biomass

Table 1. Recent advances in zeolite and mesoporous catalysts for sustainable chemical transformations

Catalyst type	Synthesis/Modification strategy	Reaction type / Application	Sustainability features	Catalytic performance	Ref.
ZSM-5 zeolite	Alkali-treatment for mesoporosity induction	Biomass conversion to aromatics	Low energy demand, reusable, high thermal stability	High selectivity (~80%) and stability	[51]
Beta zeolite	Dealumination and metal doping (*e.g.*, Fe and Zn)	Alkylation, oxidative dehydrogenation	Improved metal dispersion, green oxidants (O_2, H_2O_2)	TON: 1200, Recyclability: 5+ cycles	[52]
MCM-41 (Mesoporous)	Functionalized with sulfonic acid groups	Biodiesel synthesis (esterification)	Recyclable, non-toxic solid acid catalyst	Conversion > 90%, stable over 6 cycles	[53]
SBA-15	Loaded with transition metals (*e.g.*, Ni and Co)	Hydrodeoxygenation of lignin-derived phenolics	Reduces hydrogen consumption, bio-oil upgrading	TOF: 250 h^{-1}, improved coke resistance	[54]
Hierarchical zeolite	Desilication–recrystallization approach	Fischer–Tropsch synthesis	Enhanced mass transfer, lower CO_2 footprint	Yield increase by 25%, lifetime improved	[55]
H-Zeolite-Y	Ion-exchange with rare earth metals (*e.g.*, La^{3+} and Ce^{3+})	Catalytic cracking of waste plastics	Reduces waste, high product selectivity (olefins, fuels)	Selectivity ~70%, longevity > 100 h	[56]
Hollow zeolite microspheres	Spray-drying with binder-free precursors	CO_2 conversion to methanol	CO_2 utilization, low-temperature catalysis	CO_2 conversion: 20%, MeOH selectivity: 80%	[57]

transformation, and selective oxidation reactions [58]. Zirconium-based MOFs, such as UiO-66 and MOF-808, have been used effectively for esterification and hydrolysis reactions due to their Lewis acidic nature and thermal stability. The post-synthetic modification (PSM) of MOFs enables the grafting of functional groups, such as sulfonic acids or amines, enhancing the catalytic activity for base- and acid-catalysed reactions, respectively. Catalytically active MOFs such as MIL-101(Cr) and HKUST-1 have shown excellent performance in the oxidation of alcohols, alkene epoxidation, and photocatalytic hydrogen evolution [59]. Embedding nanoparticles within MOF matrices has emerged as a novel strategy for stabilizing active metal sites and preventing aggregation. For example, Pd@MOF and Au@MOF hybrids have achieved high selectivity in C–C coupling and hydrogenation reactions. MOFs also serve as precursors for the formation of porous carbon or metal-oxide materials upon pyrolysis, leading to stable and high-performance electrocatalysts. These findings indicate that MOFs represent a versatile and tunable class of heterogeneous catalysts for sustainable chemical synthesis [60].

MOFs are promising precursors for creating non-noble metal electrocatalysts for the oxygen evolution reaction (OER). Quasi MOFs, with disrupted connections between metal nodes and organic ligands, are of interest due to their extensively exposed active surfaces. A Ni-Fe quasi-MOF catalyst was synthesized using MIL-101(Fe) pyrolysis and ion exchange with Ni^{2+}. The optimal catalyst demonstrated a minimal overpotential, the lowest Tafel slope, and the highest double-layer capacitance. The improved OER performance is due to the robust coupling effect between Fe and Ni, which enhances the electron transfer efficiency and produces active species [61]. This study investigated the development of zirconium-based metal-organic framework nanoparticles, specifically UiO-67-Pd, for their catalytic performance in the esterification of aryl aldehydes under mild conditions. Various techniques were used to analyse the structures and properties of UiO-67-Pd. Their results showed excellent catalytic efficiency and outstanding reusability, retaining high activity and efficiency over at least five consecutive cycles, contributing to reduced operational costs [62]. MOFs have been explored for their ability to stabilize molecular catalysts in homogeneous environments. A novel, crystalline, and energetic ferrocene-functionalized Cu (I)-based MOF was synthesized under hydrothermal conditions. The inorganic-organic hybrid nature of the catalyst, formed from copper, benzene-1,3,5-tricarboxylic acid, and ferrocene monocarboxylic acid, was investigated using various techniques. The synthesized bimetallic Cu-Fc-BTC MOF demonstrated outstanding catalytic activity and high recyclability, providing excellent isolated yields across various functionalities [63]. This research suggests that ionic liquid (ILs)-based ionic MOFs are a viable method for the chemical fixation of CO_2. ILs are presented as dual active centre catalysts, with the indium ion (In3+) serving as the metal centre exhibiting enhanced catalytic activity relative to the zinc ion (Zn2+). The research indicated that a chloropropene carbonate yield of 98.1% may be attained without co-catalysts under ideal circumstances of 0.1 MPa CO2, 5.4% catalyst, and 80°C for 7 h [64]. MOFs are potential Fenton-like catalysts for pollutant degradation; however, their poor conductivity and interlaced pores limit their efficacy. A copper-based cMOF, CuHITP, has high conductivity and 1D vertical through-channels, which enhance mass transfer. It exhibits superior activity for tetracycline (TC) degradation compared with conventional MOFs. CuHITP also exhibits remarkable pH tolerance, strong resistance to anion interference, and high stability. This study suggests potential TC degradation routes over CuHITP and highlights the low toxicity and biological safety of cMOFs as efficient Fenton-like catalysts for environmental cleanup [65]. This study investigated microwave-catalysed co-pyrolysis for the conversion of biomass and waste plastics into valuable fuels. The researchers examined the co-pyrolysis properties and products of Chlorella vulgaris (CV) and marine waste plastics (MW) at various mixing ratios. The research determined that the ideal mixing ratio was 8:2, yielding the highest weight loss rate and pyrolysis oil output for 30% Fe_3O_4@C. The hydrocarbon concentration in the co-pyrolysis oil increased by 12.51%, while that of the nitrogenous compounds decreased by 41.38%. The incorporation of 30% Fe_3O_4@C increased the hydrocarbon content by 10.88%, while nitrogenous compounds decreased it by 9.76% [66]. This study developed a self-supporting Ni single-atom catalyst on carbon paper (Ni-Nx-b/CP) using a nickel metal organic framework and a calcination process. The catalyst has a three-dimensional hexagonal prism skeleton with a rich porous structure, facilitating more active sites and transport of the electrolyte and CO_2 gas. It has a significant CO partial current density (jCO) of -160.8 mA cm^{-2} at -1.0 V and a CO Faradaic efficiency (FECO) exceeding 90% in a flow cell. The Zn-CO_2 battery, which incorporates a Ni-Nx-b/CP cathode and an anode, achieves a notable power density of 1.10 mW cm-*2* at 3.46 mA cm^{-2} [67].

3.4. Carbon-based catalysts

Carbon-based materials such as activated carbon, CNTs, graphene, and graphitic carbon nitride (g-C_3N_4) have emerged as promising heterogeneous catalysts and catalyst supports due to their high conductivity, surface area, and chemical tunability. Their inert nature and stability under reaction conditions make them excellent supports for metal nanoparticles and active organic groups [68]. Functionalized graphene oxide (GO) and reduced graphene oxide (rGO) have demonstrated high activity in oxidation and coupling reactions, especially when combined with transition metals, such as Fe, Co, or Mn. CNT-supported Pd and Pt catalysts exhibit enhanced activity in hydrogenation and Suzuki coupling due to strong metal–support interactions and facilitated electron transfer. Moreover, nitrogen-doped carbon materials exhibit intrinsic catalytic activity in the oxidation and oxygen reduction reactions (ORR), making them attractive for fuel cells and electrochemical synthesis [69]. The catalytic activity of g-C_3N_4 has been intensively investigated in photocatalytic CO_2 reduction and water splitting owing to its suitable bandgap and thermal robustness. Additionally, biochar-derived catalysts are being explored for biomass valorization and pollutant degradation due to their eco-friendly origin and tunable porosity. Recent advances have also involved the synthesis of SACs anchored on carbon supports (*e.g.,* Fe–N–C) that combine the advantages of atomic dispersion and high conductivity. These studies underscore the role of carbon materials as multifunctional platforms for catalysis in environmentally benign processes [70]. This study introduces an innovative method for enhancing the carbon deposition resistance of nickel-based catalysts in the dry reforming of methane (DRM) process. The researchers synthesized hierarchical porous catalysts, including 3D ordered meso-macroporous γ-Al_2O_3-supported Ni nanoparticles (Ni/3DOMM-Al_2O_3), through a two-step process. The distinctive 3DOMM architecture increases the likelihood of collisions between reactants and active sites, thereby enhancing the distribution of Ni-based active components. The catalysts exhibited exceptional carbon-resistant catalytic activity, achieving conversion rates of 90% and 93% at 650 °C, respectively. This offers a substantial solution for Ni-based catalysts in industrial applications [71]. Graphitic carbons are commonly used as substrates for electrocatalysts, but they often cause aggregation and migration of Pt particles, reducing their activity and stability during the alkaline hydrogen evolution reaction (HER) process. This study aimed to create edge-N-doped porous graphitic carbon (NPGC) as a substrate for platinum-based catalysts. The porous architecture and edge-N doping helped disperse the Pt species and reduce the nanoparticle size, resulting in low overpotential and remarkable stability. This research provides valuable insights for designing and manufacturing efficient graphitic-carbon-supported Pt-based catalysts for future hydrogen energy systems [72]. This study investigates the CO_2-modified Fischer-Tropsch synthesis (FTS) technique to mitigate CO_2 emissions and advance carbon neutrality. It examines the efficacy of CO_2-encapsulated iron-based catalysts in reverse water-gas shift and Fischer-Tropsch synthesis processes. Nonetheless, regulating active phase development and product selectivity continues to pose a challenge. This study presents an economical and scalable method for CO_2 hydrogenation, which is essential for the development of carbon recycling and renewable energy technologies. This research emphasizes the use of co-promoters, phase compositions, support modifications, and organic ligands [73].

Figure 2 shows a classic redox (reduction–oxidation) reaction involving two reactants, A and B. In the oxidation half-reaction (depicted in blue), species A loses electrons $(-e^-)$, resulting in an increase in its oxidation state and formation of A^+. Simultaneously, in the reduction half-reaction (depicted in purple), species B gains the electrons released by A, reducing its oxidation state and forming B^-.

This electron transfer underpins many chemical and biological processes, and the graph clearly shows the direction and identity of each half reaction. The symbols (+ and −) indicate the resulting ionic charges of the oxidized and reduced species, respectively.

3.5. Biocatalysts and enzyme-immobilized systems

Biocatalysts, including enzymes and whole-cell systems, have received significant attention in heterogeneous catalysis due to their high selectivity, mild reaction conditions, and renewability. However, their practical application often suffers from instability and poor reusability. Recent studies have focused on enzyme immobilization techniques to enhance stability, activity, and recyclability [74]. Supports such as silica, chitosan, alginate beads, and MOFs have been utilized to immobilize enzymes, including lipases, oxidoreductases, and hydrolases. These systems have been successfully applied to transesterification, epoxidation, and CO_2 fixation reactions. For example, lipase immobilized on mesoporous silica has demonstrated high conversion efficiency in biodiesel production from waste oils. Additionally, cross-linked enzyme aggregates (CLEAs) and magnetic nanoparticle-based immobilization have emerged as efficient strategies for enzyme reuse and easy separation [75]. The typical catalytic cycle is shown in the top section: an enzyme forms an

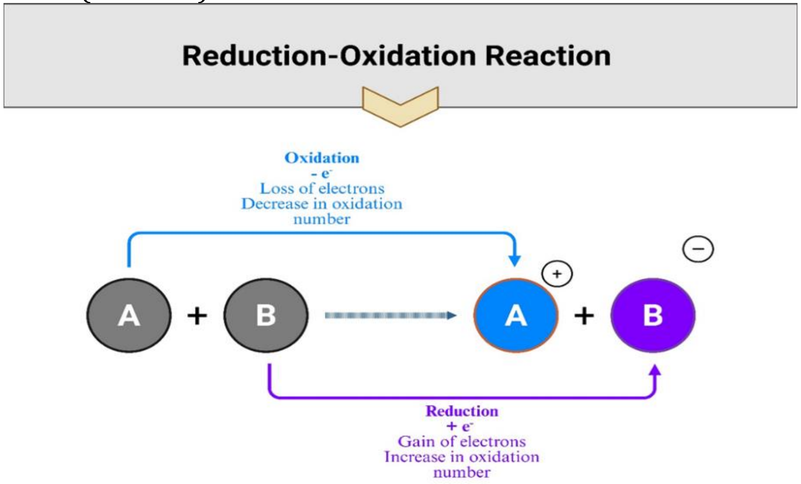
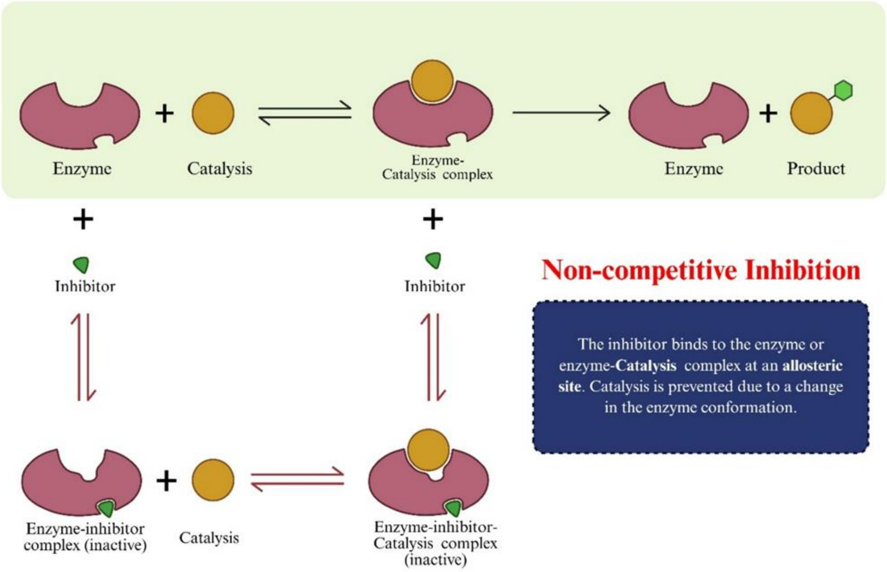


Figure 2. Mechanism of a reduction–oxidation (Redox) reaction

enzyme–substrate complex by binding to a substrate (catalysis). This complex releases the product and regenerates the enzyme by facilitating conversion of the substrate into one. An inhibitor binds to an allosteric site on the enzyme or enzyme–substrate complex, thereby displaying non-competitive inhibition. This binding alters the structure of the enzyme, rendering it inactive and incapable of catalysing the process. Unlike competitive inhibition, the inhibitor does not compete for the active site; therefore, in many circumstances, this type of inhibition is irreversible. This results in either an inactive enzyme inhibitor–substrate complex or an enzyme–inhibitor complex forming, thus halting product synthesis [76,77]. This study demonstrates the immobilization of Candida rugosa lipase onto nanocellulose (NC) from almond shells using p-toluenesulfonic acid (PTSA), sulfuric acid (SA), and a natural deep eutectic solvent (NADES1a) as a biocatalytic system. The immobilized CRL-PTSA-NADES1a and CRL-SA-NADES1a showed higher specific activities under optimal conditions and enhanced thermal stability, catalytic activity, and reusability for up to seven cycles. The half-life of the immobilized lipase was 14-16 days longer than that of the free lipase. The functional groups and morphology of free and immobilized CRL were analyzed using FTIR spectroscopy and SEM [78]. The need for economical and environmentally friendly biocatalytic processes has led to the development of resilient instruments. This study assessed the sticky characteristics of 10 Flo family related genes in Komagataella phaffii. The KpFlo11C domain of BSC1p promotes cell aggregation on carriers, thereby improving biofilm immobilization. A modified strain was developed to immobilize β-galactosidase on the cell surface, thereby enhancing the enzyme targeting and anchoring efficacy. The enzyme-cell@material biocatalyst exhibited a strong continuous synthesis of galacto-oligosaccharides at a rate of 8.16 g/L/h in a 6-L fermenter [79]. A mathematical model was created to study enzyme-catalysed reactions in a microreactor with surface-immobilized transaminases. The simplified one-dimensional model accurately predicted the performance of two microreactors coated with N-SBM-ATA-wt. The model showed strong concordance with the experimental data and could be used to develop efficient and sustainable procedures for chiral amine synthesis catalysed by surface-immobilized enzymes [80]. In this study, recombinant LMCO from Bacillus mojavensis TH308 (BmLMCO) was immobilized on hazelnut shell hydrochar (HSH) and used as a biocatalyst (HSH-BmLMCO) for the degradation of sulfamethoxazole and diclofenac. The biocatalyst exhibited optimal activity at 80 °C and pH 8, demonstrating its improved heat stability. The incorporation of Cu^{2+} enhanced its activity, while other agents, such as Tween 20, Triton X-100, and SDS, also increased its activity. The biocatalyst maintained its activity after 48 days and showed promise for bioremediation applications. This study is the first account of a biocatalyst using B. mojavensis LMCO and hydrochars derived from hazelnut shells [81]. This study evaluated the efficacy and stability of laccase immobilized on Cu-BDC to eliminate 17α-ethynylestradiol. The material showed a uniform structure before immobilization, with irregularly shaped agglomerates after immobilization. The immobilization procedure was efficient, with 88% preservation of enzyme activity. Biocatalytic systems showed enhanced tolerance to pH and temperature fluctuations, making laccase immobilization a viable approach for wastewater bioremediation [82]. The mechanisms of enzyme catalysis and noncompetitive inhibition are depicted in **Figure 3**.



The inhibitor binds to the enzyme or enzyme-**Catalysis** complex at an **allosteric site**. Catalysis is prevented due to a change in the enzyme conformation.

Figure 3. Mechanism of enzyme catalysis and non-competitive inhibition. The figure illustrates the normal catalytic pathway of an enzyme and the mechanism by which non-competitive inhibitors disrupt enzymatic activity

Recent developments also include the co-immobilization of multi-enzymatic systems on a single platform to perform cascade reactions in a one-pot system, which significantly enhances process intensification and atom economy. Enzyme–MOF composites have proven useful in promoting enantioselective reactions and biotransformations under aqueous or solvent-free conditions [83]. Advancements in genetic engineering and protein modification have allowed the tailoring of enzyme structures to improve substrate scope and operational tolerance. These innovations illustrate how biocatalysts, when engineered and immobilized effectively, can serve as powerful heterogeneous systems for sustainable chemical synthesis [84]. The biocatalysts and enzyme-immobilized systems used for sustainable chemical processes are listed in **Table 2**.

4. Applications in Sustainable Chemical Processes

4.1. Biomass conversion

Recent research has highlighted heterogeneous catalysis as a transformative tool for biomass valorization, especially for converting lignocellulosic feedstocks into biofuels and platform chemicals. Zeolite-based catalysts such as HZSM-5 have demonstrated high selectivity in catalytic fast pyrolysis (CFP) for upgrading bio-oils. For example, researchers have improved the aromatic yield by modifying HZSM-5 with metals such as Ga or Zn, thereby enhancing the deoxygenation pathways [95]. Bifunctional catalysts combining metal (*e.g.,* Pt and Ru) and acid sites on supports such as alumina or carbon have shown efficiency in the hydrodeoxygenation (HDO) of lignin-derived phenolics to alkanes under mild conditions. Solid acid catalysts, particularly sulfonated carbons derived from biomass, have been employed for the conversion of cellulose to 5-hydroxymethylfurfural (HMF), a crucial platform molecule [96]. Metal oxide-based catalysts such as ZrO_2 and TiO_2 have facilitated the conversion of hemicellulose-derived xylose to furfural in over 80% yield in aqueous media. The development of hierarchical porous

Table 2. Biocatalysts and enzyme-immobilized systems for sustainable chemical processes

Biocatalyst / Enzyme	Support material / Immobilization matrix	Immobilization technique	Catalysed reaction	Industrial/Model application	Advantages	Ref.
Lipase (Candida antarctica)	Magnetic nanoparticles (Fe_3O_4) coated with silica	Covalent bonding via glutaraldehyde	Transesterification	Biodiesel production	High reusability, easy magnetic recovery	[85]
Laccase	Chitosan-functionalized graphene oxide	Adsorption and cross-linking	Oxidation of phenols	Wastewater treatment	High surface area, eco-friendly carrier	[86]
Glucose Oxidase	Mesoporous silica (SBA-15)	Physical adsorption	Glucose to gluconic acid	Biosensors, biofuel cells	High enzyme loading and stability	[87]
Tyrosinase	Alginate–Ca^{2+} beads	Entrapment	Phenol degradation	Industrial effluent treatment	Biocompatible, cost-effective	[88]
Lipase (Thermomyces lanuginosus)	Metal-organic framework (ZIF-8)	Encapsulation	Ester hydrolysis	Organic synthesis	Thermal stability, protection from denaturation	[89]
Amylase	Polyacrylamide hydrogel	Entrapment	Starch hydrolysis	Food processing	Sustained catalytic activity	[90]
Cellulase	Biochar from agricultural waste	Adsorption	Cellulose to glucose	Bioethanol production	Sustainable carrier, low-cost	[91]
Peroxidase (Horseradish)	CNTs	Covalent immobilization	Dye decolorization	Textile wastewater treatment	High electron transfer efficiency	[92]
Alcohol Dehydrogenase	Polyvinyl alcohol cryogel	Entrapment + cross-linking	Enantioselective reduction	Chiral alcohol production	Easy scale-up and reusability	[93]
Urease	Zeolite-Y	Ion exchange	Urea hydrolysis	Fertilizer and biosensing	Stability under wide pH range	[94]

structures and magnetic catalysts has also improved their separation and recyclability, which is crucial for industrial feasibility. Notably, recent advances in the one-pot catalytic conversion of glucose to lactic acid using Sn-beta zeolites have highlighted the potential of integrated biorefinery models [97].

4.2. CO_2 utilization and conversion

Heterogeneous catalysis has emerged as a promising route for CO_2 valorization, which converts greenhouse gases into fuels and chemicals. Metal catalysts supported on oxides, such as $Cu/ZnO/Al_2O_3$ and Ni/Al_2O_3, have been widely explored for the hydrogenation of CO_2 to methane and methanol [98]. Recent studies have reported that doping Cu-based catalysts with Ga or Zr can enhance the methanol selectivity and suppress the formation of CO and hydrocarbons by stabilizing formate intermediates. MOF-derived catalysts and SACs are particularly noteworthy due to their highly dispersed and tunable active sites. For instance, Zn-doped Co-based MOFs pyrolyzed under an N_2 atmosphere have shown over 90% selectivity toward methanol in gas-phase hydrogenation [99]. Another avenue is electrochemical CO_2 reduction, in which catalysts such as Ag, Au, and Cu supported on carbon demonstrate efficient reduction to CO, formic acid, or hydrocarbons. For photocatalytic CO_2 conversion, TiO_2-based semiconductors modified with noble metals (*e.g.,* Au-TiO_2) and heterojunction systems (*e.g.,* TiO_2/g-C_3N_4) have exhibited enhanced charge separation and CO evolution under solar irradiation. Additionally, bifunctional catalysts capable of CO_2 capture and in situ conversion, such as amine-functionalized porous materials integrated with metal nanoparticles, are gaining traction [100].

4.3. Water splitting and hydrogen production

Hydrogen production through water splitting remains a key focus area for clean energy systems, and heterogeneous catalysts are central to improving the efficiency and lowering the costs. Transition metal-based catalysts, such as Ni, Co, and Mo, often supported on carbon or metal oxides, have shown significant progress in the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER). NiFe layered double hydroxides (LDHs) are currently among the most effective non-noble metal OER catalysts for alkaline media, with overpotentials as low as 270 mV at 10 mA/cm^2. In the HER, MoS_2 and CoP have gained attention because of their edge-active sites, with recent nanostructuring strategies enhancing their surface areas and conductivities [101]. Notably, doping MoS_2 with nitrogen or integrating it with conductive supports such as reduced graphene oxide (rGO) has led to marked improvements in the HER kinetics. Photoelectrocatalytic water splitting has also benefited from heterojunction photocatalysts, including $BiVO_4/WO_3$ and $ZnIn_2S_4$/g-C_3N_4 systems, which exhibit enhanced visible-light absorption and charge separation [102]. In solar-to-hydrogen (STH) conversion, perovskite-based photocatalysts and quantum dots have emerged as novel systems with the potential to exceed 10% STH efficiency. Industrially scalable water-splitting systems have also been proposed that incorporate Ni-based catalysts into membrane electrode assemblies for alkaline electrolyzers [103].

4.4. Green synthesis of fine chemicals

Heterogeneous catalysis plays a vital role in green chemical synthesis by reducing the use of hazardous reagents, simplifying reaction pathways, and enabling recyclability. Supported metal nanoparticles such as Pd/C and Au/TiO_2 are widely used for selective hydrogenation and oxidation reactions under mild conditions [104]. Au-Pd bimetallic catalysts enable the aerobic oxidation of alcohols to aldehydes in water without the use of external oxidants. Heterogenized organocatalysts such as proline-anchored silica offer sustainable alternatives for asymmetric aldol and Michael reactions. In cross-coupling reactions, heterogeneous palladium catalysts immobilized on MOFs or magnetic supports have demonstrated a high TOF and reusability in Suzuki-Miyaura and Heck reactions, reducing metal leaching [105]. Solid acid and base catalysts (*e.g.,* sulfonated mesoporous silica and MgO) have been used in one-pot cascade reactions to synthesize heterocycles and active pharmaceutical ingredients (APIs) with high atom economy. Zeolite catalysts, particularly Beta and ZSM-5, facilitate Friedel–Crafts alkylation and acylation without toxic Lewis acids. Recent developments in photocatalysis and electrocatalysis have also enabled the green functionalization of aromatic compounds under ambient conditions using visible light or low voltage [106].

4.5. Waste-to-value processes

The conversion of industrial, agricultural, and plastic waste into valuable chemicals and fuels via heterogeneous catalysis has been increasingly explored as a sustainable waste management strategy. The catalytic pyrolysis and gasification of plastic waste using metal-doped zeolites (*e.g.,* Ni/ZSM-5) have been shown to yield high-value hydrocarbons like BTX (benzene, toluene, and xylene) [107]. Upgrading plastic-derived oils through hydrocracking over Pt or Pd catalysts on mesoporous silica improves fuel quality and reduces olefin content. In electronic waste recycling, supported acid catalysts and redox-active metal oxides have been applied for the selective leaching and recovery of rare earth elements (REEs) [108]. Agricultural residues are transformed into biochar and syngas via catalytic fast pyrolysis using transition metal carbides and phosphides. Moreover, spent coffee grounds and fruit peels have been used as renewable precursors for synthesizing carbon-based catalysts for electrochemical applications [109]. One notable study demonstrated the use of eggshell-derived CaO catalysts for transesterification of waste cooking oil, achieving biodiesel yields above 95%. Furthermore, CO_2-rich flue gases were directly converted into cyclic carbonates using heterogeneous catalysts based on Zn or Ce under solvent-free and low-pressure conditions, showcasing both carbon capture and valorization. These findings emphasize the potential of the circular economy principles powered by catalytic technologies [110].

5. Challenges Future Trends and Perspectives

Heterogeneous catalysis remains a cornerstone of sustainable chemical processes. However, several scientific and technological challenges continue to impede the widespread implementation and optimization of these systems. Recent research has revealed critical bottlenecks in catalyst stability, selectivity, and scalability, demanding innovative approaches and the integration of emerging technologies to address these issues. Simultaneously, future trends in catalyst design and deployment are heavily influenced by advances in artificial intelligence (AI), renewable energy integration, and evolving policy frameworks aimed at sustainability. This section discusses these challenges and future directions, based on cutting-edge research findings from the last decade.

5.1. AI and machine learning in catalyst discovery

One of the primary challenges in heterogeneous catalysis is deactivation. Research has shown that poisoning by impurities, sintering of active metal sites, coking (carbon deposition), and structural degradation under reaction conditions substantially reduce catalyst lifetime and efficiency. For example, studies on metal-based catalysts, such as Ni, Pt, and Pd, indicate that sintering under high-temperature conditions leads to particle agglomeration, reducing the active surface area and catalytic activity. Advances in *situ* characterization techniques, including environmental TEM and XAS, have been pivotal for identifying these degradation pathways in real time. Another major challenge is achieving high selectivity towards the desired products, particularly in complex reactions, such as biomass valorization or CO_2 conversion. The multifunctional nature of biomass feedstock often results in multiple competing reaction pathways, necessitating catalysts that can precisely control their activity and selectivity. Recent research has emphasized the development of bifunctional and multifunctional catalysts that combine acid-base sites with metal centres to selectively steer reaction pathways. However, controlling these cooperative effects at the nanoscale remains difficult because of the complexity of catalyst synthesis and the dynamic nature of the catalytic surfaces under reaction conditions. Scalability and reactor integration pose other significant hurdles. Although many novel catalysts demonstrate excellent performance at the laboratory scale, translating these findings to industrial reactors often reveals challenges in mass and heat transfer, catalyst stability under prolonged use, and cost-effectiveness. For example, catalysts based on metal–organic frameworks (MOFs) show exceptional activity and selectivity in batch reactors, but suffer from stability issues when scaled to continuous flow systems due to structural fragility and moisture sensitivity. Sustainability and reliance on critical and rare metals such as platinum group metals remain problematic due to their high cost and limited availability. Recent efforts have focused on developing earth-abundant metal catalysts such as Fe, Co, and Ni. However, these often show lower activity and stability, necessitating sophisticated design strategies such as alloying, nanoengineering, and support modification. The energy input requirements for catalytic processes, especially for thermocatalytic conversions, such as biomass reforming or CO_2 hydrogenation, can be prohibitively high. This necessitates catalysts that operate effectively under mild conditions or harness alternative energy sources, such as light or electricity, to drive reactions, highlighting the need for advances in photocatalysis and electrocatalysis.

5.2. Integration with renewable energy

A growing body of research has emphasized coupling heterogeneous catalysis with renewable energy sources to reduce the carbon footprint and enhance process sustainability. Renewable electricity from solar, wind, or hydropower is increasingly being used to drive catalytic reactions, either directly via electrocatalysis or indirectly through photocatalysis. Electrocatalytic systems for the reduction of CO_2 into value-added chemicals and fuels are prime examples. Recent studies have shown that novel catalysts such as copper-based nanostructures, doped carbon materials, and metal oxides achieve higher Faradaic efficiencies and product selectivities when powered by renewable electricity. The integration of heterogeneous electrocatalysts with photovoltaic cells or wind turbines forms hybrid systems that can operate off-grid, thereby improving the feasibility of sustainable chemical production.

Photocatalysis research has advanced significantly, with catalysts designed to harness visible light for driving reactions, such as water splitting and organic transformations. Semiconductor-based catalysts, such as TiO_2 doped with nonmetals or coupled with plasmonic metals, have demonstrated improved light absorption and charge separation, enabling efficient solar-to-chemical energy conversion. The development of heterojunction and Z-scheme photocatalysts further enhances the charge carrier dynamics, boosting the reaction rates under solar irradiation. Beyond direct renewable energy coupling, recent progress has included thermochemical processes powered by renewable heat sources, such as solar thermal energy. Concentrated solar reactors have been designed to achieve the high temperatures required for catalytic biomass pyrolysis or CO_2 reforming without fossil fuel combustion, highlighting a pathway for fossil-free process intensification. Although integration with renewables shows great promise, challenges such as catalyst stability under intermittent energy supply, efficient energy storage, and cost-effective scale-up persist. Research efforts have focused on designing robust catalyst systems capable of tolerating fluctuating power inputs and coupling with energy storage devices to provide steady-state operation.

5.3. Policy and sustainability considerations

The advancement of heterogeneous catalysis in sustainable chemical processes is also deeply influenced by evolving policy frameworks and sustainability goals globally. Researchers recognize that beyond scientific innovation, translating catalytic technologies into real-world applications requires alignment with environmental regulations, economic incentives, and societal priorities. Life cycle assessment (LCA) and techno-economic analysis (TEA) have become integral research tools for evaluating the environmental impacts and commercial viability of catalytic processes.

Studies assessing catalyst synthesis routes, raw material sourcing, energy consumption, and end-of-life disposal have provided holistic sustainability metrics, guiding the development of greener catalysts. For example, replacing toxic solvents with greener alternatives during catalyst preparation reduces hazardous waste and aligns with the regulatory requirements. Governments and international organizations are increasingly promoting circular economy principles, advocating for catalysts that enable efficient recycling and reuse of resources. Research highlights efforts to design catalysts from abundant, non-toxic materials with high recyclability, and to develop processes that minimize waste generation. Policy incentives such as carbon pricing and subsidies for renewable technologies also drive research toward catalytic processes that reduce greenhouse gas emissions. Several projects have demonstrated the catalytic conversion of CO_2 into fuels and chemicals as part of carbon capture and utilization (CCU) strategies, supported by policy frameworks that encourage decarbonization. Importantly, the integration of sustainability criteria into catalyst development necessitates interdisciplinary collaboration among chemists, engineers, economists, and policymakers. Future research should focus on developing standardized sustainability assessment frameworks and enhancing stakeholder engagement to facilitate technology adoption.

6. Conclusion

Recent progress in heterogeneous catalysis has led to significant advancements in catalyst design, functionality, and applications toward sustainable chemical processes. The development of novel metal-based catalysts, zeolites, MOFs, and carbon-based materials has enhanced the catalytic efficiency and selectivity through tailored surface properties and nano-engineering approaches, such as single-atom and bimetallic catalysts. These innovations have enabled the effective conversion of biomass, CO_2 utilization, and green synthesis pathways, contributing to more environmentally friendly chemical production. Furthermore, advancements in photocatalysis and electrocatalysis have opened new avenues for renewable energy integration, particularly for hydrogen production and waste valorization. Despite these achievements, challenges related to catalyst deactivation, scalability, and economic viability remain critical, guiding ongoing research toward improved regeneration techniques and industrial application strategies. Emerging trends, including the use of artificial intelligence for catalyst discovery and the integration of catalysis with renewable energy systems, highlight promising directions for sustainable chemistry.

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Conflict of Interest

Authors have declared that there is no conflict of interest exists.

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