



Biodegradable Heterogeneous Catalysts: Advancing Sustainable Chemical Transformations

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Abstract

Conventional chemical processes often rely on non-renewable, toxic catalysts and generate substantial waste, conflicting with sustainability imperatives. Biodegradable heterogeneous catalysts, derived from renewable biomass (e.g., chitosan, cellulose, lignin) or agricultural residues, integrate high efficiency with environmental compatibility through recyclability, low toxicity, and facile separation. These systems align with green chemistry principles by minimizing energy use, hazardous reagents, and persistent pollutants. This review examines synthesis strategies (sol-gel, green reduction, pyrolysis), catalytic mechanisms (surface adsorption, bond activation, intermediate formation), and applications in organic transformations (oxidation, reduction, multicomponent reactions), biodiesel production via transesterification (>90% yields reported), and environmental remediation (photocatalytic pollutant degradation). Biomass-derived carbons and biopolymer-supported metals (e.g., Fe, Cu) offer earth-abundant alternatives to noble metals, with recent advances in nanostructured hybrids improving stability and activity. Challenges include limited thermal durability, deactivation, and scale-up hurdles, addressed through innovative designs like magnetic recovery and AI-guided optimization. Future directions emphasize circular bioeconomy integration, electrocatalytic/photocatalytic hybrids, and industrial viability to foster sustainable manufacturing and resource-efficient chemical industries. (218 words)

Keywords: Green Chemistry; Biodegradable Heterogeneous Catalysts; Biomass-Derived Supports; Sustainable Catalysis; Biodiesel Production; Environmental Remediation

Introduction

Chemical manufacturing drives economic progress but contributes to pollution through hazardous reagents, non-recyclable catalysts, and energy-intensive processes. Green chemistry advocates catalytic systems that reduce waste at source, prioritize atom economy, and employ renewable feedstocks (Anastas and Warner, 1998). Heterogeneous catalysis dominates industrial applications (>90% of processes) due to phase separation, reusability, and robustness (Friend and Xu, 2017).

Traditional supports (e.g., alumina, silica) and metals (e.g., Pd, Pt) often pose toxicity and disposal risks. Biodegradable alternatives—derived from natural polymers (chitosan, cellulose) or biomass waste—offer low environmental footprint, abundance, and compatibility with mild conditions (Sarangi et al., 2024). This review synthesizes principles, preparation, mechanisms, applications, advantages, limitations, and prospects of biodegradable heterogeneous catalysts for eco-friendly transformations.

Principles of Biodegradable Heterogeneous Catalysis

These catalysts adhere to green chemistry tenets:

Use of renewable, biodegradable supports (e.g., polysaccharides, lignin) to replace synthetic polymers.

Operation under mild conditions (ambient temperature/pressure, aqueous media) to cut energy and solvent use.

High reusability via filtration/magnetic separation, minimizing waste and cost.

Chitosan excels in chelating metals (e.g., Fe, Cu) for C–H activation and cross-coupling. Biomass-derived carbons provide acidic/basic sites for transesterification.

Synthesis Approaches

Sol-gel: Hydrolysis/condensation yields porous networks.

Green reduction: Plant extracts reduce metals onto supports.

Pyrolysis: Biomass carbonization produces high-surface-area catalysts (e.g., biochar from agri-waste).

Immobilization: Metal nanoparticles anchored via coordination or impregnation.

Types of Biodegradable Heterogeneous Catalysts Table 1. Common biodegradable supports and applications

Support/Biopolymer	Key Features	Typical Applications
Chitosan	Amino groups for metal coordination	Oxidation, coupling reactions (Kaur et al., 2025)
Cellulose	High surface area, modifiable hydroxyls	Esterification, acid catalysis
Lignin/Biochar	Aromatic structure, porosity	Biomass conversion, biodiesel (Yadav et al., 2023)
Starch/Alginate	Gel-forming, encapsulating	Nanoparticle stabilization

Mechanisms

Heterogeneous catalysis proceeds via:

1. Reactant adsorption on surface active sites.
2. Bond polarization/activation.
3. Intermediate formation.
4. Desorption of products, regenerating sites.

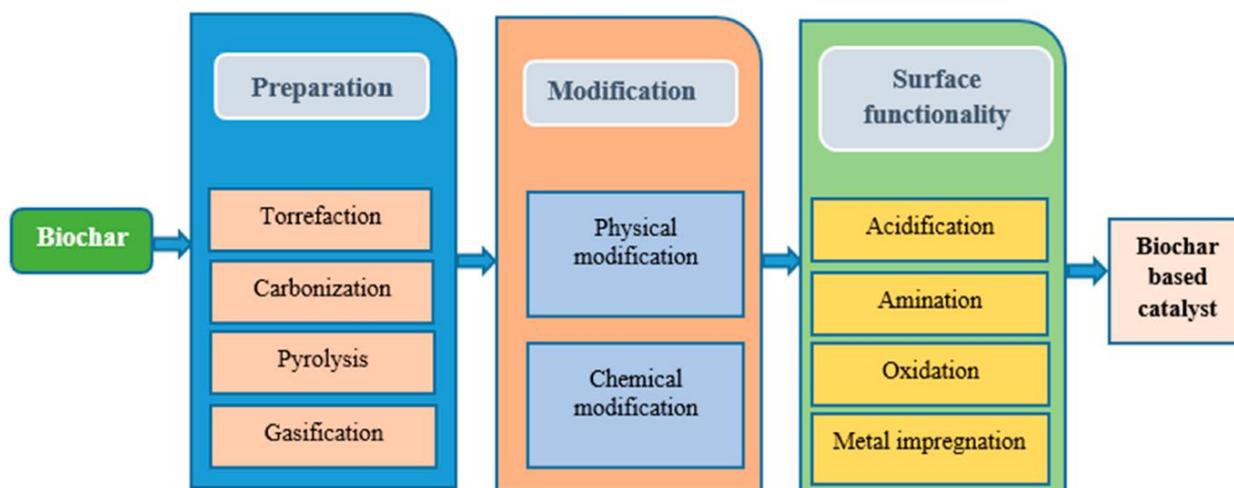


Fig. 1. General mechanism of heterogeneous catalysis

For example, in chitosan-Fe systems, Fe sites facilitate oxidative addition, while the biopolymer stabilizes intermediates.

Applications Organic Synthesis

Biodegradable catalysts enable efficient, selective reactions (e.g., oxidation, reductions, heterocycle synthesis) with high yields and recyclability (Zhang et al., 2025).

Biodiesel Production

Transesterification of oils/fats using biomass-derived bases/acids yields >90% biodiesel; easy recovery and low corrosivity enhance sustainability (Ao et al., 2024; Yadav et al., 2023).

Environmental Remediation

Photocatalytic systems degrade pollutants via reactive oxygen species; biopolymer supports improve stability in aqueous media (Liu et al., 2024).

Advantages

Biodegradability reduces pollution.

Reusability lowers costs.

Renewable sourcing promotes circularity.

Non-toxicity ensures safer handling.

Challenges and Limitations

Thermal/mechanical instability limits high-temperature use.
 Activity sometimes inferior to noble metals.
 Deactivation (leaching, fouling).
 Scale-up difficulties (uniformity, cost).
 Hybrid designs (e.g., metal nanoparticles on magnetic biochar) mitigate these.

Future Prospects

Emerging trends include:
 Nanostructured hybrids for enhanced selectivity.
 Electrocatalytic/photocatalytic integrations.
 AI/machine learning for rational design.
 Circular approaches valorizing waste into catalysts.
 These will accelerate adoption in sustainable manufacturing.

Conclusion

Biodegradable heterogeneous catalysts bridge efficiency and environmental responsibility, enabling green transformations in synthesis, bioenergy, and remediation. Advances in renewable supports and hybrid systems promise scalable, low-impact chemical industries.

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Author Contributions

YM, BS and MS conceived the concept, wrote and approved the manuscript.

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Competing interest

The authors declare no competing interests.

Ethics approval

Not applicable.



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