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Magnetic Catalysts for Environmental Remediation and Sustainable Chemical Processing: A Multidisciplinary Review

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Abstract
Magnetic catalysts have emerged as multifunctional materials that combine catalytic activity with rapid separation under an external magnetic field. This combination addresses a persistent limitation of conventional homogeneous and nanoscale heterogeneous catalysts: difficult recovery from liquid reaction media. Magnetite, maghemite, spinel ferrites, magnetic biochars, core–shell nanoparticles, magnetic metal–organic frameworks, and noble-metal-decorated magnetic supports have been investigated for wastewater treatment, advanced oxidation, photocatalysis, heavy-metal transformation, organic synthesis, biomass conversion, hydrogenation, carbon–carbon coupling, and biodiesel production. Their magnetic cores permit catalyst recovery without energy-intensive centrifugation or filtration, while surface coatings and catalytic phases provide adsorption, oxidation, reduction, acid–base, or metal-mediated reaction sites. This multidisciplinary review examines the design, preparation, characterization, reaction mechanisms, environmental applications, and sustainable-processing potential of magnetic catalysts. Particular attention is given to heterogeneous Fenton and photo-Fenton reactions, peroxide and persulfate activation, photocatalytic pollutant degradation, reduction of nitroaromatic contaminants, recyclable palladium and nickel catalysts, and magnetic solid acids for renewable-fuel production. The effects of particle size, surface area, oxidation state, porosity, magnetic saturation, active-phase dispersion, and interfacial electron transfer are discussed. Although laboratory studies frequently demonstrate high catalytic activity and repeated magnetic recovery, practical deployment remains restricted by nanoparticle aggregation, metal leaching, surface passivation, loss of magnetization, complex water matrices, mass-transfer limitations, and insufficient life-cycle evaluation. Future research should prioritize non-toxic compositions, waste-derived supports, continuous-flow magnetic separation, standardized recyclability testing, process intensification, techno-economic analysis, and complete environmental-risk assessment. Magnetic catalysts can contribute significantly to circular chemical manufacturing when catalytic performance, recoverability, material safety, and resource efficiency are optimized simultaneously.

Introduction

Industrial development has generated complex streams of wastewater, contaminated soil, chemical waste, spent solvents, and greenhouse-gas emissions. Textile dyes, pharmaceuticals, pesticides, phenolic compounds, chlorinated chemicals, heavy metals, and persistent organic contaminants are difficult to remove through conventional biological treatment. At the same time, the chemical industry requires catalysts that minimize energy consumption, hazardous reagents, solvent use, and material waste. Catalysis is central to sustainable chemistry because an effective catalyst can reduce reaction temperature, shorten processing time, improve selectivity, and decrease the formation of unwanted by-products. However, conventional homogeneous catalysts dissolve in the reaction mixture and may require neutralization, extraction, precipitation, or chromatography before the product can be isolated. These recovery steps consume energy and solvents and may produce additional waste. Heterogeneous catalysts simplify separation because they exist in a different phase from the reactants and products. Nevertheless, finely divided heterogeneous nanoparticles can remain suspended in a liquid and may be difficult to recover through ordinary filtration. Very small particles can pass through filters, block membranes, or require high-speed centrifugation. Failure to recover them also creates economic loss and the possibility of environmental nanoparticle release. Magnetic catalysts are designed to overcome this separation problem. They contain a magnetically responsive component, generally Fe_3O_4, γ-Fe_2O_3, $CoFe_2O_4$, $NiFe_2O_4$, $ZnFe_2O_4$, or another ferrite. After reaction, an external magnet or magnetic separator attracts the catalyst, allowing the treated liquid or product phase to be removed. The catalyst can then be washed and reused. Magnetic materials may function as the active catalyst, as a catalyst support, or as a separable core beneath another catalytic phase. Magnetite can participate directly in Fenton-like reactions because it contains both Fe^{2+} and Fe^{3+}. Alternatively, Fe_3O_4 can support palladium, gold, nickel, copper, metal oxides, enzymes, acidic groups, or photocatalytic semiconductors. The environmental value of magnetic separation depends on more than the number of reuse cycles. A complete sustainability assessment must consider the energy and chemicals required to synthesize the catalyst, the toxicity and scarcity of its active metals, catalyst loss during operation, washing requirements, deactivation, regeneration, and end-of-life recovery. A catalyst should not be classified as sustainable merely because it can be attracted by a magnet.

Design, Synthesis, and Characterization of Magnetic Catalysts

The performance of a magnetic catalyst begins with the selection of its magnetic core. Magnetite is commonly used because it is relatively abundant, chemically versatile, and strongly responsive to magnetic fields. Its inverse-spinel structure contains Fe^{2+} and Fe^{3+} ions, allowing electron transfer between different oxidation states. This mixed-valence chemistry is particularly valuable for peroxide activation and redox catalysis. Maghemite is chemically related to magnetite but contains predominantly Fe^{3+} and cation vacancies. It can provide good magnetic response and greater oxidative stability under some conditions. Spinel ferrites represented by MFe_2O_4 introduce divalent ions such as Co^{2+}, Ni^{2+}, Mn^{2+}, Zn^{2+}, Mg^{2+}, or Cu^{2+}. Changing the divalent ion modifies magnetic saturation, surface acidity, electrical conductivity, redox behaviour, and resistance to dissolution. Magnetic nanoparticles are frequently synthesized through co-precipitation. Ferrous and ferric salts are mixed in an alkaline solution, producing iron-oxide particles. The method is inexpensive and potentially scalable, but particle size and aggregation depend strongly on pH, temperature, mixing rate, salt ratio, ionic strength, and oxygen exposure. Hydrothermal and solvothermal synthesis provide greater control over crystallinity and morphology. Metal precursors are heated in a sealed reactor, where elevated temperature and pressure promote controlled nucleation and growth. Spheres, rods, cubes, porous structures, and hierarchical magnetic particles can be produced by adjusting solvents, mineralizing agents, surfactants, and reaction time. Sol–gel, combustion, microwave-assisted, electrochemical, and

sonochemical methods are also used. Microwave heating can shorten reaction time and produce rapid volumetric heating. Combustion methods may generate porous powders but can also cause irregular temperature distribution and particle sintering. Green synthesis uses plant extracts, polysaccharides, proteins, biomass-derived carbon, or microorganisms as reducing, stabilizing, or functionalizing agents. A bio-inspired Fe_3O_4-supported palladium catalyst has been prepared using *Fritillaria imperialis* flower extract, which acted as a functionalizing and stabilizing medium. The recovered material was applied to nitroarene reduction and was reused magnetically without substantial reported activity loss.

Bare magnetic particles tend to aggregate because of magnetic attraction and high surface energy. Aggregation reduces exposed surface area and blocks catalytic sites. Surface coatings are therefore commonly applied. Silica, carbon, graphene oxide, polymers, cellulose, chitosan, lignin, cyclodextrins, and metal–organic frameworks can stabilize the magnetic core and provide functional groups for attaching catalytic species. Silica coatings protect magnetite from oxidation and acidic dissolution. Their hydroxylated surfaces can be functionalized with amine, thiol, carboxyl, phosphine, or acidic groups. Carbon shells provide electrical conductivity and chemical resistance. Polymer coatings improve dispersion but must withstand the temperature, solvent, and pH of the intended reaction. A core–shell catalyst may contain an Fe_3O_4 core, a protective SiO_2 or carbon shell, and an external active phase. The shell prevents unwanted interaction between the magnetic core and the reactants while maintaining magnetic recoverability. However, an excessively thick shell lowers the magnetic response per unit catalyst mass and can increase diffusion resistance. Active metals such as palladium, platinum, gold, nickel, copper, and ruthenium can be deposited on magnetic supports. Nanoscale dispersion increases the proportion of exposed metal atoms and can improve catalytic activity. Magnetic Fe_3O_4@C-supported palladium nanoparticles have been used in Suzuki and Heck coupling reactions, demonstrating the combination of fine metal dispersion and magnetic recovery. Catalyst characterization should establish structure, chemical composition, surface area, active-site accessibility, magnetic properties, and stability. X-ray diffraction identifies crystalline phases, while transmission and scanning electron microscopy reveal particle dimensions, morphology, coating thickness, and active-metal distribution. Brunauer–Emmett–Teller analysis measures surface area and pore properties. X-ray photoelectron spectroscopy identifies surface oxidation states, including the balance of Fe^{2+} and Fe^{3+}. Fourier-transform infrared and Raman spectroscopy can confirm coatings, organic functional groups, metal–oxygen bonding, and carbon structure. Vibrating-sample magnetometry measures saturation magnetization, remanence, and coercivity. High saturation magnetization generally improves magnetic recovery, but adding a non-magnetic catalytic coating reduces magnetization on a total-mass basis. Catalyst design must therefore balance catalytic loading against magnetic separability. Inductively coupled plasma analysis should be performed before and after catalysis to quantify metal leaching. Apparent heterogeneous activity may partially result from dissolved metal ions. Separating the catalyst and testing the remaining liquid can help distinguish true surface catalysis from homogeneous contributions.

Magnetic Catalysts in Environmental Remediation

Heterogeneous Fenton and Fenton-like oxidation

The classical Fenton reaction uses Fe^{2+} to activate hydrogen peroxide and generate highly reactive oxidants:

$$\mathbf{Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + \bullet OH}$$

The hydroxyl radical can oxidize many organic contaminants. In homogeneous Fenton treatment, dissolved iron may produce sludge and generally performs best under acidic conditions. Magnetic heterogeneous catalysts attempt to retain iron in a reusable solid phase.

Magnetite is suitable because its surface contains Fe^{2+} and Fe^{3+} sites. Surface Fe^{2+} reacts with H_2O_2, while reduction of Fe^{3+} regenerates active Fe^{2+}. The efficiency of this cycle depends on surface oxidation state, pH, peroxide concentration, pollutant adsorption, and electron-transfer pathways. Fe_3O_4 nanoparticles have been applied as heterogeneous electro-Fenton catalysts for degradation of reactive dyes. One study of Reactive Blue 19 examined pH, catalyst loading, current density, temperature, and reaction mechanism and demonstrated the feasibility of using magnetite as a recoverable iron source. Combining magnetite with another oxide can improve the redox cycle. Fe_3O_4/CeO_2 was investigated for the degradation of 4-chlorophenol. Cerium redox sites contributed to peroxide activation, while the magnetic component enabled catalyst recovery. The study also showed that surface reactions and limited dissolved-iron contributions could operate simultaneously. Nanoscale confinement can accelerate Fenton reactions by concentrating reactants within small pores and increasing contact with catalytic iron sites. Experiments using Fe_3O_4-functionalized nanoreactors demonstrated that the dimensions of the confined reaction environment can influence radical-mediated oxidation kinetics. A major difficulty is the non-productive decomposition of H_2O_2 into water and oxygen. Excess peroxide can also consume hydroxyl radicals. Efficient catalysts should promote pollutant oxidation rather than simple peroxide loss. Electron-conductive supports, oxygen vacancies, mixed-valence metals, and interfacial junctions can improve oxidant utilization. Magnetite has also been combined with pyrogenic carbon derived from crop residues. The carbon supplies defects and electron-transfer sites, while Fe_3O_4 provides iron redox centres. Coactivation of H_2O_2 by straw-derived carbon and magnetite illustrates how waste biomass can be integrated into a catalytic oxidation system.

Photo-Fenton and photocatalytic treatment

Photo-Fenton catalysis combines light absorption with peroxide activation. Photons can regenerate lower-valence metal centres, promote electron–hole separation, and increase radical production. Magnetic recovery is especially valuable because conventional photocatalyst powders can be difficult to remove from treated water. Magnetic Fe_3O_4/α-FeOOH heterojunctions have been developed for visible-light-assisted degradation of tetracycline. The interaction between the two iron phases improved visible-light absorption and charge separation, while the magnetic phase enabled easier recovery. The reported material operated across a broader pH interval than many conventional Fenton systems.

Graphitic carbon nitride is a metal-free semiconductor capable of visible-light activation. Combining it with magnetite adds magnetic separation and can improve charge-transfer behaviour. Magnetically separable Fe_3O_4@g-C_3N_4 materials have been investigated for adsorption, oil removal, photocatalysis, and photoactivated Fenton reactions. Other magnetic photocatalysts include Fe_3O_4/ZnO, Fe_3O_4/TiO_2, ferrite-based heterojunctions, and magnetic composites containing silver phosphate. The magnetic component must be positioned carefully because direct contact with a semiconductor can either improve electron separation or create recombination sites.

Pollutant reduction and transformation

Not all environmental remediation requires oxidative destruction. Nitroaromatic pollutants can be reduced to corresponding amines, which may be less toxic or useful as chemical intermediates. Gold- or palladium-coated magnetic particles can catalyse reduction reactions while permitting external magnetic recovery. Magnetic nanomotor ensembles containing magnetite cores and gold catalytic surfaces have been used for 4-nitrophenol reduction. A programmable magnetic field generated collective movement and microstirring, while near-infrared illumination enhanced performance through a photothermal effect. This work illustrates the possibility of combining catalysis, remote motion, and targeted pollutant treatment. Heavy-metal remediation may involve adsorption followed by catalytic oxidation or reduction. Arsenite can be oxidized to arsenate before adsorption, while toxic Cr(VI) can be reduced to less mobile Cr(III). Magnetic supports can combine reactive metal sites with chelating groups, activated carbon, or ion-exchange phases. An important limitation is that pollutant disappearance does not necessarily demonstrate complete detoxification. Chromatographic analysis should identify transformation products, while total organic carbon testing should evaluate mineralization. Toxicity assays are needed because partially oxidized intermediates can remain biologically active.

Sustainable Chemical Processing and Renewable-Fuel Production

Magnetic catalysts can improve chemical manufacturing by combining heterogeneous catalysis with simplified catalyst isolation. Their applications include hydrogenation, oxidation, carbon–carbon coupling, multicomponent synthesis, biomass conversion, esterification, transesterification, and production of fine chemicals. Palladium-catalysed Suzuki and Heck reactions are important routes for producing pharmaceuticals, agrochemicals, polymers, and functional organic molecules. Homogeneous palladium catalysts can be highly active but are difficult to separate completely from products. Residual palladium is particularly undesirable in pharmaceutical manufacturing. Palladium immobilized on surface-modified $NiFe_2O_4$ has been used as a magnetically recoverable catalyst for Suzuki and Heck coupling. The ferrite support permits removal through a magnetic field, potentially reducing filtration and metal contamination of the product. Fe_3O_4@C-supported palladium provides a related core–shell approach. The carbon layer protects the magnetic core and provides a surface for metal deposition. Such systems illustrate how the magnetic function can be separated structurally from the catalytic function.

Nickel offers a less expensive alternative to noble metals for selected hydrogenation and coupling reactions. Magnetic nickel catalysts can be supported on Fe_3O_4, cyclodextrin, carbon, silica, or polymers. However, nickel leaching, oxidation, and sensitivity to air require careful control.
Magnetic catalysts also support biomass valorization. Biomass contains cellulose, hemicellulose, lignin, proteins, lipids, and other compounds that can be converted into fuels and chemicals. Solid acids, bases, and metal catalysts are used for hydrolysis, dehydration, esterification, transesterification, and hydrogenation. Biodiesel is produced by converting triglycerides and free fatty acids into fatty-acid alkyl esters. Homogeneous acid or base catalysts can create wastewater and require neutralization. Magnetic solid catalysts can be recovered and reused, reducing catalyst contamination of the biodiesel and glycerol phases. A $MoO_3/ZnFe_2O_4$ magnetic solid acid has been evaluated for converting waste frying oil into biodiesel. Under the reported optimized conditions, the material produced 97.6% fatty-acid-methyl-ester conversion and maintained conversion above 90% through six reaction cycles. Waste-derived catalytic supports can further improve circularity. Magnetic carbonaceous acids have been prepared from hydrolysates of Jatropha hulls. In a 5 L batch-reactor investigation, the catalyst produced an average biodiesel yield of 95.9% and a reported catalyst recovery rate of 94.3% after five cycles. This example connects agricultural-waste valorization, renewable-fuel production, solid-acid catalysis, and magnetic separation. The environmental superiority of a magnetic catalyst should not be inferred from product yield alone. Some biodiesel catalysts require high temperature, large alcohol-to-oil ratios, strong acids during synthesis, or lengthy reaction periods. Energy use, methanol recovery, catalyst preparation, and wastewater production must be included in the assessment.
Magnetic catalysts may also be applied in biorefineries for the production of platform chemicals such as furfural, 5-hydroxymethylfurfural, levulinic acid, sugar alcohols, and organic acids. Acidic or metallic active sites can be attached to a magnetic carbon or ferrite support. Magnetic recovery could be particularly useful when the biomass feed creates suspended solids that complicate conventional filtration. Enzymes can be immobilized on magnetic carriers to create magnetically recoverable biocatalysts. Immobilization may increase enzyme stability and allow repeated use. However, the magnetic support, coupling chemistry, pore structure, and reaction conditions must preserve the enzyme's active configuration.

Catalyst Recovery, Reactor Engineering, and Sustainability Assessment

Magnetic recovery is governed by the magnetic moment of the particles, the field gradient, liquid viscosity, flow velocity, reactor dimensions, and distance from the magnet. A strong magnetic field without a sufficient gradient may align particles but fail to transport them effectively. Laboratory recovery is commonly demonstrated by placing a permanent magnet against a small glass vial. Industrial recovery is more complicated because large liquid volumes, continuous flow, opaque media, and high solids content reduce separation efficiency. Scale-up requires magnetic drums, high-gradient magnetic separators, magnetically assisted settlers, or specially designed flow channels. Nanoparticles may respond strongly to a magnet but settle slowly when the field is removed. This can benefit redispersion but can also lead to catalyst escape. Larger magnetic clusters are easier to separate but possess less surface area. Hierarchical particles containing nanoscale active sites within micron-scale magnetic structures may provide a practical compromise. Immobilizing the magnetic catalyst in beads, membranes, foams, fibres, or monoliths can reduce nanoparticle release. Nevertheless, immobilization introduces diffusion resistance and may lower catalytic surface accessibility. The optimum form depends on reaction rate, viscosity, pollutant concentration, and required hydraulic throughput. Catalyst-reuse tests should report activity, selectivity, recovery mass, metal leaching, magnetic saturation, and structural changes after every cycle. Simply stating that a catalyst was reused several times does not explain whether reduced activity resulted from physical loss, poisoning, aggregation, oxidation, or dissolution. Surface passivation occurs when reaction intermediates, natural organic matter, salts, polymers, or inorganic precipitates cover active sites. Wastewater containing carbonate, phosphate, chloride, sulfate, and dissolved organic matter may behave differently from laboratory solutions prepared with one pollutant in deionized water. Regeneration may involve solvent washing, thermal treatment, chemical oxidation, reduction, or pH adjustment. These operations consume resources and can damage the catalyst. A catalyst that requires aggressive regeneration after every cycle may offer limited environmental benefit. Life-cycle assessment should compare magnetic catalysis with competing processes such as activated carbon, membrane filtration, biological treatment, homogeneous Fenton oxidation, conventional heterogeneous catalysis, and incineration. Boundaries should include raw-material extraction, synthesis, operation, recovery, regeneration, transport, and disposal. Key green-chemistry indicators include atom economy, reaction mass efficiency, energy intensity, solvent hazard, catalyst productivity, metal loss, E-factor, and carbon footprint. Magnetic recovery can lower separation energy, but only if producing and regenerating the magnetic catalyst does not create a larger burden. Techno-economic analysis should evaluate catalyst cost, lifetime, magnetic-separator cost, energy use, maintenance, product value, and waste-treatment savings. Noble-metal catalysts may be economically acceptable when recovery is highly efficient and the product is valuable. For high-volume wastewater, inexpensive iron- and manganese-based systems are more realistic.

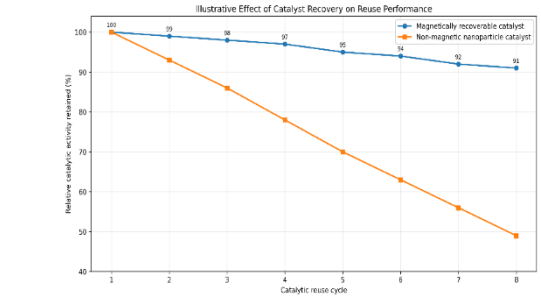
Challenges and Future Research Perspectives

Nanoparticle aggregation remains a major challenge. Magnetic attraction and surface energy cause particles to form clusters, decreasing accessible surface area. Coatings, porous supports, and hierarchical structures can reduce aggregation, but they add synthetic steps and may lower magnetization. Metal leaching is another concern. Dissolved iron may contribute to Fenton chemistry, while palladium, nickel, cobalt, or copper can contaminate treated water or chemical products. Regulatory limits may require extremely low residual-metal concentrations. Magnetic cores can oxidize or dissolve under strongly acidic conditions. Magnetite may transform toward maghemite or other iron phases, changing both catalytic and magnetic behaviour. Protective shells improve stability but may restrict access to redox-active iron sites. Catalyst selectivity is critical in chemical processing. A highly active magnetic catalyst may produce side reactions if active-metal particle size or oxidation state changes during reuse. Sintering, leaching, and poisoning must therefore be monitored through post-reaction characterization. Environmental studies should move beyond single model dyes. Real wastewater contains mixtures of pollutants, suspended particles, microorganisms, salts, and natural organic matter. Future research should use industrial effluents and compare performance with established treatment methods. Continuous-flow systems are necessary for industrial translation. Magnetic catalysts should be tested under realistic residence times, hydraulic conditions, and pollutant loads. Computational fluid dynamics and magnetic-field modelling can help design separators that prevent catalyst loss. Green synthesis should increasingly use agricultural residues, lignin, cellulose, biochar, and recovered metals. However, variability in biological feedstocks may affect catalyst reproducibility. Standardized pretreatment and quality-control procedures will be required. Critical and toxic metals should be minimized. Iron-, manganese-, zinc-, magnesium-, and nickel-based catalysts may replace palladium or platinum in some reactions, although their activity and selectivity may be lower. Single-atom and bimetallic designs may reduce noble-metal loading. Process intensification could combine magnetic catalysis with light, ultrasound, electricity, microwaves, or mechanical mixing. These combinations may accelerate reactions but also increase equipment complexity and energy consumption. Net environmental benefit should be demonstrated quantitatively. Machine learning can relate catalyst composition and synthesis parameters to activity, magnetization, stability, and leaching. Useful models require standardized datasets containing negative as well as successful results. Safe-by-design principles should guide development. Particle size, coating, degradability, and magnetic response should be optimized to prevent environmental persistence. Toxicological studies should evaluate aquatic organisms, soil microorganisms, plants, and human exposure. The most successful future systems will likely be structurally hierarchical: a recoverable magnetic core or framework, a chemically stable protective layer, an accessible high-surface-area support, and a minimal quantity of precisely positioned catalytic species.

Singh and Sohail (2026) examined medical negligence in Malaysian hospitals through a qualitative thematic analysis of medico-legal court cases. Their study explored organisational and governance-related factors contributing to healthcare failures, including communication problems, documentation weaknesses, and inadequate risk management systems. The findings emphasized the importance of strengthening healthcare governance and adopting system-based approaches to improve patient safety.

Qazi and Sohail (2026) investigated the factors influencing investors' intention to participate in socially responsible investing among Pakistan Stock Exchange investors. The study focused on attitude, subjective norms, and perceived behavioral control as key determinants of investment intention. The results indicated that investors' positive attitudes significantly influence their willingness to engage in socially responsible investment practices.

Mousumi and Sohail (2026) studied the relationship between service quality, customer engagement, and customer loyalty in the Malaysian telecommunications sector. Their research highlighted that effective service quality dimensions, including reliability, responsiveness, and customer support, contribute to stronger customer relationships. The study suggested that improving service quality can enhance customer engagement and promote long-term loyalty.



Author-generated conceptual data illustrating how efficient magnetic recovery may reduce catalyst loss. The values are not experimental measurements and should not be used for quantitative comparison.

Summary

Magnetic catalysts integrate chemical reactivity with external magnetic recovery. This combination can simplify product purification, reduce catalyst loss, and enable repeated use in environmental and industrial processes. Iron oxides and ferrites may act directly as Fenton-like catalysts or provide magnetic supports for photocatalysts, noble metals, enzymes, acidic groups, carbon materials, and metal–organic frameworks. Their applications include degradation of dyes and pharmaceuticals, peroxide activation, nitroaromatic reduction, heavy-metal transformation, cross-coupling reactions, hydrogenation, biomass valorization, and biodiesel production. Environmental performance depends on active-site chemistry, oxidation state, porosity, surface area, pollutant adsorption, oxidant utilization, and electron transfer. Magnetic performance depends on saturation magnetization, particle dimensions, aggregation, and field gradient. Both functions must be optimized together. Laboratory studies demonstrate that magnetic catalysts can be recovered and reused, but industrial translation requires realistic wastewater testing, continuous-flow reactors, low metal leaching, long-term stability, standardized reuse protocols, and efficient magnetic separation. A multidisciplinary approach is required. Materials science controls structure and magnetic behaviour; catalysis determines reaction pathways; environmental engineering evaluates contaminant removal; reactor engineering enables scale-up; and life-cycle analysis establishes whether the complete process is genuinely sustainable.

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