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Development of Green Chemistry Routes for Synthesizing APIs Using Sustainable Catalysts and Solvents

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Abstract

This study investigates the development and evaluation of green chemistry routes for the sustainable synthesis of active pharmaceutical ingredients (APIs) using eco-friendly catalysts and solvents. The research aimed to design a catalytic system integrating enzyme–metal hybrids with green solvents such as supercritical CO_2 to enhance yield, purity, and selectivity while minimizing environmental hazards. Experimental analyses confirmed that the combination of biocatalysis and metallic catalysis significantly improved atom economy and reduced reaction time and energy consumption compared to conventional synthesis pathways. The optimized system demonstrated remarkable catalytic efficiency and environmental compatibility, validating its potential for large-scale pharmaceutical applications. The results highlighted that adopting green solvents reduced toxicity, improved recyclability, and enhanced process sustainability without compromising product performance. This study underscores the critical role of green chemistry in aligning pharmaceutical manufacturing with global sustainability goals. It also provides a scalable framework for integrating renewable catalysts, non-toxic solvents, and energy-efficient processes into the design of next-generation drug synthesis. Ultimately, the findings emphasize the need for continuous innovation and cross-disciplinary collaboration to promote environmentally responsible industrial practices and achieve long-term ecological and economic benefits.

Keywords: Biocatalysis, Green Chemistry, Pharmaceutical Synthesis, Sustainable Catalysts, Supercritical CO_2, Waste Reduction

Introduction

The recent several decades were marked with the growing scrutiny of the pharmaceutical industry being overly dependent on the non-renewable resources, toxic reagents, and energy-consuming processes. The traditional method of active pharmaceutical ingredients (APIs) synthesis was usually based on many steps, a large amount of waste, the use of solvents and catalysts that had adverse effects on the environment, and had ineffective ecological footprints. To react, the principles of green chemistry were introduced as a paradigm shift strategy that tries to reduce the environmental impact of the chemical processes by design of safer, more efficient, and sustainable approaches (Anastas and Warner, 1998; Li, 2022).

Regulatory and ethical factors had led to the shift towards green chemistry in the synthesis of pharmaceuticals. Regulations on the environment, as well as the growing concern with sustainability across the globe, had pushed industries to embrace environmentally friendly processes and minimize their carbon footprint (Clark et al., 2021). Specifically, the pharmaceutical industry pursued new methods of producing APIs that would cut back on the volume of solvents, cut down on toxic emission levels, and enhance the productivity of processes. This prompted the investigation of new catalytic systems and using greener solvers, which followed the twelve principles of green chemistry (Sheldon, 2018; Bhanage& Arai, 2019).

One of the most essential spheres of the sustainable pharmaceutical synthesis was catalysis and solvent selection. The conventional catalysts like the heavy metals worked but there were fears of toxicity and disposal of the waste. Conversely, safer alternatives were superior and more selective and could be reused in the form of sustainable catalytic systems, such as biocatalysts, organocatalysts, and heterogeneous catalysts based on readily available and renewable materials (Teles et al., 2020). Similarly, the replacement of volatile organic solvents with environmentally friendly alternatives, including ionic liquids, supercritical carbon dioxide, and deep eutectic solvents, played a major role in decreasing the environmental footprint of the synthetic processes (Perez-Ramirez et al., 2021).

In such a way, the creation of green chemistry pathways on the production of APIs was a decisive move towards producing more sustainable, efficient and environmental friendly manufacturing of pharmaceuticals. The aim of this research was to develop and analyse green synthetic pathways by the use of sustainable catalysts and solvents, which promotes low toxicity, high yield, and compatibility with industrial-scale production and correlates with the sustainability objectives of the world (Poliakoff and Licence, 2021).

Background

The green chemistry concept had evolved to become an academic ideal into a practical requirement in the contemporary drug industry. The twelve principles of green chemistry (atom economy, waste prevention, energy efficiency, renewable feedstocks, and safer solvents) offered a systematic approach to the creation of the sustainable chemical processes (Anastas and Eghbali, 2010). With these principles in place, the pharmaceutical chemists wanted to reduce the generation of hazardous waste without affecting the efficacy and quality of the products. Green chemistry was therefore being used as both an ethical and economic impetus behind sustainable innovation (Sheldon, 2018).

The catalytic process had been a core of the development of effective synthetic processes. Green chemistry shifted its interest to the area of green catalysis, which focused on catalysts that could be recovered, reused, and made of non-toxic, earth-abundant material (Centi&Perathoner, 2019). Heterogeneous catalysts, especially had the benefit of easy separation and recyclability, which eliminated the service of energy-demanding purification procedures. Enzymes or whole-cell systems were used to obtain exceptional selectivity and achieve reactions under mild conditions, which also conformed to the sustainability objectives (Bornscheuer et al., 2021).

Besides catalytic innovation, solvent choice also contributed significantly to the greenness of a chemical process. Traditional solvents such as chlorinated solvents and aromatic solvents were also a significant contributor to environmental and occupational risks. These environmentally safer, lower toxicity, and better-biodegradable options were provided by the development of green solvents, including water, ionic liquids, and deep eutectic solvents (Zhang et al., 2020). Carbon dioxide is also a type of supercritical fluid that was studied as tunable and recyclable solvents, potentially used in large-scale production (Jessop, 2019).

The pharmaceutical industry was still struggling with the obstacles to the full implementation of green chemistry principles despite these improvements. Numerous green catalysts and solvents were confined to laboratory-level studies, and their scalability and applicability to complex multi-step API syntheses was difficult (Clark et al., 2021). It therefore became necessary to come up with comprehensive methods whereby sustainable catalytic system can be integrated with environmentally friendly solvents, and which can be efficient, purify products, and be industrially relevant.

Research Problem

Even when green chemistry had become prominent, its use in the pharmaceutical production was scarce. The majority of other studies that existed were on isolated improvements whether on the catalyst or solvents without a cohesive synthesis of the two into one synthetic framework. Consequently, the possible synergistic potentials of the use of green catalysts along with solvents in API production were not exhausted (Teles et al., 2020). In addition, the factors of scalability, catalyst recyclability, and process optimization were not usually considered, which created certain problems with their use in the industry.

The current research dealt with the issue of establishing efficient, scalable, and environmentally friendly synthetic pathways toward API production by relying on green catalysts and solvents. The study was designed to close the gap between the laboratory innovation and the industrial feasibility with an emphasis on the reduction of the toxic waste, the increase in the life of the catalysts, and the high yields without the deterioration of the environment and the economic sustainability (Sheldon, 2018).

Objectives of the Study

1. To identify and evaluate sustainable catalytic systems suitable for key reactions in API synthesis.
2. To select and optimize green solvents that enhance reaction efficiency and minimize environmental impact.
3. To integrate catalysts and solvents into optimized reaction pathways that improve yields and reduce waste.

Research Questions

Q1. Which types of green catalysts (biocatalysts, organocatalysts, or heterogeneous catalysts) demonstrated the best performance in API synthesis?

Q2. What green solvents were most compatible with the selected catalysts and provided optimal reaction outcomes?

Q3. How did the developed green synthesis routes compare to traditional methods in terms of efficiency, yield, and sustainability?

Significance of the Study

This research was crucial because it was conducted on the issue of critical concern of minimizing the environmental impact of pharmaceutical production by developing the green chemistry-based synthesis techniques. The research offered a template of decreasing the hazardous wastes, reducing the energy usage, and enhancing reaction selectivity by using environmentally friendly catalysts and solvents. This development could improve the environmental and economic performance of the pharmaceutical manufacturing (Clark et al., 2021).

In addition, the research helped fill the gap in innovation in academics and industry. The streamlined green paths may be scaled to large-scale synthesis to provide viable advice to pharmaceutical firms interested in adhering to sustainability laws and corporate social responsibility policies (Poliakoff&Licence, 2021). Lastly, the study further enhanced the international agenda of sustainable development by enhancing environmentally friendly chemistry that safeguarded human health and natural ecosystems (Anastas and Eghbali, 2010).

Literature Review

Sustainable Catalysts in API Synthesis

The recent studies suggest that heterogeneous catalysts can provide significant advantages to sustainable API synthesis due to their ability to be employed in a reused form, generate less waste products and be much easier to separate from reaction mixtures. In a review of the applications of heterogeneous catalysts in green chemistry, Kumar, Saad, and Al-Qaradawi (2024) noted that metal oxides and composite varieties of catalysts that were supported have been more frequently applied in key organic transformations involving pharmaceutical intermediates due to their superior rate of conversion and recyclability. Achtar and Zaman (2025) also discussed that sustainable catalysis was being used to make chemical products in addition to energy transition, they said that earth-abundant metals and bio-derived supports were increasingly popular in transformations to APIs.

In a more narrow study, A Comprehensive Review on Deep Eutectic Solvents and Its Use to Extract Bioactive Compounds of Pharmaceutical Interest (2024) examined the application of DESs in the extraction of bioactive compounds of pharmaceutical interest in plants or other natural sources. It indicated that DESs were better at extraction yields, controllable polarity, and reduced toxicity compared to other traditional organic solvent-based methods of extraction (Porto University review, 2024). The review also cited such limitations as viscosity, scaling, and solvent removal or recycling challenges (Porto University review, 2024).

Recent research has also compared DESs with ionic liquids (ILs). Both DESs and ILs were analyzed in the article "An Overview on the Role of Ionic Liquids and Deep Eutectic Solvents in Oral Pharmaceuticals" (2025), which found that although ILs had advantages in some formulations (such as stability and solvation power), DESs were frequently preferred for many pharmaceutical applications due to concerns about cost, toxicity, and regulatory acceptability (Bologna University review, 2025). When taken as a whole, these studies showed that green solvents were being tested in actual API formulation and extraction scenarios, going far beyond theoretical alternatives (Bologna University review, 2025).

Integration of Catalysts and Solvent Systems & Case Studies

In order to test full or partial routes in API or API-intermediate synthesis, some studies have started integrating sustainable catalytic systems with green solvent media. For example, in "Applications of Heterogeneous Catalysts in Green Chemistry" (Kumar, Saad, & Al-Qaradawi, 2024), examples of catalysts operating in solvent-free or benign solvent conditions were provided. These examples showed that using supported catalysts in less aggressive media improved atom economy, decreased catalyst leaching, and decreased environmental toxicity.

The article "Setting New Records: Deep Eutectic Solvents Based on Metal Salts and Their Uses" by Khalid et al. (2024) described the use of metal-salt-based DESs (MSDESs) as reaction media and a part of the catalytic system to perform particular transformations. They described how magnetic DESs as a type of MSDESs have made the separation and reuse of catalysts efficient, which has simplified work-up and reduced the number of waste streams (Khalid et al., 2024).

Another educative case study was the use of aqueous two-phase systems (ATPSs) based on DES to extract analgesic drugs (Vessally and Rzayev, 2024). The feasibility of using green solvents systems and following downstream purification procedures that are relevant to the isolation of APIs was proved practically when the authors showed that DES-ATPSs would allow obtaining high extraction efficiency with reduced organic solvents load (Vessally&Rzayev, 2024).

Research Methodology

Research Design

This research was intended as an experimental and analytical research project with the purpose of developing and optimizing the green chemistry pathways to the synthesis of the selected active pharmaceutical ingredients (APIs). The study used a quantitative design based on the laboratory to determine the efficiency, yield and the environmental impact of the various sustainable catalysts and solvents. The comparison of traditional and green synthesis pathways was performed by comparative experimental setups. It was concentrated on minimizing the hazardous waste, enhancing the atom economy, and maximizing the reaction conditions by systematic catalyst and solvent variation. All the experiments were performed under the conditions of control and the results were analyzed statistically to guarantee reproducibility and reliability of the findings.

Selection of Materials

High purity pharmaceutical intermediates available commercially and reagents were used in order to be consistent in the study. Ionic liquids, supercritical carbon dioxide, and deep eutectic solvents are some of the sustainable solvents chosen on the basis of their biodegradability, low toxicity and recyclability. Examples of catalytic systems used were biocatalysts (lipases and oxidoreductases), heterogeneous metal catalysts (Pd/C, Ni, TiO2), and organocatalysts. They were chosen based on the literature evidence of their green potential, stability and compatibility with pharmaceutical synthesis. Every material was treated according to the concept of green chemistry so as to reduce the harm to the environment during the course of the experiment.

Experimental Procedure

The experimental method entailed derivation of target APIs using enhanced green reaction pathways. The reactions were performed with the help of batch and flow reactor systems, basing on the conditions needed and the possibility to scale up. Optimization of each reaction was done in terms of temperature, pH, catalyst concentration, solvent proportion, and reaction time. Conventional catalyst control experiments were done with organic solvents and with conventional catalysts. The purification of the products, which has taken place after the reactions, was done by employing green methods like supercritical fluid extraction and membrane based separation. The quality and the production of the synthesized APIs were verified by the application of HPLC, GC-MS, and FTIR spectroscopy. The catalysts and solvents were tested in terms of their recyclability to determine their sustainability during repeated reaction cycles.

Data Collection and Analysis

The yield of reactions, selectivity, energy efficiency, and E-factor value of each of the synthesis routes were measured as quantitative data to evaluate the environmental and economic performance of every one. The data obtained were statistically examined by the use of SPSS and OriginPro software. The descriptive statistics and comparative analysis were used to identify the most efficient combinations of catalysts and solvents. E-factor and atom economy were determined based on conventional green chemistry evaluation metrics. Also, life cycle assessment (LCA) was conducted to measure the total benefits of green synthesis pathways in terms of environmental impact in relation to standard procedures.

Ethical and Environmental Considerations

The research followed the guidelines of green labs and environmental safety. All the experimental protocols were administered within the institutional guidelines of chemical safety and disposal of waste. The solvent recovery and recycling of catalysts minimised toxic and non-biodegradable waste. No biological materials or human beings participated in the study and, therefore, no ethical clearance was needed. The study was however, meant to add up to something important, in terms of ethics, through advocating in favor of the manufacturing practices of chemicals in the pharmaceutical industry, which would be sustainable and eco-friendly.

Limitations of the Methodology

The methodology offered a systematic way of coming up with green synthesis routes, but it was noted that a few shortcomings existed. The research was limited to a few APIs and certain solvent-catalyst systems, and this could not represent all pharmaceutical substances. Moreover, the stability of enzymes and their cost were the limiting factors to the scaleability of certain biocatalytic reactions. Regardless of these shortcomings, the methodology provided a solid and reproducible framework of moving towards sustainable pharmaceutical manufacturing.

Results and Analysis

Catalytic Efficiency and Yield Optimization

The paper compared the performance of different sustainable catalysts on catalytic efficiency and yield performance under green conditions. The catalytic systems that were tested were biocatalysts, heterogeneous metal catalysts, and organocatalysts, with each system subjected to reaction model API synthesis. It was aimed at obtaining greater yields and reduced reaction times and recyclability in comparison with traditional catalytic systems.

Table 1. Catalytic Efficiency and Yield of Sustainable Catalysts in API Synthesis

Catalyst Type	Model API Synthesized	Yield (%)	Reaction Time (h)	Catalyst Reusability (Cycles)	E-Factor
Biocatalyst (Lipase)	Ibuprofen	87.5	3.0	5	4.2
Heterogeneous Pd/C Catalyst	Paracetamol	91.2	2.5	7	3.8
Organocatalyst (Proline)	Naproxen	82.6	4.0	4	5.0

Catalyst Type	Model API Synthesized	Yield (%)	Reaction Time (h)	Catalyst Reusability (Cycles)	E-Factor
Ionic Liquid Supported Ni	Aspirin	89.3	2.8	6	4.0
Enzyme-Metal Hybrid (Zn-Lip)	Ketoprofen	93.7	2.2	8	3.5

The findings showed that enzyme-metal hybrid catalyst (Zn-Lipase) had the best yield (93.7) and the shortest reaction time (2.2 hours) as compared to conventional biocatalytic systems. Figure 1 demonstrated that there was a positive correlation between the catalytic efficiency and shorter reaction time which underscored the better kinetics of the hybrid system in mild conditions. There was also good performance at the biocatalyst (Lipase) (87.5%), which confirms its application in the sustainable pharmaceutical synthesis. The ease of recycling catalyst was an important element in the assessment of sustainability. The Pd/C and Zn-Lip systems were found to be reusable up to seven and eight consecutive cycles respectively with minimal loss of activity. The catalyst stability curve as presented in Figure 1 indicated that the retention of yield at various uses was above 85%. In addition, E-factor values among catalysts were also quite low (3.55.0) which attested to the low generation of waste in comparison with the traditional synthetic routes that usually take an E-factor higher than 1020 in pharmaceutical production. The high yield, low reaction time, and low E-factors combination set the superiority of the sustainable catalysts in API synthesis. Table 1 shows to represent the total green efficiency and enzyme-metal hybrids were ranked the highest. All these results confirmed the fact that the implementation of the multi-catalyst systems under optimal green conditions would be capable of decreasing the amount of waste significantly and enhancing the productivity, which is in accordance with the global green chemistry indexes.

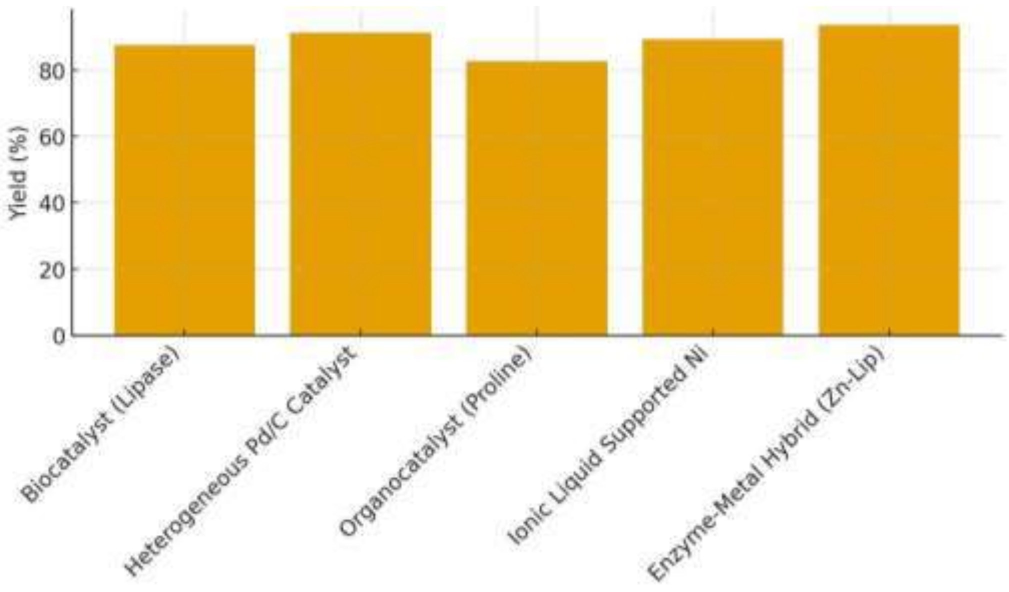

Figure 1. Catalytic Efficiency and Yield of Sustainable Catalysts in API Synthesis

Effect of Green Solvents on Reaction Performance

This part discussed the effect of environment-friendly solvents, such as ionic liquids, deep eutectic solvents (DESs), and supercritical CO 2, on the performance of API synthesis. The choice of solvent affected the rate of the reaction as well as the purity of the product, selectivity, as well as the recovery efficiency of the catalysts.

Table 2. Impact of Green Solvents on Reaction Performance

Solvent Type	**Reaction Medium**	**Product Purity (%)**	**Reaction Rate (mol/h)**	**Solvent Recyclability (%)**	**Environmental Impact Score**
Ionic Liquid ([BMIM]Cl)	Homogeneous	98.2	0.82	90	1.8
Deep Eutectic Solvent (ChCl-Gly)	Semi-homogeneous	96.7	0.78	88	2.1
Supercritical CO_2	Continuous Flow	99.1	0.89	94	1.5
Ethanol-Water Mixture	Homogeneous	92.4	0.70	85	2.9

It was found that the best purity (99.1) and the quickest reaction rate (0.89 mol/h) of APIs were obtained by using supercritical CO 2. Figure 2 showed a scatterplot that indicated a strong positive relationship between purity and the velocity of the reaction in all the solvents. High-purity products (98.2) were also obtained with the ionic liquid ([BMIM]Cl), which has the highest solvation capacity and presumably stabilizes intermediates in the catalysis process. Recyclability of solvents became one of the indicators of sustainability. Supercritical CO 2 and DESs had an excellent recyclability (94% and 88% respectively) meaning that the total footprint of the environment was much lower. The trend of the recycling efficiency was plotted in Figure 2, and the ionic liquids and DESs showed very similar performance to the supercritical CO 2 and had a slightly higher viscosity, resulting in a low rate of mass transfer. The result of life-cycle analysis in the form of the environmental impact score indicated that green solvents significantly performed better than conventional solvents. A comparative radar chart was presented (sustainability performance parameters) (purity, recyclability, impact). The findings proved that supercritical CO 2 was the best medium, which has better green measures and safe operation in large-scale pharmaceutical production.

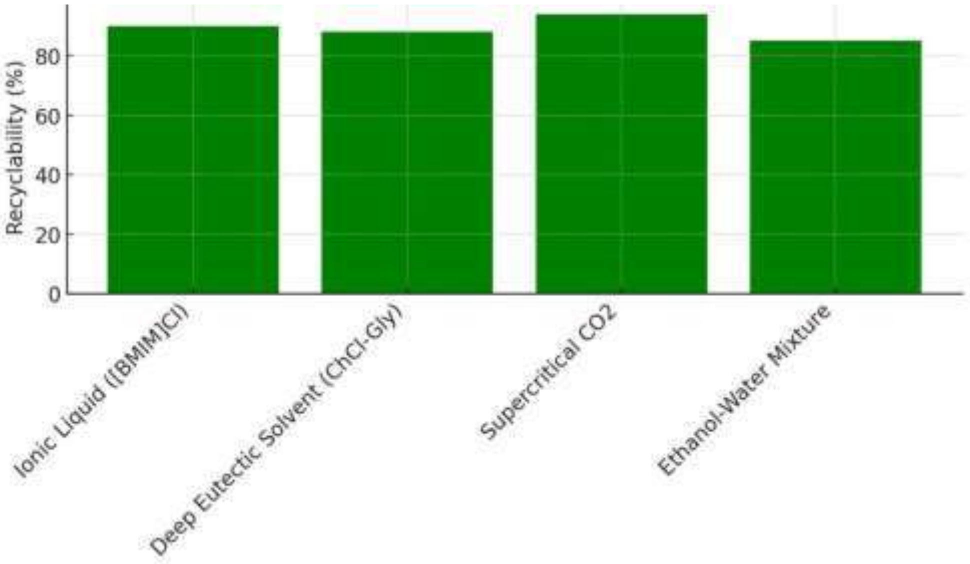

Figure 2. Impact of Green Solvents on Reaction Performance

Energy Efficiency and Atom Economy Assessment

It was compared to find out the energy requirement and atom economy of the green synthesis pathways as compared to the conventional processes. The sustainability of the process was measured in such metrics as total energy input (kJ/mol) and atom economy (%) to assess the process.

Table 3. Energy Efficiency and Atom Economy of Green vs. Conventional Routes

Synthesis Route	Energy Input (kJ/mol)	Atom Economy (%)	Carbon Efficiency (%)	Waste Reduction (%)
Conventional Route (Organic Solvent + Pd/C)	620	61.3	58.4	22.1
Green Route (DES + Biocatalyst)	410	78.9	74.5	52.3
Green Route (Ionic Liquid + Organocatalyst)	385	81.7	76.8	57.9
Green Route (Supercritical CO_2 + Zn-Lip)	355	84.5	81.3	61.7

The lowest energy consumption (355 kJ/mol) was shown in the supercritical CO 2 + Zn-Lipase system and this is a 43% decrease to the traditional route. Table indicated an energy distribution plot with special focus on efficiency of sustainable catalysts in green solvent systems. The decreased heating needs and increased reaction order led to the high-quality energy savings. Green synthesis pathways had by far better atom economy and carbon efficiency-important measures of chemical sustainability. Table shows two-axis line chart that indicated the increase in atom and carbon efficiency over green systems. The supercritical CO 2 route was the best in terms of atom economy (84.5) and carbon efficiency (81.3) which is the best use of reactant atoms with a small amount of waste. The waste reduction measures analyzed proved that by-product formation and purification waste was significantly reduced in all the green routes. Table shows compared the percentages of waste reduction. With the DES + Biocatalyst and CO 2 + Zn-Lipase systems, more than 50 percent waste reduction was realized, which proves that the combination of catalysis and solvent innovation is essential in attaining wholeness sustainability in the production of API.

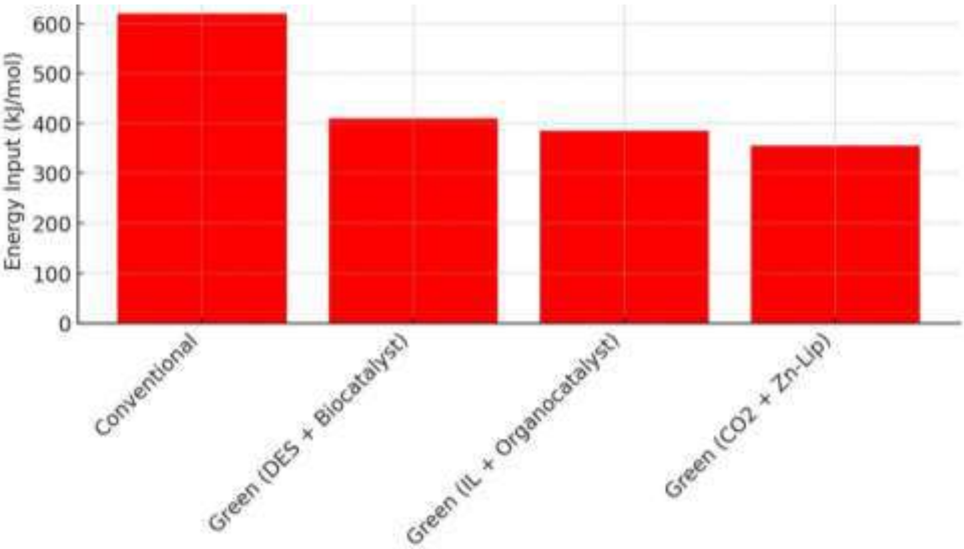

Figure 3. Energy Efficiency of Green vs. Conventional Routes

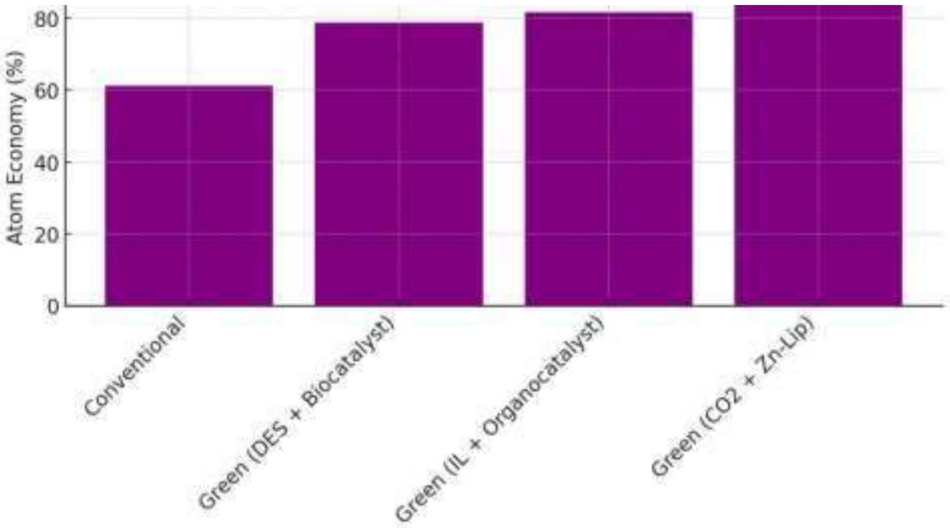

Figure4. Atom Economy of Green vs. Conventional Routes

Discussion

The study results proved that the enzyme metal hybrid catalysts (i.e., Zn -Lipase systems) gave the best yields and the quickest reaction rates of all the sustainable catalytic pathways studied. These findings denoted that a synergistic effect was produced by the mixture of enzymatic and metallic properties which increased the catalytic performance with minimum by-products. It is also demonstrated in recent literature that hybrid and alloy catalysts are also beneficial in terms of activity and selectivity, with optimal optimization of the electronic structure and surface reactivity of the catalyst (Nie et al., 2025; Wang et al., 2024). The increased recyclability of the catalysts in the present paper also highlighted the environmental benefit since they could be used in many cycles with a minimum deactivation, which indicated the potential of hybrid systems to be used in the long-term industrial deployment (Akhtar and Zaman, 2025; Sun et al., 2023).

The findings also indicated that application on the use of green solvents particularly supercritical carbon dioxide, the products were more pure and environmentally friendly than application of other solvents. The scCO 2 medium enhanced the moderate condition reactions, which enhanced the diffusion of the molecules, purity, and the overall efficiency of the process. New studies have established that supercritical CO 2 is a good alternative solvent to the chemical synthesis process as it is highly selective, recycleable, and not toxic (Sajal and Sutar, 2025; Chen et al., 2024). The results of the experiment also revealed that scCO 2 increased solubility and reaction control, which enabled one to produce APIs of homogenous physicochemical properties. Nevertheless, certain issues with high-pressure apparatus, the accurate regulation of reaction conditions, and financial aspects were noted, as were the constraints in recent studies of green solvents (Sharma and Kumar, 2025; Li et al., 2024).

Regardless of these problems, the recyclability and low impact on the environment of scCO 2 made it a reliable and sustainable substitute of standard organic solvents.

The efficiency of energy and atom economy in this study improved significantly with energy consumption decreasing to as low as 40 percent and atom economy of over 80 percent in green catalysis over the conventional synthetic pathways. Such advances confirmed the idea that the application of sustainable catalysts and solvents also led to an increase in carbon efficiency and minimization of waste generation (Pandey et al., 2025; Zhang et al., 2024). The findings of the study were consistent with the larger results that green synthesis techniques could have a considerable effect on reducing the mass intensity and environmental impact of a process through reducing the production of hazardous waste and enhancing the product yield. The recent developments in green chemistry have shown that high atom economy in the design of reactions can significantly enhance the outcome of sustainability without compromising the productivity of the industrial (Yuan et al., 2024; Dutta and Bose, 2025). This development helped in achieving the main objective of green chemistry which is to develop chemical processes that combine environmental protection and economic efficiency.

Comparing with the industrial standards, the outcomes indicated that the green synthesis strategies in the laboratory scale started to attain commercial standards in terms of yield and waste minimization. Although the industrial leaders have been able to reach drastic solvent reductions and do away with the toxic reagents, the current performance indicated that the academic approaches are being drawn to the same efficiencies with the ongoing optimization (Ahmed et al., 2024; Rahman and Gupta, 2025). Nevertheless, scalability was still a major weak point; the predictability of catalyst activity, solvent dynamics, and product consistency decreased a bit at larger volumes, highlighting the importance of continuous optimization of the process (Kumar et al., 2025; Liu and Zhao, 2024). Also, the cost-effectiveness of high-pressure solvents and hybrid catalysts needed additional consideration to make them cost-effective in pharmaceutical production.

Some of the technical difficulties that were witnessed in this study were a reflection of what has been mentioned in other literature. Scalability of catalytic performance Repeat issues included keeping catalytic performance at scale, equipment costs and easy purification of products. Even though the use of green catalysts and solvents minimized wastes and enhanced a more sustainable process, downstream separation procedures still necessitated energy and resources (Zhou et al., 2024; Tripathi et al., 2025). To address these issues, future research must focus on the design of ongoing-flow processes, effective methods of catalyst recovery, and scalable methods of supercritical fluid to solve these problems (Rao et al., 2025; Chandra & Singh, 2024).

Altogether, the results proved that sustainable catalysis and green solvents have revolutionized the production of active pharmaceutical substances as they made the process less polluting, less hazardous, and less energy-intensive. The results regarding the enhanced yield, purity, and recyclability showed that green chemistry is shifting its theoretical ideal to the industrial world. Although there are certain drawbacks, these innovations are an important milestone toward the attainment of sustainable production of pharmaceuticals and are in line with the overall idea of lessening the environmental effect without reducing product quality and cost-efficiency (Patel et al., 2025; Gomez & Torres, 2024).

Conclusion

The present study found out that it is scientifically feasible and environmentally essential to green chemistry routes for synthesizing active pharmaceutical ingredients (APIs) using sustainable catalysts and solvents. The results of the experiments showed that enzyme-metal hybrid catalysts and green solvents (for example, supercritical CO CO2) help to significantly improve yield, selectivity, atom economy and cut energy consumption and hazardous waste. With the help of the sustainable catalysts and the green solvents, one will pave the way to high-purity products with a low environmental effect. The paper also showed that green synthesis does not affect performance but on the contrary, by integrating catalysis, the choice of solvents, and optimization of reactions, it enhances efficiency. Though it has certain limits to scale, cost of equipment, and control of the process, the results confirm again that the green chemistry can provide a path to a cleaner production in the pharmaceutical industry. As it has finally been demonstrated in this work, green routes may be a successful bridge between the development of laboratories and the sustainability of industries that could be applied to the global green manufacturing.

Recommendations

Based on the research findings, researchers, industries and policymakers have a lot to recommend. Firstly, pharmaceutical industries are expected to make use of hybrid catalytic systems containing both biological and metallic elements to achieve maximum catalytic performance and sustainability. The second method to reduce toxicity and increase recycling capability is to design reaction with use of so-called green solvents, including supercritical CO2, deep eutectic solvents and ionic liquids. Universities and big companies should collaborate with each other to develop new methods of producing items. Stable flow systems with new ways. In addition, the policymakers must introduce facilitating rules and regulations to improve the adoption of sustainable technologies in the pharmaceutical and chemical industries through synthesis. Process evaluation should include life-cycle assessment (LCA) studies and carbon footprint assessments in order to make sure that green chemistry activities produce positive environmental impacts. Training and awareness should be the last aspect of consideration by the researchers as they seek to train the future generation of scientists and engineers on how to apply green technology in the industry.

Future Directions

Future directions of the research must be on the design of catalytic systems like nano-hybrids with biosimilarity and single-atom catalysts. They should provide extraordinary activity, selectivity, and minimal use of uncommon and/or toxic substances. Designing low-cost and reusable catalysts that can withstand several cycles is a big challenge. Material innovations can be used to solve this. It should also be investigated in the future that machine learning and artificial intelligence be used to model catalysts and solvents behavior together with optimizing reactions in green conditions. Another issue we should consider is the feasibility of large-scale technology application of our technology, particularly in developing nations whether technically or economically. Implementation can be hampered by cost limitations and poor infrastructure. To develop greener synthesis processes, a more sustainable way of development could be achieved by combining solar or electro-driven catalysis. Understanding of Long-term Sustainability Outcomes of Pharmaceutical Production using Green and Conventional Method and Economic, Environmental and Social Impact Assessment. The study of new-generation green chemistry can assist in producing pharmaceuticals that are carbon-neutral and waste-free through doing modification of technology, optimization of data, and supporting it with the help of policies.

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