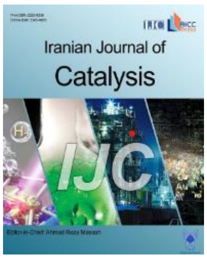

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Review Article

Environmental Hazards of Catalysts: A Critical Review on their Impact and Sustainable Alternatives

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Abstract

Catalysts are essential in industrial, chemical, and environmental applications, enabling efficient, selective, and sustainable chemical transformations. While conventional and nanostructured catalysts have significantly improved reaction rates and product yields, their use raises environmental concerns due to the presence of heavy metals and engineered nanoparticles, which can persist in soil and water, bio accumulate, and disrupt ecosystems. Improper disposal, limited recycling infrastructure, and insufficient regulatory frameworks exacerbate these risks. This review critically examines the environmental hazards of catalysts across their life cycle, including leaching, bioaccumulation, Eco toxicity, and airborne particulate release. It also highlights emerging low-impact strategies, such as TiO_2-alternative photo catalysts, biocatalysts, and earth-abundant metal-based systems, reporting representative performance metrics like reaction efficiency, selectivity, and recyclability. By integrating life cycle assessment, eco-design principles, and circular economy approaches, these strategies demonstrate potential for reducing environmental footprint while maintaining high catalytic performance. The article provides insights for researchers, industry, and policymakers aiming to develop sustainable, low-risk catalytic technologies, bridging catalysis science with environmental management and regulatory frameworks.

Keywords: Bioaccumulation; Catalysts; Environmental impact; Heavy metals; Sustainable catalysis

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1. Introduction

Catalysis plays a fundamental role in modern chemical industry, environmental protection, and energy conversion technologies by enabling chemical reactions to proceed with enhanced efficiency, selectivity, and reduced energy consumption. Advances in heterogeneous catalysis, nanostructured catalysts, and photocatalytic systems have significantly expanded their applications in addressing global challenges such as water pollution remediation, sustainable fuel production, and renewable energy conversion [1–3].

One of the most important applications of catalysts is in water and wastewater treatment, where they are employed to remove persistent organic pollutants, dyes, pharmaceuticals, and emerging contaminants. Semiconductor-based photo catalysts, particularly TiO_2-based materials, have been widely investigated due to their strong oxidative power, chemical stability, and low cost. Under light irradiation, these materials generate reactive species capable of mineralizing complex organic molecules into less harmful products [4]. To overcome limitations such as rapid charge recombination and limited visible-light absorption, recent research has focused on catalyst engineering strategies including defect creation, heterojunction construction, and surface modification. In particular, oxygen-vacancy-rich photo catalysts have attracted significant attention, as anion vacancies enhance charge separation, extend light absorption, and increase catalytic activity. Recent comprehensive studies on oxygen-vacancy-mediated photo catalysis and photo electrochemical water splitting demonstrate substantial improvements in pollutant degradation and hydrogen generation efficiencies, especially in TiO_{2-x}–MoS_2-based hetero structures [5–7].

Catalysts are equally indispensable in fuel production and energy-related processes, especially in hydrogen generation, water splitting, and fuel upgrading. With the increasing demand for low-carbon energy systems, electro catalysts and photo catalysts have become central to sustainable hydrogen production and CO_2 conversion technologies. Recent studies highlight the critical role of catalyst composition, surface chemistry, defect engineering, and Nano structuring in enhancing hydrogen evolution reaction (HER), oxygen evolution reaction (OER), and fuel-processing efficiencies [8–10]. Transition-metal-based catalysts and nanostructured materials offer promising alternatives to noble metals due to their high activity and potential scalability.

Despite these technological advancements, the environmental and health implications associated with widespread catalyst use have not been systematically addressed. Many industrial catalysts contain toxic or potentially hazardous metals such as platinum (Pt), palladium (Pd), nickel (Ni), chromium (Cr), and vanadium (V). During catalyst synthesis, operation, regeneration, or disposal, these metals may be released into the environment through leaching, abrasion, or particulate emissions, leading to contamination of soil, water, and air [11, 12]. The increasing use of nanocatalysts further intensifies these concerns due to their high surface reactivity, enhanced environmental mobility, and potential interactions with biological systems.

In soil and aquatic environments, catalyst-derived metals and nanoparticles undergo complex physicochemical processes, including adsorption onto mineral surfaces, complexation with organic matter, redox transformations, and aggregation. These processes control their mobility, bioavailability, and persistence, influencing ecological and toxicological outcomes. Heavy metals and metal-based nanoparticles can accumulate in soils, be taken up by plants and microorganisms, and enter food chains, posing long-term risks to ecosystem health [13–15]. Moreover, nano-sized catalysts such as TiO_2, ZnO, and CeO_2 can generate reactive oxygen species (ROS), inducing oxidative stress, cellular damage, and adverse biological responses in exposed organisms [16].

Managing the end-of-life of catalysts is a critical but often underestimated challenge. Improper disposal, limited recycling infrastructure, and energy-intensive regeneration processes can worsen environmental pollution. While closed-loop recycling and metal recovery systems exist in some industrial sectors, their global adoption is uneven. Regulatory frameworks frequently lag behind technological advances, especially for nanomaterials and emerging catalyst classes [17].

While extensive research has focused on improving catalytic performance and efficiency, a comprehensive and integrated evaluation of the environmental hazards associated with conventional and nanostructured catalysts alongside sustainable alternatives remains limited. There is a clear need to bridge catalysis science with environmental chemistry, toxicology, waste management, and policy perspectives.

Therefore, this review critically examines the environmental hazards posed by conventional catalysts, Nano catalysts, and emerging catalytic materials throughout their life cycle. The review focuses on contamination pathways, Eco toxicological and human health risks, disposal and recycling challenges, and existing regulatory frameworks.

In parallel, advances in green and sustainable catalysis including earth-abundant metals, biocatalysts, renewable materials, circular economy strategies, and AI-assisted catalyst design are discussed as pathways toward environmentally responsible and sustainable catalytic technologies.

2. Types and uses of catalysts

Catalysts are broadly categorized based on their physical state (Table 1), composition, and mode of action. In addition to physicochemical characteristics, Table 1 also summarizes qualitative differences in lifecycle energy consumption, reflecting the relative energy demands associated with catalyst synthesis, operation, separation, and end-of-life management. The two principal classifications are homogeneous and heterogeneous catalysts. Homogeneous catalysts exist in the same phase (usually liquid) as the reactants, allowing uniform interaction at the molecular level. They are widely used in fine chemical synthesis and organic transformations due to their high selectivity and activity [18].

However, their separation and recovery from reaction mixtures often pose environmental challenges. In contrast, heterogeneous catalysts operate in a different phase—typically solid catalysts in liquid or gas-phase reactions. They are extensively employed in petroleum refining, automotive exhaust treatment, and chemical manufacturing. Their ease of separation, reusability, and stability under harsh conditions make them ideal for industrial applications [19].

A significant subset of heterogeneous catalysts includes metal-based catalysts, often composed of precious or transition metals such as platinum (Pt), palladium (Pd), rhodium (Rh), copper (Cu), or nickel (Ni) supported on materials like alumina, silica, or zeolites.

Table 1. Comparative overview of different catalyst types based on key physicochemical and environmental attributes

property	homogeneous catalysts	heterogeneous catalysts	Nano catalysts	biocatalysts
phase	liquid phase	solid phase	solid (Nano-sized particles)	aqueous/biological systems
operating temperature	low to moderate	moderate to high	typically, low to moderate	mild (often room temperature)
ease of separation	difficult (requires extraction)	moderate (e.g., filtration)	easy (can be magnetically or physically separated)	easy (especially if immobilized)
toxicity potential	often high (metal complexes)	generally lower than homogeneous	medium to high (depends on nanoparticle type)	very low (biodegradable and specific)
chemical stability	limited (degrades under harsh conditions)	high (stable under thermal/chemical stress)	high (due to nanoscale structure)	moderate (sensitive to pH, temp)
lifecycle energy consumption	moderate (complex synthesis & separation)	moderate to high (high-temperature calcination)	high (nanofabrication & surface control)	low (biological production, mild conditions)

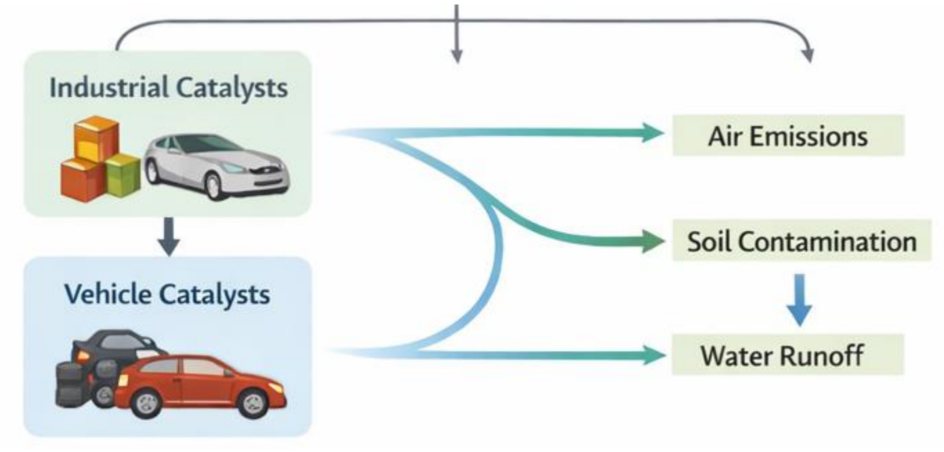

Figure 1. Environmental pathways of catalysts

These catalysts are effective in hydrogenation, dehydrogenation, oxidation, and reforming reactions but can pose toxicity risks due to metal leaching and dust formation [20]. Nano catalysts, a more recent development, refer to catalysts composed of nanoparticles (1–100 nm), often designed to increase surface area and active site availability. They exhibit superior catalytic efficiency and selectivity in various reactions, including environmental remediation (e.g., photo catalysis using TiO_2 or ZnO). However, their environmental behavior, fate, and potential toxicity are not yet fully understood and are subject to ongoing investigation [21, 22]. Biocatalysts, including enzymes and whole-cell catalysts, offer an environmentally benign alternative. Their specificity, biodegradability, and ability to function under mild conditions make them promising for green chemistry applications. However, their industrial use is limited by factors such as sensitivity to temperature, pH, and product inhibition [23]. Each class of catalysts, while beneficial in improving process efficiency and sustainability, carries distinct environmental and safety considerations (Fig. 1) that must be addressed through careful selection, monitoring, and lifecycle management.

3. Environmental hazards of catalysts

The primary routes through which spent or leached catalysts exert environmental harm were shown in Fig. 2. Available studies suggest that emissions of platinum group elements (PGEs) from automotive catalysts occur via both particulate dispersion into the atmosphere and leaching into surrounding soils and sediments. Atmospheric measurements in urban environments indicate detectable concentrations of PGE-bearing particles in air (for example, Pt, Pd, and Rh in PM10) linked to vehicle traffic and catalyst wear [24].

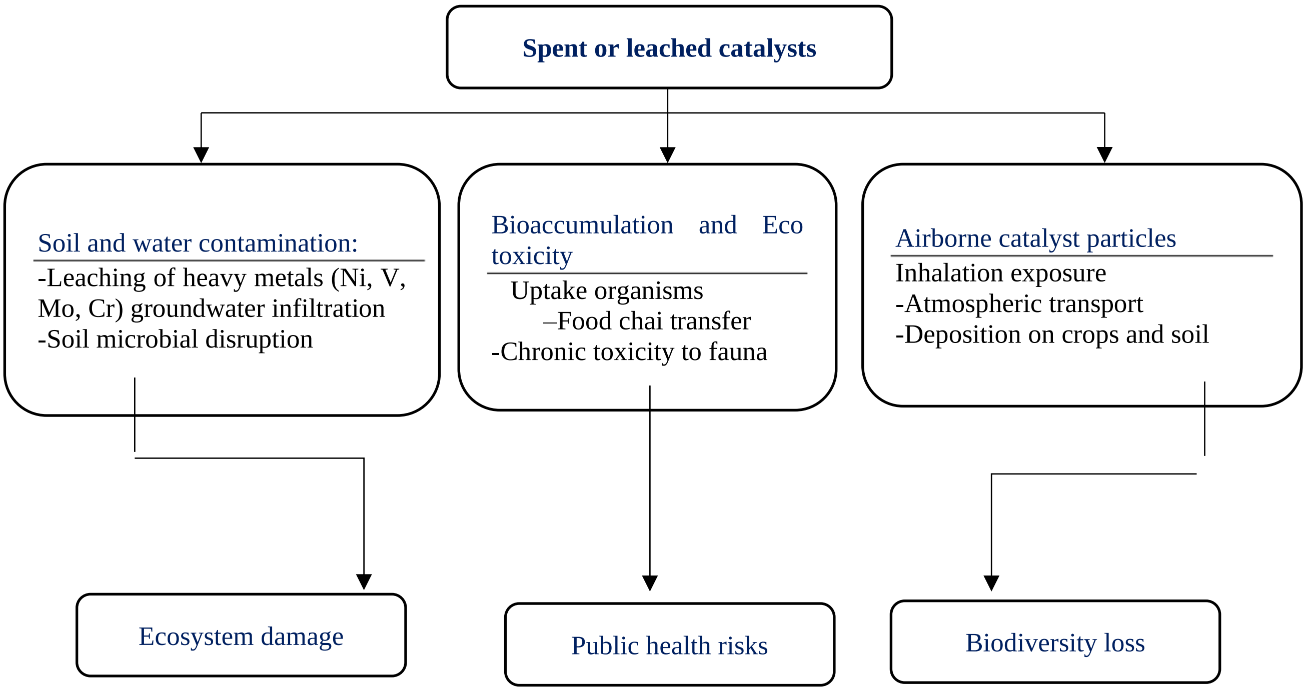

Figure 2. Major environmental pathways and impacts of catalyst pollution

Table 2. Overview of environmental hazards associated with different catalyst categories

catalyst type	primary environmental risk	affected medium	severity	persistence
homogeneous	leaching of toxic metal complexes	water, soil	medium–high	medium
heterogeneous	metal oxide dust, used catalyst dumping	soil, air	medium	high
Nano catalysts	nanoparticle mobility and Eco toxicity	water, biota	high	very high (bioactive)
biocatalysts	deactivation products (biodegradable)	minimal	low	low (biodegradable)
organic / organometallic (homogeneous)	ligand toxicity, poor recyclability, metal leaching	water	medium	medium

In parallel, roadside soils and sediments exhibit accumulation of Pt and Pd derived from catalyst abrasion and runoff, illustrating the importance of soil and water pathways for long-term environmental exposure [25]. While industry-wide quantitative partitioning of these pathways is limited, the Fig. 2 has been updated to reflect the dual significance of both airborne dispersion and leaching for environmental contamination.

These include soil and water contamination via heavy metal leaching, bioaccumulation and Eco toxicity through uptake by flora and fauna, and airborne catalyst particles causing respiratory exposure and surface deposition. The resulting impacts encompass ecosystem degradation, risks to human health, and biodiversity loss. Table 2 summarizes the major environmental risks posed by various types of catalysts. Homogeneous catalysts typically present high leaching potential, while heterogeneous catalysts can contribute to dust emissions and long-term environmental persistence. Nano catalysts raise concerns due to their mobility, reactivity, and poorly understood toxicological profiles. In contrast, biocatalysts offer low toxicity and are generally biodegradable. In addition to heterogeneous, Nano-, and biocatalysts, organic and organometallic catalysts constitute an important class widely applied in fine chemical synthesis, pharmaceutical manufacturing, and homogeneous catalytic processes. Organ catalysts are often regarded as environmentally benign due to their metal-free nature; however, their large-scale application can still pose environmental concerns related to poor recyclability, high catalyst loading, and persistence of organic residues in aqueous waste streams. Certain organ catalysts and reaction promoters may exhibit aquatic toxicity or resistance to biodegradation, particularly when

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fluorinated, highly functionalized, or used in combination with hazardous solvents [26, 27].

Organometallic catalysts, such as Pd-, Ru-, Rh-, and Ir-based complexes bearing phosphine, amine, or N-heterocyclic carbene ligands, present additional environmental challenges. Although often used at low concentrations, their homogeneous nature leads to high leaching potential and difficult separation from reaction media, increasing the likelihood of release into wastewater. Toxicity may arise not only from the metal center but also from ligand degradation products, which can exhibit cytotoxicity and limited biodegradability [28]. Moreover, recovery and recycling of homogeneous organometallic catalysts typically require energy-intensive separation or immobilization strategies, emphasizing the need to include these catalyst sub-types in comprehensive environmental risk assessments.

3.1. Soil and water contamination

The improper disposal of spent catalysts or accidental release during industrial processes can lead to the leaching of heavy metals and other toxic substances into soils and aquatic systems. For example, catalysts containing vanadium, nickel, molybdenum, or chromium are widely used in hydrocracking and desulfurization units in oil refineries. These metals can persist in the environment, migrate through soil profiles, and contaminate groundwater resources [29, 12].

Beyond the disposal of spent catalysts, catalyst deactivation and regeneration processes themselves can pose significant environmental burdens (Fig. 3). Thermal regeneration methods such as calcination or oxidative treatment often require high energy input and may generate secondary emissions, including metal oxides, fine particulates, and gaseous pollutants, which can subsequently contaminate soil and water if not properly controlled. Chemical regeneration using acidic or alkaline solutions may produce metal-rich effluents and mobilize residual toxic metals, increasing their environmental bioavailability and Eco toxicological risk. Several studies have emphasized that hydrometallurgical and regeneration treatments of spent catalysts can result in acidic wastewater streams and solid residues requiring careful management. Therefore, sustainable catalyst management should account not only for end-of-life disposal but also for the environmental footprint and emission pathways associated with regeneration and reactivation processes [12, 30].

Studies have shown that even small amounts of catalyst residues, such as Pt or Pd, from automotive catalytic converters can accumulate in road dust and runoff, ultimately entering streams and rivers [31]. Recent experimental studies indicate that platinum group metals can be significantly leached from spent automotive catalysts under typical extraction conditions. For example, optimized ozone and hydrochloric acid leaching achieved approximately 80–85 % extraction of Pt and Pd from simulated spent auto-catalyst material at 90 °C and 5.0 M HCl, respectively [32].

In hydrometallurgical treatments with calcination and acid leaching, Pt leachability reached around 84 % and Pd up to ~85 % under favourable catalytic converter pretreatment conditions [33]. Furthermore, novel deep eutectic solvent systems have reported leaching efficiencies of up to ~90 % for Pt and ~95 % for Pd from spent automotive catalysts under mild conditions [34]. These metals often bind to sediments and can remain bioavailable for long periods, creating long-term ecological risk.

In addition, Nano catalysts such as TiO_2, CeO_2, and ZnO nanoparticles used in environmental and energy applications are known to be mobile in aqueous systems. Their small size allows them to penetrate soil pores and interact with microbial communities, potentially altering soil fertility and water quality [35].

Chemical behavior and mechanistic interactions of catalysts in soil environments: When released into terrestrial environments, spent catalysts and catalyst-derived particles undergo a range of physicochemical transformations that govern their mobility, bioavailability, and ecological impact.

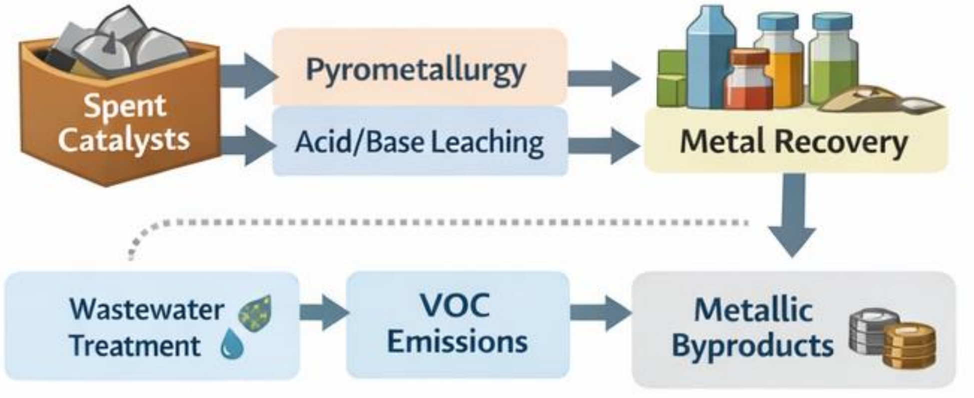

Figure 3. Catalyst recycling and regeneration

From a chemical perspective, the behavior of catalyst materials in soil is controlled by parameters such as pH, redox potential (E_h), ionic strength, and the presence of natural organic matter, including humic and fulvic acids [13, 36]. Transition-metal-based catalysts commonly used in industrial processes—such as Ni, V, Mo, Co, Cr, Pt, and Pd can undergo partial dissolution through proton-promoted or ligand-assisted leaching mechanisms. Under acidic soil conditions, metal oxides and sulfides may release soluble ionic species (e.g., Ni^{2+}, Co^{2+}, MoO_4^{2-}, VO_4^{3-}), increasing their mobility and potential for groundwater contamination. In contrast, alkaline conditions often favor precipitation or surface immobilization through adsorption onto clay minerals and iron or manganese oxides [14]. Redox reactions play a critical role in determining the toxicity of catalyst-derived metals in soil. For example, chromium-containing catalysts may undergo oxidation from relatively less toxic Cr (III) to highly toxic and carcinogenic Cr (VI) species in the presence of manganese oxides, while vanadium can cycle between V(IV) and V(V) states depending on soil redox conditions. These transformations directly influence metal speciation, persistence, and biological uptake [37]. Soil organic matter strongly affects catalyst behavior through complexation and surface interactions. Functional groups such as carboxylates and phenolics in humic substances can chelate metal ions, forming stable organometallic complexes that either enhance mobility or reduce acute toxicity by lowering free metal ion concentrations.

Additionally, adsorption of catalyst particles onto organic matter may alter their surface reactivity and catalytic activity in situ [16, 38]. For nanostructured catalysts, surface-driven mechanisms dominate their environmental interactions. High surface area, crystal defects, and exposed active sites can catalyze redox reactions that generate reactive oxygen species (ROS), including hydroxyl radicals ($^{\bullet}OH$), superoxide anions ($^{\bullet}O_2^-$), and hydrogen peroxide (H_2O_2). These ROS can induce oxidative stress in soil microorganisms, disrupt enzymatic activity, and impair key biogeochemical cycles such as nitrogen fixation and organic matter decomposition [39].

In comparison with conventional dissolved metal species, Nano catalysts such as CeO_2 exhibit distinct mechanisms of toxicity and bioaccumulation. While soluble metal ions (e.g., Ni^{2+}, Cr(VI), Pt^{2+}, and Pd^{2+}) primarily induce oxidative stress through ionic redox reactions and Fenton-like processes, CeO_2 nanoparticles generate reactive oxygen species mainly via surface-mediated redox cycling between Ce^{3+} and Ce^{4+} states [19, 40]. This particle-driven mechanism enables sustained ROS production even at low environmental concentrations (Fig. 4).

Table 3. Comparative toxicity characteristics of Nano catalysts and conventional metal catalysts

catalyst type	ROS generation mechanism	bioaccumulation	dominant toxicity
CeO_2 nanoparticles	surface redox cycling	high	chronic oxidative stress
TiO_2 nanoparticles	photo-induced ROS	moderate	growth inhibition
Ni^{2+}, Cr (VI) ions	ionic redox/Fenton	moderate	acute toxicity
Pt/Pd ions	protein binding + ROS	low–moderate	enzymatic inhibition

Figure 4. ROS generation by Nano catalysts

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Moreover, Nano catalysts tend to bio accumulate through particle uptake and tissue retention, leading to chronic toxicity, particularly in primary producers (algae), invertebrates, and soil microorganisms [15]. In contrast, conventional metal ions are generally more mobile and are associated with acute toxicity in higher trophic organisms but may exhibit lower long-term bioaccumulation [41]. These differences highlight the importance of distinguishing nanoparticle-induced chronic oxidative stress from the acute toxicity pathways of traditional metal contaminants when assessing long-term ecological risks (Table 3).

3.2. Bioaccumulation and Eco toxicity

Catalyst components, particularly metal-based and Nano-scale species, can be taken up by plants and animals, leading to bioaccumulation in food webs. Platinum group elements (PGEs), for instance, have been detected in aquatic organisms, indicating trophic transfer and long-term exposure potential [42]. Chronic exposure to low levels of these metals can cause oxidative stress, DNA damage, and enzyme inhibition in aquatic fauna. Nano catalysts further complicate Eco toxicological profiles due to their high surface reactivity and potential to produce reactive oxygen species (ROS). Studies on zebrafish and Daphnia magna have shown that exposure to CeO_2 and ZnO nanoparticles causes developmental abnormalities, oxidative damage, and mortality even at sub-lethal concentrations [43, 44]. Moreover, soil microbes which play a vital role in nutrient cycling can be inhibited by catalyst residues, resulting in impaired soil health and reduced plant productivity [45].

In contrast to bulk metal particles, Nano catalysts such as CeO_2, TiO_2, and ZnO exhibit enhanced bioavailability due to their small size and high surface reactivity. Cerium oxide nanoparticles, for example, can alternate between Ce^{3+} and Ce^{4+} oxidation states, enabling redox cycling that promotes ROS generation at biological interfaces. This redox activity can disrupt cellular antioxidant defences, leading to lipid peroxidation, DNA strand breaks, and mitochondrial dysfunction in soil-dwelling organisms. Compared with conventional metal species, Nano catalysts often display species-specific toxicity, as their uptake pathways vary across bacteria, fungi, plants, and invertebrates. These differences highlight the need for mechanistic, chemistry-based risk assessment frameworks rather than generalized toxicity assumptions.

3.3. Airborne catalyst particles

In industrial and vehicular settings, catalysts can be released into the atmosphere as fine particulate matter. Emissions from diesel particulate filters (DPFs), refinery stack discharges, and manufacturing facilities can contain particles with embedded metals like V, Ni, or Pt. These particles can travel long distances, settle on crops, and be inhaled by humans and animals [46].

Airborne catalyst particles, especially in the Nano-size range, pose significant respiratory hazards. Their small diameter allows deep penetration into the lungs, potentially leading to inflammation, fibrosis, or even carcinogenic effects upon chronic exposure [47]. The atmospheric deposition of such particles also contributes to the secondary contamination of soil and water systems. Although filtration and scrubber technologies exist to reduce such emissions, their global implementation remains inconsistent, especially in developing countries.

4. Human health risks

The use of metal-based and nanostructured catalysts in industrial processes and consumer products has raised growing concerns about human exposure to hazardous substances. Several exposure pathways exist, including inhalation of airborne catalyst particles, dermal contact in occupational settings, and ingestion via contaminated water or food chains [3, 42].

Platinum group elements (PGEs) such as Pt, Pd, and Rh are widely used in automotive catalytic converters and often found in urban air and road dust. These metals can enter the human body through inhalation, potentially leading to allergic reactions, oxidative stress, and inflammatory responses [48]. Occupational exposure to these elements in metal refineries and catalyst handling facilities is associated with chronic respiratory issues and dermatitis [49].

Nickel, chromium, and vanadium, commonly used in hydro processing and reforming catalysts, are classified as potential carcinogens. Long-term exposure has been linked to increased risk of lung and nasal cancers, particularly among refinery workers or those handling spent catalysts [50]. Leaching of these metals into the drinking water sources also presents a risk of renal dysfunction, neurotoxicity, and developmental abnormalities in sensitive populations [29, 51].

Nano catalysts, due to their ultrafine size and high reactivity, may penetrate biological membranes, cross the blood-brain barrier, and accumulate in vital organs. Several in vitro and in vivo studies have shown that exposure to nano-TiO_2, ZnO, or CeO_2 can lead to oxidative DNA damage, mitochondrial dysfunction, and pro-inflammatory cytokine release [47, 52]. The chronic health effects of long-term low-dose exposure to Nano catalysts remain largely unknown, but early findings raise considerable toxicological concerns.

Importantly, most toxicological assessments of catalysts have focused on acute effects, while data on chronic and multigenerational impacts are still limited. This knowledge gap poses challenges for regulatory frameworks, which often fail to fully account for nanoparticle behavior, synergistic toxicity, and cumulative exposure in real-world scenarios.

5. Disposal and recycling challenges

The end-of-life management of industrial catalysts presents a major environmental and regulatory challenge. Due to their composition often involving toxic heavy metals or rare earth elements spent catalysts must be treated as hazardous waste under many national and international regulations [53]. However, inadequate disposal practices, particularly in developing countries, often result in the uncontrolled dumping of spent catalysts into landfills or natural environments, posing serious threats to ecosystems and public health [12].

Landfilling is still one of the most common disposal methods for deactivated catalysts, despite its well-known drawbacks. Over time, rainwater and acidic conditions may lead to metal leaching into soil and groundwater, contaminating local water supplies and agricultural land [29]. The long-term environmental burden of buried catalysts is exacerbated by their low biodegradability and high chemical stability.

Incineration, though capable of reducing waste volume, is often unsuitable for metal-based catalysts, as it may release toxic metal oxides or volatile organic compounds into the atmosphere. Moreover, the high energy demand, and emission of secondary pollutants limit its sustainability [54].

Recycling and regeneration of spent catalysts offer a more sustainable alternative. Hydrometallurgical and pyro metallurgical processes are commonly used to recover valuable metals such as Pt, Pd, Ni, and Mo. However, these processes are often energy-intensive, chemically aggressive, and associated with secondary waste generation, including acidic effluents and solid residues [55]. In many cases, the economic viability of recycling is low, especially when the metal content is diluted or the catalyst is heavily deactivated.

Recent efforts have focused on developing eco-friendly regeneration methods, such as bioleaching using microorganisms or low-temperature selective leaching agents. These approaches aim to minimize the use of strong acids and reduce environmental footprints, but scalability and efficiency remain technical bottlenecks [56]. Additionally, the lack of global standards for catalyst recycling contributes to fragmented practices and weak enforcement. While some multinational companies have established take-back systems and closed-loop recycling, these models are not yet widely adopted across the chemical and petrochemical industries. Strengthening the regulatory framework, incentivizing recovery, and promoting circular economy principles are essential to reducing the environmental impact of spent catalysts.

6. Policy frameworks and global challenges

Regulatory frameworks play a central role in mitigating the environmental hazards posed by catalysts throughout their life cycle, from production to disposal. In the European Union, several policy instruments regulate the use and management of catalysts. The REACH regulation (Registration, Evaluation, Authorization, and Restriction of Chemicals) requires producers and importers to demonstrate the safety of catalyst substances before they can be marketed, ensuring that hazardous metals such as Cr, Ni, or V undergo rigorous risk assessments [57]. Complementary directives such as the Waste Framework Directive (2008/98/EC) and the Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EU) impose obligations for recovery and recycling of catalyst-containing components, promoting a circular approach within industrial sectors [58, 59]. Recent industry guidance further clarifies how spent catalysts should be classified and managed under these regulations [60].

In the United States, the Environmental Protection Agency (EPA) regulates spent catalysts under the Resource Conservation and Recovery Act (RCRA). Certain refinery catalysts, including hydrotreating and hydro refining catalysts, are specifically listed as hazardous wastes (K171 and K172), which require strict storage, transport, and treatment procedures [53]. Studies highlight that these controls not only aim to reduce environmental risks but also encourage recovery of valuable metals such as Ni, Mo, and Co, aligning regulatory control with circular economy principles [61].

Other high-income economies, including Japan and South Korea, have adopted extended producer responsibility (EPR) schemes, compelling catalyst manufacturers and users to take responsibility for post-consumer recovery and recycling. These policies incentivize closed-loop models, ensuring that precious metals like Pt, Pd, and Rh are returned to production streams rather than lost to landfills [62].

However, in many developing countries, regulatory enforcement and waste infrastructure remain weak. Spent catalysts are often stockpiled, openly dumped, or shipped across borders under poorly monitored trade. These practices create risks of soil and water contamination from leaching heavy metals, as well as occupational hazards for informal recyclers. Transboundary movement of hazardous catalysts often disguised as recyclable materials remains a significant challenge despite the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal [63]. Weak governance and limited technical capacity in low- and middle-income nations allow illegal shipments and unsafe recovery practices to persist.

Addressing these disparities requires a multi-layered policy approach. At the global level, harmonized standards and enforcement mechanisms under the Basel Convention are essential to prevent illegal dumping. Capacity building in waste management through technology transfer, training, and financial support is critical for countries lacking infrastructure. At the regional level, integrating circular economy principles into legislation can ensure that catalyst life cycles are managed sustainably. Finally, at the industry level, stronger public–private partnerships are needed to scale up safe recovery networks, trace material flows, and integrate life cycle assessment (LCA) into catalyst design.

Ultimately, the effectiveness of policy frameworks depends not only on the strength of regulations but also on monitoring, enforcement, and international cooperation. Bridging the regulatory gap between developed and developing economies will be decisive in reducing the environmental hazards of catalysts and in ensuring equitable progress toward global sustainability goals.

7. Catalysts in the circular economy

The management of industrial catalysts is increasingly being guided by circular economy principles, aiming to reduce waste, maximize resource efficiency, and mitigate environmental impacts. Catalysts, particularly those containing platinum-group metals (PGMs), are not only valuable economically but also environmentally, making their recovery, reuse, and safe disposal critical for sustainable chemical manufacturing. This section reviews catalyst management within a circular economy framework, focusing on industrial recycling practices, policy and regulatory drivers, and the challenges and opportunities for global adoption.

7.1. Industrial closed-loop recycling

Several industrial leaders have implemented closed-loop recycling systems for spent catalysts. Umicore (Belgium) operates an integrated recovery network for PGMs from automotive, chemical, and refinery catalysts, converting them into reusable metal salts and alloys. Johnson Matthey (UK) has developed technologies for reclaiming PGMs from spent catalysts and reintroducing them into production cycles, reducing the demand for primary mining and preventing hazardous waste accumulation [64]. These systems demonstrate that catalyst recycling can be economically viable while simultaneously decreasing the ecological footprint of catalyst-intensive industries. Economic assessments indicate that closed-loop recycling of platinum group metals (PGMs) from spent automotive and industrial catalysts can recover 80–90 % of Pt and Pd, significantly reducing dependence on primary mining. Case studies from refineries show that recovered Pt can offset material costs by up to 25–30 %, with payback periods of less than three years under current market prices [65, 66]. These findings highlight that industrial catalyst recycling is not only environmentally beneficial but also economically feasible, supporting wider adoption of circular economy practices.

Despite these successful examples, the implementation of green catalysis and closed-loop recycling has not been uniformly effective across all regions. In several developing and emerging economies, the absence of dedicated catalyst recycling infrastructure, high initial capital investment requirements, and limited regulatory enforcement have resulted in continued landfilling or informal disposal of spent catalysts. Reports from refinery and chemical sectors in parts of Asia, Africa, and Latin America indicate that although spent catalysts contain valuable PGMs, recovery is often economically unattractive without centralized collection systems and stable metal markets. In such cases, mitigation efforts fall short due to fragmented supply chains, lack of technical expertise, and insufficient policy incentives. These contrasting case studies highlight that successful adoption of green catalysis depends not only on technological readiness but also on economic viability, regulatory frameworks, and institutional capacity.

Although closed-loop recycling offers economic and environmental benefits, alternative waste management methods such as incineration are sometimes applied for spent catalysts that cannot be recycled. Incineration can reduce waste volume but may release toxic metal oxides (e.g., PtO_2, PdO, TiO_2, ZnO) and volatile organic compounds (VOCs) originating from residual organic ligands or supports. These emissions contribute to air pollution, respiratory hazards, and secondary environmental contamination. Therefore, proper recycling or stabilization methods are essential to minimize environmental and health risks [11].

7.2. Policy incentives and regulatory drivers

Government policies play a crucial role in promoting the transition from a linear to a circular economy in catalyst management. Achieving a greener, circular model requires system-wide redesigning of rules and incentives across the value chain, from product design to recycling and end-of-life management [67]. Integrating green chemistry principles into catalyst design and recovery helps minimize hazardous waste, improve recyclability, and foster the use of sustainable alternatives. Regulatory frameworks and incentives also encourage industries to invest in recycling infrastructure and adopt environmentally responsible practices.

7.3. Challenges, opportunities, and global perspectives

Despite successes in industrial recycling and policy support, global adoption remains uneven. Advanced

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economies in Europe, North America, and Japan have the infrastructure, corporate networks, and regulatory enforcement to implement circular catalyst systems effectively. In contrast, many developing countries face challenges including lack of recycling infrastructure, limited technical expertise, and weaker regulatory enforcement.

To further illustrate how differing recycling infrastructures affect catalyst waste management, several case studies from around the world are presented. In Europe, stringent regulations and well-established recycling networks have enabled high recovery rates of spent catalysts. For example, in Belgium and the Netherlands dedicated facilities recover platinum group metals (PGMs) from automotive and industrial catalysts at rates exceeding 70 %, minimizing landfill disposal and environmental risk [68]. In contrast, in India, which generates an estimated 120,000 tons of spent catalysts annually, only about 25–30 % of this waste enters formal recycling channels due to limited infrastructure, regulatory enforcement, and collection challenges, with the remainder often processed informally or landfilled, posing significant environmental hazards [68].

In addition to technical and economic challenges, the social and ethical dimensions of catalyst production, use, and disposal are critical. Mining of platinum group metals and other critical raw materials can disproportionately affect local communities, leading to environmental degradation, occupational hazards, and socio-economic disparities [69]. Improper disposal of spent catalysts in areas with limited regulatory oversight may exacerbate environmental justice concerns, as vulnerable populations often reside near informal waste processing or landfill sites. Addressing these social implications requires incorporating community engagement, equitable waste management strategies, and international best practices alongside technical and economic considerations.

Similarly, in parts of Middle East and Africa, despite substantial catalyst use in petrochemical sectors, local recycling capacity remains underdeveloped and less than 15 % of spent catalysts are recycled regionally, leading to export for processing or accumulation in landfills [68]. These examples underscore the importance of robust recycling frameworks and policy support to mitigate the environmental impacts associated with improper disposal of spent catalysts.

Integrating catalyst recycling into a broader circular economy framework offers multiple benefits. Recovered metals reduce dependence on primary mining and secure supply chains for critical materials. Environmental protection is enhanced by minimizing soil and water contamination from improperly disposed catalysts. Economically, reclaimed metals can offset production costs and create new industrial markets for recycling services. These considerations highlight the critical need for coordinated efforts combining industrial practice, policy measures, and international collaboration (Table 4).

8. Green and sustainable catalysis: Principles and outlook

As environmental concerns surrounding conventional catalysts continue to rise, the concept of green catalysis has emerged as a promising pathway to minimize ecological and human health impacts. Green catalysis (Fig. 5) integrates the principles of green chemistry with the efficiency of catalysis to design systems that are less toxic, more selective, and environmentally benign throughout their life cycle [71].

One key direction in this field is the development of non-toxic and earth-abundant metal catalysts, such as Fe, Cu, Mn, and Zn, to replace hazardous or scarce metals like Pt, Pd, and Cr. These metals not only reduce environmental and supply-chain risks, but also offer cost advantages. Recent studies have demonstrated effective catalytic performance of iron- and copper-based systems in oxidation and C–C coupling reactions under mild conditions [72, 73], highlighting their potential for sustainable industrial applications.

Biocatalysts enzymes and whole-cell systems—are another sustainable alternative. They exhibit high substrate specificity, operate under mild pH and temperature conditions, and are biodegradable. Advances in protein engineering and immobilization technologies have further improved their stability, recyclability, and operational efficiency, making them increasingly attractive for pharmaceutical synthesis, fine chemical production, and biomass conversion [23].

Heterogeneous photo catalysis using materials such as TiO_2 and ZnO under visible light is widely explored for environmental remediation. While some of these materials can pose risks in nanoparticle form, ongoing efforts to immobilize them on inert supports or encapsulate them in biodegradable matrices help mitigate potential release and enhance reuse [74].

Another promising trend is the use of catalysts derived from natural and renewable sources, including clay minerals, bio char, and lignocellulosic waste. These materials provide high surface area, tunable properties, and significantly lower environmental footprints. When combined with green solvents (e.g., water, supercritical CO_2) and renewable energy sources (e.g., solar or electrochemical activation), these systems can effectively align catalytic processes with circular economy principles [75].

Importantly, life cycle assessment (LCA) and eco-design frameworks are increasingly employed to evaluate the full environmental impact of catalysts from production to disposal.

Table 4. Examples of industrial catalyst recycling practices

company	type of catalyst/application	metals recovered	recycling method/process
Umicore	automotive, industrial/refinery, spent industrial catalysts	Pt, Pd, Rh (platinum group metals)	combination of pyro metallurgical processes and multi-stage chemical separation [70]
Johnson Matthey	industrial and automotive catalysts	Pt, Pd, and other PGMS	closed-loop recycling combined with pyro metallurgy and chemical leaching/multi-stage chemical separation [64]

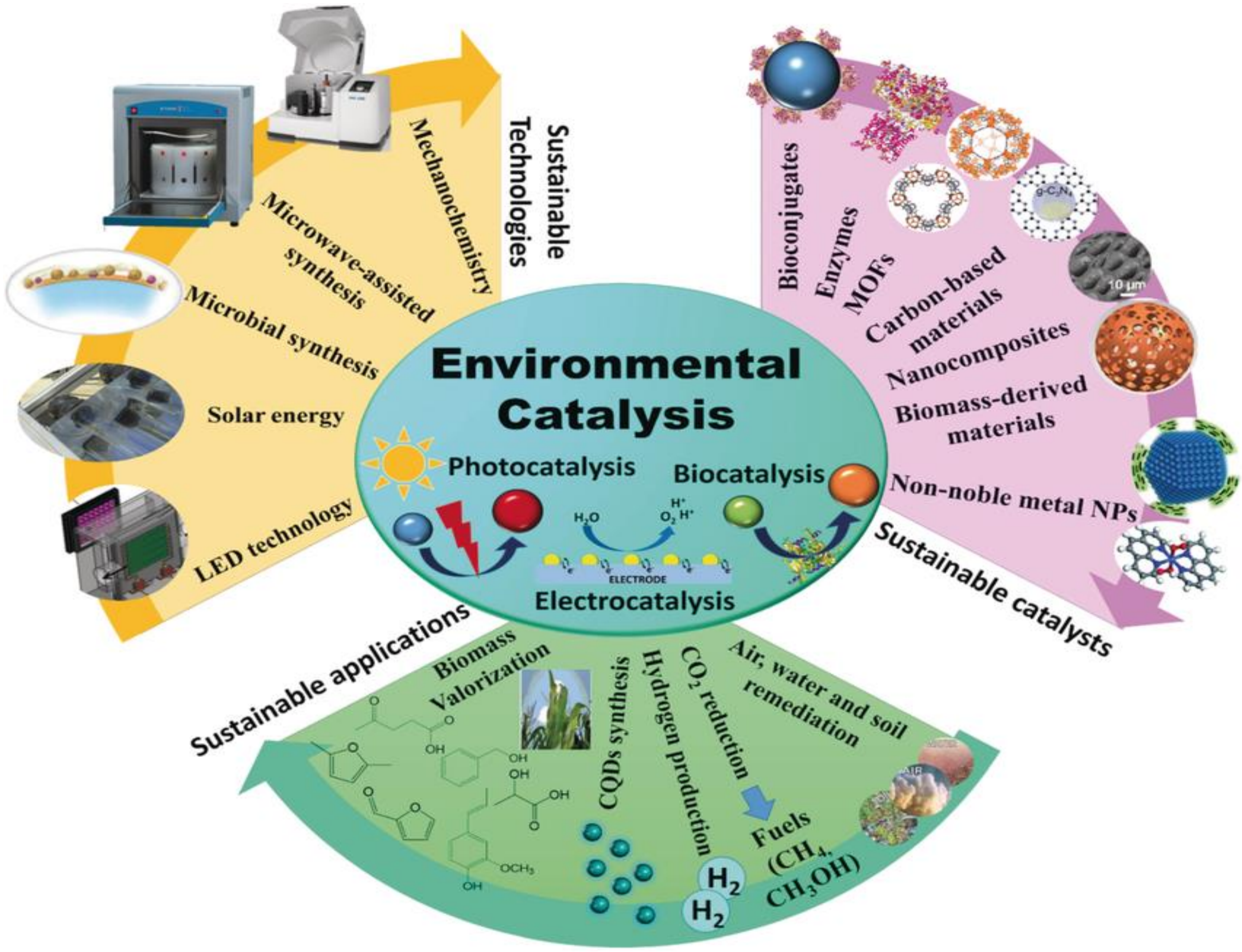

Figure 5. Schematic representation of sustainable catalytic materials [3]

These tools guide researchers and industries in selecting materials and methods that achieve performance targets while minimizing ecological and human health risks [17]. While challenges remain in terms of scalability, durability, and performance under industrial conditions, the growing regulatory and public pressure is accelerating innovation toward green catalysis. Integrating fundamental research with policy support and industrial implementation is essential for realizing sustainable catalytic systems and advancing a circular economy.

8.1. Emerging sustainable materials

Emerging materials play a key role in advancing green catalysis by enhancing efficiency, reducing environmental impact, and promoting sustainability.

Metal–Organic Frameworks (MOFs): MOFs are composed of metal ions coordinated to organic ligands, forming porous structures with tunable surface areas that enable efficient and recyclable catalytic processes [76, 77]. MOFs have been applied in CO_2 capture, selective oxidation, and photocatalytic reactions, with recent work focused on enhancing thermal and chemical stability for industrial applications.

Biopolymer-Based Supports: Supports based on chitosan, cellulose, or other biopolymers offer biodegradable and low-toxicity options for immobilizing active metals [78]. These materials have been demonstrated to be effective in organic synthesis, environmental remediation (e.g., adsorption of heavy metals from wastewater), and green catalytic processes, aligning with green chemistry principles.

Earth-Abundant Metal Catalysts: Non-toxic metals such as Fe, Cu, Mn, and Zn are emerging as alternatives to Pt, Pd, and Cr, reducing environmental and supply risks while offering cost benefits [64, 11]. These metals have shown effective performance in oxidation reactions, C–C coupling, and hydrogenation under mild conditions, providing practical routes for sustainable catalysis.

Biocatalysts: Enzymes and whole-cell systems are highly selective, biodegradable, and capable of operating under mild conditions. Advances in immobilization and protein engineering have improved their stability and recyclability, making them suitable for pharmaceutical synthesis, biomass conversion, and industrial-scale biotransformation [23].

Recent studies have provided quantitative examples of bio-based catalysts in green chemical processes. Lipase immobilized on magnetic cellulose nanoparticles and encapsulated in copper-based metal–organic frameworks showed biodiesel yields of ~78% under optimized conditions, retaining ~59% activity after seven reuse cycles and ~70% after 30 days of storage [79]. Magnetic bio char-based lipase catalysts achieved ~95.7% biodiesel conversion and maintained ~85.7% activity after ten reuse cycles, demonstrating excellent operational stability [80]. Additionally, cellulose/chitin composite aerogel beads used for lipase immobilization retained >90% of initial activity even after five recycling runs, indicating high selectivity and robustness [81]. These examples confirm that bio-based catalysts can deliver high efficiency, selectivity, and stability, supporting their application in sustainable industrial processes.

Heterogeneous Photo catalysis: Heterogeneous photo catalysis using nanomaterials such as TiO_2, ZnO, and CeO_2 under visible light is widely explored for environmental remediation. Nano catalysts, due to their ultrafine size and high surface reactivity, can penetrate biological membranes and accumulate in vital organs such as the liver, kidneys, and brain. Several in vitro and in vivo studies have shown that exposure to these nanoparticles can generate reactive oxygen species (ROS), leading to oxidative DNA damage, mitochondrial dysfunction, lipid peroxidation, and activation of pro-inflammatory cytokines such as TNF-α and IL-6 [78, 16].

Chronic exposure may result in histopathological changes in organs and disturbances in metabolic and immune pathways. Efforts to immobilize nanoparticles on inert supports or encapsulate them in biodegradable matrices help reduce environmental and biological risks [4]. Table 5 summarizes photo catalyst properties, toxicity, and applications. Recent studies highlight that engineered Nano catalysts significantly affect soil microbial communities through alterations in bioavailability, diversity, and functional activity. Metal-based nanoparticles, including TiO_2, ZnO, and CeO_2, can reduce microbial biomass and diversity, disrupt community structure, and impair key enzymatic activities involved in nutrient cycling [16, 82, 83]. These effects are mediated by nanoparticle bioavailability and surface-mediated ROS generation, indicating that long-term ecological risk assessment must account for nanoparticle interactions with soil microbes.

Natural and Renewable Catalysts: Natural and renewable catalysts derived from clay minerals, bio char, and lignocellulose wastes often exhibit high specific surface area, tunable porosity and surface chemistry, and a lower life-cycle environmental footprint compared with many conventional supports. These catalysts have been successfully applied in wastewater treatment, biofuel production, and biomass valorization. When coupled with green solvents (e.g., water, bio-derived solvents, supercritical CO_2) and renewable-energy-driven activation (solar/electrochemical), these materials can help align catalytic processes with circular-economy goals [84].

Life Cycle Assessment (LCA) and Eco-Design: LCA and eco-design frameworks guide the evaluation of catalysts' environmental impacts from production to disposal, helping select materials and methods that balance performance with safety. Integrating LCA considerations into the development of emerging catalytic materials ensures both efficiency and sustainability are achieved across the catalyst life cycle (Fig. 6) [85].

8.2. Industrial implementation and challenges

While promising, emerging green catalysts face several challenges in industrial implementation. Scaling up laboratory-scale catalytic systems often encounters difficulties related to catalyst stability, mass transfer limitations, and reaction reproducibility. Durability under harsh industrial conditions, such as high temperature, pressure, or corrosive media, remains a critical concern. Bridging research with policy support and industrial adoption is crucial.

Table 5. Comparison of traditional and green catalysts [23]

property	traditional catalysts	green catalysts
toxicity	high	low
selectivity	moderate	high
environmental impact	significant	minimal
cost	high	competitive

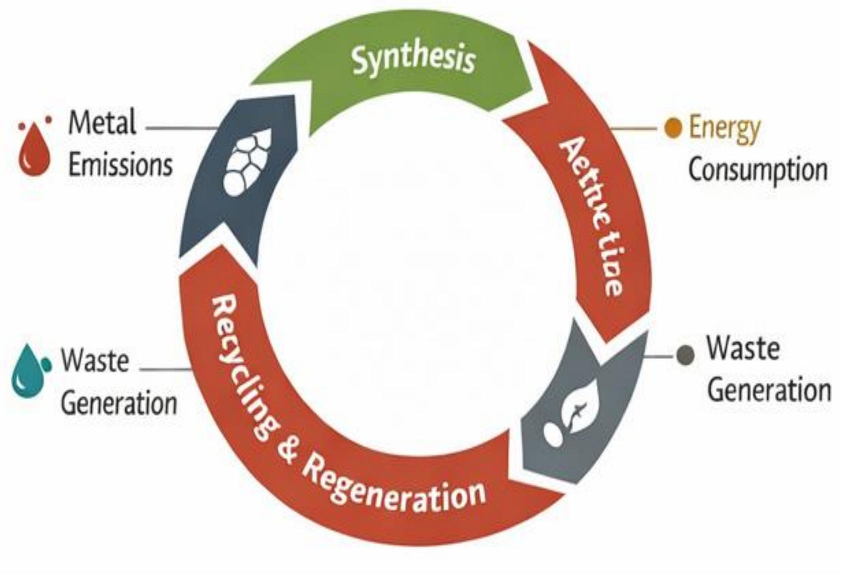

Figure 6. Catalyst life cycle and environmental impact

Pilot-scale studies and techno-economic assessments can help determine the feasibility of implementing green catalysts in chemical manufacturing, pharmaceutical production, and wastewater treatment. Moreover, integration with existing production infrastructure and adaptation to process-specific conditions are key to successful industrial deployment. Collaborative efforts between academia, industry, and regulators can accelerate the transition to sustainable catalytic systems, while training and capacity building in developing countries can help address gaps in expertise and infrastructure.

8.3. Catalysis for renewable energy transitions

Catalysts play a central role in advancing renewable and low-carbon energy technologies. Earth-abundant metal catalysts such as Fe, Ni, and Co are actively studied for water electrolysis, providing cost-effective hydrogen production pathways without reliance on platinum [86]. Laboratory and pilot-scale studies have demonstrated high activity and stability under alkaline and neutral pH conditions, supporting hydrogen production for fuel cells and energy storage. Photo catalysts based on TiO_2, g-C_3N_4, and doped heterojunctions are investigated under visible light for solar-driven CO_2 reduction, pollutant degradation, and wastewater treatment [87]. Recent advancements include surface modification, heterojunction engineering, and immobilization on renewable supports, improving efficiency and reusability.

In energy storage applications, electro catalysts derived from metal–organic frameworks (MOFs) have shown promise for oxygen reduction reaction (ORR) and oxygen evolution reaction (OER) in fuel cells and metal–air batteries [88]. These catalysts offer tunable porosity, high surface area, and structural stability, contributing to enhanced performance and long-term durability. Integrating renewable-energy-driven catalytic processes with industrial and municipal systems can accelerate the transition toward a circular and low-carbon economy, aligning catalysis research with environmental sustainability goals.

9. AI and computational catalysis for sustainability

Recent advances in artificial intelligence (AI), machine learning (ML), and computational modeling are transforming the field of catalysis, offering powerful tools for sustainable catalyst discovery and optimization. These approaches reduce experimental trial-and-error, accelerate the screening of catalyst candidates, and provide predictive insights into performance, toxicity, and stability.

9.1. High-throughput virtual screening and big data approaches

Traditional catalyst development often relies on laborious synthesis and testing, which is time-consuming and resource-intensive. In contrast, high-throughput computational screening combined with machine learning (ML) algorithms enables the rapid evaluation of a large number of candidate materials in silicon. For example, Ulissi et al. (2017) [89] demonstrated that ML models combined with density functional theory (DFT) can predict surface reaction energies and scaling relations efficiently, significantly accelerating the identification of promising catalytic materials. Similarly, ML-based approaches, such as those described by Jørgensen et al. (2018) [90] in the context of polymer solar cells, illustrate how neural networks can learn complex structure–property relationships to screen large chemical spaces quickly. These advances highlight the potential of ML and computational methods to reduce experimental workload and guide the sustainable design of catalysts.

9.2. AI-guided discovery of sustainable alternatives

One of the major challenges in sustainable catalysis is the reliance on scarce and potentially toxic metals, such as platinum (Pt), palladium (Pd), and chromium (Cr). Data-driven and machine learning (ML) approaches are increasingly applied to identify earth-abundant and less hazardous alternatives. According to Zhu et al. (2023) [91], ML frameworks can systematically screen metals, alloys, and oxides to predict catalytic activity and stability, enabling the design of high-performance catalysts using abundant elements like iron (Fe), cobalt (Co), and nickel (Ni). These computational strategies allow researchers to optimize active sites, support structures, and reaction pathways while minimizing environmental and economic costs. By guiding the selection of safer and more sustainable catalysts, such data-driven approaches represent a significant step toward greener energy technologies and reduced dependence on critical raw materials. In addition to screening and design, machine learning (ML) models have been increasingly applied to predict catalyst degradation and lifetime, aiding the optimization of catalyst use and maintenance strategies. Recent research highlights that ML algorithms including supervised learning, ensemble methods (e.g., random forests), and deep learning frameworks can integrate operational, structural, and reaction condition data to model catalytic activity loss over time and forecast deactivation trends. For example, ML models that combine reactor sensor data with historical performance metrics have been shown to predict catalyst deactivation profiles and identify key predictors of activity decline in industrial processes, outperforming traditional empirical models in flexibility and predictive power [92, 93]. These predictive capabilities support proactive regeneration scheduling, maintenance planning, and catalyst design for improved durability, thereby enhancing process sustainability.

9.3. Life cycle assessment (LCA) integration

Another important frontier in sustainable catalysis is the integration of computational design with environmental impact assessment. As highlighted by Artz et al. (2018) [17], life cycle assessment (LCA) can be combined with catalyst development to evaluate not only catalytic performance but also carbon footprint, energy consumption, and potential environmental impacts of proposed catalytic processes. This approach allows researchers to identify catalysts and reaction pathways that maximize efficiency while minimizing ecological and resource-related burdens. By integrating LCA considerations early in the design phase, it becomes possible to prioritize candidates that meet both performance and sustainability objectives, bridging the gap between computational chemistry, green chemistry principles, and environmental science. Such strategies are particularly relevant for processes involving CO_2 conversion, where selecting optimal catalysts can significantly reduce the environmental footprint relative to conventional petrochemical routes.

9.4. Predicting toxicity and environmental behavior

AI is also being applied to forecast the Eco toxicological properties of Nano catalysts. Qi and Wang (2024), [94] developed machine learning (ML) models to predict the aquatic ecological risk of engineered nanoparticles (ENPs) at the community level. They collected toxicity threshold data for twelve metal- and carbon-based nanoparticles, expressed as hazardous concentrations for 5% of species (HC5), and trained multiple supervised ML models including Adaboost, artificial neural networks, decision trees, random forest, and support vector machines to perform both classification and regression predictions. The models achieved high accuracy, with classification accuracy ranging from 71.4% to 100% and regression determination coefficients (R^2) between 0.702, and 0.999. Furthermore, the inclusion of Nano structural descriptors such as metal oxide sublimation enthalpy, zeta potential, and specific surface area enhanced both the predictive performance and mechanistic interpretability of the models. These AI-driven tools can therefore be used to screen Nano catalysts with potentially high ecological risks, guide safer design strategies, and inform the development of environmental regulations for engineered nanoparticles.

9.5. Challenges and opportunities

Despite these advances, several challenges remain in applying AI to catalyst discovery. Machine learning models require large and high-quality datasets, which are not always available for specialized catalysts. Additionally, many models still lack interpretability, making it difficult to extract mechanistic insights. To address these limitations, researchers are increasingly exploring hybrid computational approaches, where traditional methods such as density functional theory (DFT) and molecular dynamics are combined with advanced algorithms, including emerging quantum computing techniques [95]. Hariharan and colleagues [95] highlight that quantum computing algorithms can model complex interactions in heterogeneous catalysis, including strongly correlated regions and spin-dependent phenomena, which are challenging for classical methods alone. Embedding strategies allow quantum algorithms to handle the most demanding parts of the system, while conventional quantum chemistry algorithms manage the remainder. Such hybrid approaches, integrating AI, DFT, molecular dynamics, and quantum computing, promise to enhance predictive accuracy and mechanistic understanding, paving the way toward autonomous laboratories where robotic synthesis, automated characterization, and AI-driven optimization operate in closed loops, drastically accelerating sustainable catalyst discovery.

10. Conclusion

Catalysts are indispensable to modern industry and environmental technologies, offering essential benefits in terms of reaction efficiency, energy savings, and product selectivity. However, this review has shown that the environmental hazards associated with conventional and nanostructured catalysts cannot be overlooked. The improper handling, disposal, and lack of effective recycling strategies for spent catalysts lead to the release of toxic metals and nanoparticles into the environment, with adverse consequences for soil, water, air, and human health. Furthermore, adopting regulatory frameworks such as the EU-REACH system can standardize the classification, handling, and recycling of spent catalysts, ensuring environmental safety and international compliance. Such policies would encourage circular economy strategies, promote industrial recycling, and mitigate the risks associated with hazardous catalyst disposal.

Key concerns include the leaching of heavy metals, bioaccumulation in food chains, Eco toxicity to aquatic and terrestrial organisms, and respiratory and carcinogenic risks in humans. The environmental behavior of engineered Nano catalysts, in particular, remains poorly understood and demands further investigation using real-world exposure models.

To address these challenges, the development of green and sustainable catalysts is a critical priority. Transitioning to earth-abundant, non-toxic metals, biocatalysts, and renewable materials offers a pathway toward safer and more sustainable catalytic technologies. Additionally, life cycle assessment (LCA), eco-design tools, and circular economy principles should be systematically applied to guide catalyst development and end-of-life management. Integrating AI-driven design, circular economy principles, and renewable energy applications provides a holistic pathway to sustainable catalysis in the 21st century. Looking forward, the establishment of international regulatory frameworks, similar to EU-REACH or OECD guidelines, could standardize catalyst waste management, ensure safer handling of emerging Nano catalysts, and promote cross-border collaboration. Anticipated regulatory updates and global harmonization efforts are expected to incentivize sustainable catalyst design, accelerate adoption of green technologies, and mitigate environmental and health risks associated with novel catalytic materials.

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