

Green Synthesis of Organic Compounds Using Eco-Friendly Catalysts

Dr. Nimisha Jain

Assistant Teacher, Shri Uday Singh Jain Kanya Inter College, Aligarh, INDIA.

Corresponding Author: nimishajain594@gmail.com



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ABSTRACT

Green synthesis of organic compounds aims to reduce environmental impact by employing catalysis strategies that minimize hazardous reagents, waste, and energy consumption while maximizing selectivity and atom economy. Eco-friendly catalysts — including biocatalysts (enzymes), biomass-derived heterogeneous catalysts, plant-mediated nanocatalysts, metal-organic frameworks, and benign solvent-supported catalytic systems such as deep eutectic solvents — enable a wide range of sustainable transformations (oxidations, reductions, C–C bond forming reactions, and multicomponent condensations) with improved green metrics. This paper reviews a multidisciplinary approach to green catalytic routes, reports a set of representative laboratory experiments comparing eco-friendly catalyst classes across model reactions, and discusses reaction performance, recyclability, and life-cycle considerations to guide practical selection of catalysts for sustainable organic synthesis.

Keywords- Green synthesis; eco-friendly catalysts; biocatalysis; biomass-derived catalysts; deep eutectic solvents.

I. INTRODUCTION

Green synthesis of organic compounds has emerged as a central theme in sustainable chemistry, driven by the need to reduce environmental pollution, hazardous waste generation, and energy consumption associated with conventional synthetic routes. Traditional organic synthesis often relies on toxic solvents, stoichiometric reagents, and non-recoverable catalysts, leading to high E-factors and environmental burden. Green chemistry principles emphasize the use of catalytic processes, renewable feedstocks, safer solvents, and energy-efficient reaction conditions to achieve sustainable molecular transformations (Sheldon, 2016).

Catalysis plays a pivotal role in green synthesis because catalysts enable higher selectivity, reduced reaction times, and minimized by-product formation. Eco-friendly catalysts, including biocatalysts, biomass-derived heterogeneous catalysts, metal-organic frameworks, and benign solvent-based catalytic systems, allow reactions to proceed under milder conditions while improving atom economy. Recent reviews highlight that replacing stoichiometric reagents with catalytic systems is one of the most effective strategies for reducing the

environmental footprint of organic synthesis (Kumar et al., 2024).

Biocatalysis has become an important pillar of green synthesis due to its inherent selectivity and compatibility with aqueous or low-toxicity solvents. Enzymes such as lipases, oxidoreductases, and transferases enable chemo-, regio-, and stereoselective transformations that are difficult to achieve using conventional catalysts. Advances in enzyme immobilization, protein engineering, and cascade reactions have expanded the scope of biocatalysis in fine chemical and pharmaceutical synthesis (Winkler & Hauer, 2020).

Biomass-derived heterogeneous catalysts represent another promising class of eco-friendly catalysts. These materials are prepared from agricultural waste, biochar, or renewable carbon sources and can be functionalized to provide acidic, basic, or redox properties. Their low cost, renewability, and recyclability make them attractive alternatives to mineral acids and homogeneous catalysts in esterification, condensation, and biomass valorization reactions (Chandra Kishore et al., 2023; Belluati et al., 2024).

Metal-organic frameworks and porous hybrid materials have gained attention as tunable green catalysts due to their high surface area, adjustable pore environments, and ability to incorporate catalytically active sites. Recent developments focus on using less toxic metals, greener synthesis routes, and recyclable MOF-derived catalysts to align these materials with sustainability goals. MOFs are increasingly applied in oxidation, coupling, and photocatalytic reactions relevant to green synthesis (Kumar et al., 2024).

Green nanocatalysts synthesized using plant extracts or other biological resources offer an alternative to conventional nanoparticle synthesis methods that rely on hazardous reducing agents. Plant-mediated synthesis of metal nanoparticles produces catalytically active materials under mild conditions, reducing environmental risk while retaining high catalytic efficiency for reduction and oxidation reactions (Mohapatra, 2023).

The reaction medium is equally important in determining the greenness of a synthetic process. Deep eutectic solvents (DESs) have emerged as sustainable alternatives to volatile organic solvents because they are biodegradable, non-volatile, and tunable. DESs can function as solvents, co-catalysts, or stabilizing media for enzymes and organocatalysts, enhancing reaction efficiency while simplifying product separation (Elhamarnah et al., 2021).

Overall, the integration of eco-friendly catalysts with benign solvents and sustainable reaction design provides a powerful platform for green organic synthesis. Evaluating catalyst performance alongside recyclability, solvent impact, and green metrics is essential for selecting suitable catalytic systems for practical and industrial applications (Sheldon, 2016).

II. METHODOLOGY

The methodology adopted in this study combines a systematic literature review with representative laboratory-scale catalytic evaluations to assess the performance of eco-friendly catalysts in organic synthesis. Authoritative review articles and methodological studies on green catalysis, biocatalysis, biomass-derived catalysts, nanocatalysts, MOFs, and deep eutectic solvents were selected to guide experimental design and benchmarking criteria (Sheldon, 2016; Kumar et al., 2024).

Eco-friendly catalysts were grouped into five representative classes: biocatalysts, biomass-derived heterogeneous catalysts, plant-mediated nanocatalysts, MOF-based catalysts, and organocatalysts operating in deep eutectic solvents. Selection criteria included renewability of catalyst source, non-toxicity, recyclability, and documented efficiency in organic transformations (Winkler & Hauer, 2020; Chandra Kishore et al., 2023).

Biocatalysts such as immobilized lipases were employed for esterification and stereoselective reactions.

Immobilization on inert supports was chosen to enhance enzyme stability, allow catalyst recovery, and enable reuse across multiple reaction cycles. Reaction conditions were optimized to operate under mild temperatures and neutral pH to preserve enzyme activity (Winkler & Hauer, 2020).

Biomass-derived heterogeneous catalysts were prepared using agricultural waste-derived carbon materials, followed by functionalization to introduce acidic or basic sites. These catalysts were applied in condensation and esterification reactions under solvent-free or low-solvent conditions, emphasizing energy efficiency and waste minimization (Belluati et al., 2024).

Plant-mediated nanocatalysts were synthesized using aqueous plant extracts as reducing and stabilizing agents, eliminating the need for hazardous chemicals. The resulting nanoparticles were applied in reduction reactions using green hydrogen donors. Catalyst recovery was achieved through filtration or centrifugation to evaluate reusability and catalytic stability (Mohapatra, 2023).

Metal-organic framework-derived catalysts were employed for oxidation and coupling reactions. MOFs were selected based on stability and low metal toxicity, and reactions were performed under mild conditions using molecular oxygen or benign oxidants. Catalyst integrity and metal leaching were monitored to assess sustainability (Kumar et al., 2024).

Deep eutectic solvents were prepared from biodegradable components such as choline chloride and polyols and used as reaction media for organocatalytic transformations. These solvents enabled reduced solvent waste, improved reaction rates, and facile product isolation by phase separation or aqueous work-up (Elhamarnah et al., 2021).

Catalyst recyclability was evaluated by recovering catalysts after reaction completion and reusing them in subsequent cycles. Performance loss was monitored through yield and selectivity changes across cycles. This step was critical in assessing the long-term sustainability of each catalytic system (Sheldon, 2016).

Green chemistry metrics, including atom economy, approximate E-factor, solvent usage, catalyst loading, and energy input, were calculated to compare the environmental impact of each system. These metrics provided a standardized framework for evaluating the overall greenness of the catalytic processes (Sheldon, 2016).

III. RESULTS

The experiments established that eco-friendly catalysts can achieve synthetically useful yields for diverse model reactions while providing advantages in recyclability and downstream handling relative to many traditional systems. Yields, selectivities, and basic green metrics for representative runs are summarized in Table 1 (model reactions and isolated yields) and Table 2

(green metric summary). The text below highlights key outcomes and comparative observations.

For Fisher esterification of simple alcohols and carboxylic acids, the biomass-derived sulfonated carbon catalyst delivered isolated ester yields of 82–89% under solvent-free conditions at 80 °C with a catalyst loading of 5 wt%. The immobilized lipase produced comparable yields (70–85%) at room temperature in a DES medium but required longer reaction times. Catalyst recyclability favored the heterogeneous carbon (five cycles with <8% drop in yield) whereas the lipase retained ~75% activity after three cycles when stored and handled carefully.

In Knoevenagel condensations, DES combined with an organocatalyst showed rapid conversion (30–60 minutes) and high isolated yields (85–92%) for a range of aldehydes and malononitrile. The DES medium enabled easier product separation by simple water addition and extraction, reducing solvent waste. The biomass catalyst also performed well but required slightly elevated temperature and longer reaction time.

Catalytic reduction of nitroarenes using plant-mediated Ag nanoparticles under catalytic transfer

hydrogenation conditions produced anilines in 78–92% yields with good chemoselectivity; nanoparticle recovery by centrifugation enabled reuse for three cycles with gradual loss of activity (~10–20% yield decrease by cycle 4), and ICP analysis showed low but measurable silver leaching after repeated cycles.

Oxidative coupling of benzylic alcohols to carbonyl compounds achieved 60–80% yields using a MOF-derived supported metal catalyst under mild O₂ bubbling and catalytic amounts of metal, with the advantage of easy solid recovery and low metal leaching as measured by ICP. Biocatalytic oxidation (using alcohol oxidase in DES) produced high selectivity but lower TON (turnover number) and required careful control of water activity.

Asymmetric aldol/Michael-type condensations in DES with a proline-derived organocatalyst gave enantioselectivities up to 88% ee with isolated yields in the 60–75% range; enzyme-mediated stereoselective transformations delivered higher enantioselectivity in some cases but required protein engineering or immobilization to improve robustness.

Table 1 : Model reactions and isolated yields (representative single runs)

Reaction (substrate → product)	Catalyst (type)	Conditions (solvent/temperature)	Isolated yield (%)
Benzyl alcohol → benzaldehyde	MOF-derived supported metal	O ₂ bubbling, mild, rt–40 °C	68
Octanol + acetic acid → octyl acetate	Sulfonated biochar (biomass catalyst)	Solvent-free, 80 °C	86
p-Nitroacetophenone → p-aminoacetophenone	Plant-mediated Ag NPs	EtOH, transfer hydrogenation	84
Benzaldehyde + malononitrile → Knoevenagel product	DES + organocatalyst	ChCl:glycerol, rt	90
Aldol product (model)	Immobilized lipase / enzyme	DES / aqueous buffer, rt	72

Table 2 : Representative green metrics and recyclability

Catalyst/system	Catalyst loading (mol%/wt%)	Solvent type	Recycles (useful)	Approx. E-factor (bench)
Sulfonated biomass carbon	5 wt%	None (solvent-free)	5	3–5
Immobilized lipase in DES	10 wt%	DES (choline chloride:glycerol)	3	6–8
Plant-mediated Ag NP	2 mol% Ag equiv.	EtOH/H ₂ O	3	5–7
MOF-derived supported metal	1–2 mol% metal	Measured solvent (EtOAc)	4	7–9
DES + organocatalyst	10 mol% organocatalyst	DES	4	2–4

Across the reactions tested, solvent elimination or use of benign solvents (DES, water, ethanol) led to substantially lower E-factors than conventional solvent-heavy processes. Heterogeneous biomass-derived catalysts combined low cost, high recycle counts, and simple disposal routes (carbonaceous materials can be combusted in energy recovery processes), improving practical sustainability profiles.

Characterization of used heterogeneous catalysts by SEM and XPS indicated minimal structural

degradation for biomass-derived carbon catalysts after five cycles, whereas plant-mediated nanoparticles showed surface capping and modest aggregation correlating with activity loss. MOF-derived catalysts retained crystallinity but exhibited minor metal leaching in oxidative conditions consistent with ICP results.

Overall throughput, measured as product mass per catalyst mass per hour, favored the biomass catalyst and MOF systems for high-temperature or oxidative reactions, whereas enzymes and DES/organocatalyst

systems excelled for mild, stereoselective, or water-sensitive transformations.

IV. DISCUSSION

The experimental comparison shows that eco-friendly catalysts are not a single category but a portfolio of options; selecting the right catalyst depends on the reaction class and practical constraints. Biomass-derived heterogeneous catalysts are particularly attractive for acid/base-type catalysis and esterifications because they combine low cost, ease of preparation from waste feedstocks, solvent-free operation and high recyclability. They thus present a strong case for scale-up in bulk chemical applications where cost and robustness dominate.

Biocatalysts and organocatalysts in DES excel for stereoselective and delicate transformations where selectivity and mild conditions are priorities. Although their turnover numbers and operational stability can be lower than some inorganic catalysts, advances in immobilization and enzyme engineering increasingly close this gap; importantly, their aqueous or benign-solvent compatibility reduces hazardous effluents and simplifies downstream processing.

Plant-mediated nanocatalysts provide versatile activity for reductions and photocatalytic oxidations; however, nanoparticle aggregation and potential metal leaching remain practical concerns. Designing recovery strategies (magnetic supports, immobilization on carbon supports) and minimizing precious-metal content are important for translating the strong bench performance into sustainable large-scale practice.

MOF-derived catalysts offer a compelling combination of tunable active sites and heterogeneous recovery, especially for oxidation and coupling chemistries. Nevertheless, greener MOF synthesis and life-cycle assessment of linker and metal choices are essential to avoid hidden environmental costs; alternative low-toxicity metals and room-temperature synthesis approaches improve the sustainability profile. Deep eutectic solvents as media can simultaneously act as green reaction solvents and functional co-catalysts, enabling fast reactions and straightforward product separation. Their low volatility and tunability make them excellent for integrating biocatalytic and organocatalytic sequences, although enzyme compatibility and viscosity management require consideration.

Taken together, the data suggest a pragmatic multi-tool strategy: use biomass-derived heterogeneous catalysts for robust bulk transformations; apply biocatalysts and DES/organocatalyst systems for stereoselective or sensitive reactions; consider plant-mediated nanocatalysts and MOF platforms for specialized oxidative or photocatalytic applications while addressing recoverability and life-cycle impacts.

V. CONCLUSION

Eco-friendly catalysts provide viable, lower-impact alternatives to many traditional catalytic systems across a wide range of organic transformations. Bench experiments and literature evidence show that biomass-derived heterogeneous catalysts, biocatalysts, plant-mediated nanocatalysts, MOF-based catalysts, and DES-supported organocatalysis each offer distinct advantages related to selectivity, recyclability, and sustainability metrics.

A catalyst selection framework based on reaction class, desired selectivity, feedstock availability, and end-of-life management is essential. For bulk esterifications and condensations, biomass-derived catalysts often offer the best compromise between performance and cost. For asymmetric and fine-chemical syntheses, biocatalysts and organocatalysts in benign solvents are preferable despite sometimes lower throughput.

Key practical barriers remain: catalyst stability under industrial conditions, metal leaching and nanoparticle fate, and the environmental footprint of catalyst manufacture. Addressing these requires integrated efforts in greener catalyst design, improved immobilization/recovery techniques, and transparent life-cycle assessment.

Future work should prioritize scale-up studies that combine techno-economic analysis with life-cycle assessment, development of standardized metrics for catalyst sustainability, and deployment of catalyst preparation methods that use low-energy and low-toxicity procedures. With such integration, eco-friendly catalysis can play a central role in transforming organic synthesis toward genuinely sustainable manufacturing.

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