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Development of Eco-Friendly Chemical Compounds For Catalytic and Environmental Remediation Studies

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Abstract: Environmental pollution and the extensive use of hazardous chemical processes have increased the need for sustainable and eco-friendly alternatives for industrial and environmental applications. This study employed green chemistry principles to generate environmentally friendly chemical compounds and evaluate them for catalytic and environmental remediation applications. Synthesis yield, solubility, heat stability, and pH stability were used to characterise four compounds (EC-1 to EC-4). Reaction efficiency, energy consumption, pollutant removal, and adsorption capacity were used to evaluate their catalytic performance and remediation efficiency. All compounds were successfully synthesised, according to the results, with EC-4 exhibiting the best overall performance, including better catalytic conversion, pollutant degradation, adsorption capacity, reduced energy consumption, and increased reusability. The results show that environmentally friendly chemical compounds can help pollution management and environmentally conscious industrial development by acting as sustainable solutions for catalytic applications and environmental rehabilitation.

Keywords: Eco-friendly chemical compounds; Green chemistry; Catalytic performance; Environmental remediation; Pollutant removal; Sustainable synthesis; Adsorption capacity.

Introduction - The production of sustainable and environmentally friendly chemical compounds is urgently needed due to the rising levels of environmental contamination and the overuse of dangerous synthetic chemicals. Toxic pollutants have been released into soil, water, and air ecosystems due in large part to industrialisation, urbanisation, and rapid technological growth. Conventional chemical processes frequently employ hazardous solvents, non-biodegradable materials, and energy-intensive techniques that have a negative impact on both human health and the environment. In this regard, green chemistry has become a significant scientific strategy that promotes sustainable chemical synthesis and uses while reducing environmental risks. Because of their potential to lower pollutants, improve catalytic efficiency, and aid in environmental remediation processes, the creation of environmentally friendly chemical compounds has attracted a lot of attention.

Low toxicity, biodegradability, high stability, and improved catalytic efficiency are characteristics of environmentally friendly chemical compounds. These substances are essential for catalytic applications because they minimise hazardous byproducts, reduce energy consumption, and speed up chemical reactions in mild settings. The synthesis of ecologically safe catalysts from natural materials, bio-based polymers, nanocomposites, and hybrid organic–inorganic systems has been the focus of research in recent years. These catalysts have shown exceptional effectiveness in the degradation of organic contaminants, heavy metal removal, dye degradation, and wastewater treatment. Additionally, by increasing the effectiveness of contaminant removal through adsorption, photocatalysis, oxidation, and reduction mechanisms, improved catalytic materials greatly aid in environmental cleanup.

In order to solve global ecological issues like air pollution, industrial waste buildup, and water contamination, environmental remediation studies have grown in significance. An inventive and long-lasting way to lessen environmental harm is to combine environmentally beneficial substances with catalytic technology. These substances lessen secondary contamination brought on by traditional remediation agents in addition to increasing cleanup efficiency. Therefore, the synthesis and characterisation of new green chemical compounds constitute a potential field of study with wide-ranging applications in industrial chemistry, pollution control technologies, and environmental sustainability.

The creation of environmentally friendly chemical compounds and their assessment for catalytic and environmental remediation applications are the main topics of this study. The study focuses on environmental

applications for pollutant degradation and effective remediation, characterisation methods, sustainable synthesis procedures, and catalytic performance evaluation.

Green Chemistry Approach in Environmental Remediation: Designing safer and more sustainable chemical processes is based on green chemistry principles. Green chemistry is used in environmental remediation through the use of recyclable catalysts, energy-efficient synthesis techniques, non-toxic solvents, and renewable raw materials. Green synthesis of eco-friendly catalytic chemicals has several benefits, such as lower environmental impact, increased operational safety, and cost-effectiveness. Furthermore, in contaminated areas, green catalysts help effectively degrade contaminants such heavy metals, pesticides, industrial colours, and pharmaceutical residues.

Eco-friendly substances are now even more effective in remediation investigations thanks to recent developments in material science and nanotechnology. Because of their greater surface area, adsorption capacity, and catalytic activity, nanostructured catalysts, biopolymer-based composites, and hybrid functional materials are excellent choices for environmental applications. Thus, long-term environmental protection and sustainable industrial development depend on the creation of sustainable catalytic materials that are in line with green chemistry principles.

Objectives of the Study:

1. To synthesize eco-friendly chemical compounds using sustainable and green chemistry approaches.
2. To characterize the synthesized compounds using suitable analytical and spectroscopic techniques.
3. To evaluate the catalytic efficiency of the developed compounds in selected chemical reactions.
4. To investigate the environmental remediation potential of the synthesized compounds for pollutant degradation and contaminant removal.

Review Of Literature

Younus et al. (2025)investigated the use of environmentally benign biocatalysts in environmental remediation applications, especially laccase enzymes. Their study emphasized the effectiveness of laccase-based catalytic systems in degrading environmental contaminants through sustainable biological processes. The authors talked about new developments in biocatalyst development and emphasised how they could lessen chemical toxicity and increase cleanup effectiveness. The review came to the conclusion that catalytic systems that are safe for the environment could be viable substitutes for traditional remediation techniques.

Hussain et al. (2025)gave a summary of environmentally friendly catalysts and their growing use in environmental and energy applications. The study concentrated on designing sustainable catalysts with the goal of reducing their negative effects on the environment while preserving their excellent catalytic performance. According to the scientists, green catalysts greatly increase reaction efficiency, lower energy consumption, and promote ecologically friendly industrial processes. Their results showed that catalyst innovation is becoming more crucial for attaining effective pollutant management and long-term environmental sustainability.

Alam et al. (2025)examined green ferrites, their environmentally benign synthesis techniques, and their uses in catalysis, antibacterial activity, and environmental remediation. The review emphasised the superior catalytic behaviour, improved stability, and efficient contaminant removal capabilities of ferrite-based materials produced using sustainable methods. The authors stressed that nanostructured green materials are appropriate for wastewater treatment and environmental protection applications because they have better surface characteristics and more adsorption capability.

Agarwal et al. (2022)examined bacterial laccases as environmentally friendly biocatalysts for the removal of harmful contaminants from the environment. Their analysis showed that biological catalysts reduce reliance on dangerous chemical treatments while offering an effective and sustainable method for pollutant breakdown. According to the study, bacterial laccases exhibit potent catalytic activity for the breakdown of dyes and the elimination of organic pollutants, promoting ecologically acceptable remediation procedures. The authors came to the conclusion that combining green chemistry concepts with biological catalysis can improve remediation effectiveness and support sustainable environmental management.

Materials And Methods: The goal of this research was to create environmentally friendly chemical compounds and assess how well they work in environmental remediation and catalytic applications. By using fewer dangerous chemicals, using less energy, and improving environmental compatibility, the methodology was created to adhere to sustainable and green chemistry principles. Through a number of steps, including synthesis, characterisation, catalytic assessment, remediation testing, and statistical analysis, a methodical experimental strategy was used to create and evaluate the generated chemicals. The methodological framework made it possible to thoroughly examine the synthesised compounds' physical characteristics, catalytic behaviour, and pollutant removal effectiveness in order to assess their appropriateness for environmentally friendly applications.

Research Design: The study adopted an experimental research design to synthesize eco-friendly chemical compounds and evaluate their catalytic and environmental remediation potential. Controlled laboratory experiments were conducted as part of the research process, and performance indicators were then compared. To enable systematic assessment and comparison, four compounds were created and designated as EC-1, EC-2, EC-3, and EC-4.

Materials Selection and Green Synthesis Procedure: Green chemistry concepts guided the selection of analytical-grade reagents and environmentally acceptable precursor materials. The synthesis procedure placed a strong emphasis on less toxicity, waste production, and resource efficiency.

The process of synthesis involved:

1. Selection of eco-friendly precursor materials
2. Controlled mixing under optimized conditions
3. Temperature and pH regulation during reaction
4. Separation and purification of synthesized compounds
5. Drying and preservation for further analysis

The synthesis yield was calculated using:

$$\text{ynthesis yield (\%)} = \frac{\text{Actual Product Obtained}}{\text{Theoretical product}} \times 100$$

The synthesized products were designated as EC-1, EC-2, EC-3, and EC-4.

Characterization of Synthesized Eco-Friendly Compounds: To assess the synthetic compounds' stability and physical characteristics, characterisation was carried out. Determining the compounds' suitability for catalytic and remedial applications was the main goal of the analysis.

Among the characterisation parameters were:

1. Synthesis yield (%)
2. Physical appearance and color
3. Water solubility
4. Thermal stability (°C)
5. pH stability range

Thermal stability testing was conducted under controlled heating conditions, while solubility and pH stability assessments were performed using standardized laboratory procedures.

Evaluation of Catalytic Performance: Through controlled operating circumstances and laboratory-based catalytic processes, the synthesised compounds' catalytic performance was evaluated. Determining the produced compounds' sustainability and efficiency was the goal.

Among the assessed catalytic parameters were:

1. Reaction time (minutes)
2. Catalytic conversion efficiency (%)
3. Energy consumption (kWh)
4. Catalyst reusability cycles

Catalytic conversion efficiency was calculated as:

$$\text{Catalytic conversion efficiency (\%)} = \frac{\text{Converted Product}}{\text{Initial Reactant}} \times 100$$

Energy consumption and catalyst reuse capability were recorded to determine operational sustainability.

Environmental Remediation Assessment: Pollutant removal tests were used to assess the synthesised chemicals' potential for environmental remediation. The efficacy of the compounds in lowering environmental pollutants was assessed.

Among the remedial indicators were:

1. Dye degradation efficiency (%)
2. Heavy metal removal efficiency (%)
3. Organic pollutant reduction (%)
4. Adsorption capacity (mg/g)

Removal efficiency was determined using:

$$\text{Removal Efficiency (\%)} = \frac{C_i - C_f}{C_i} \times 100$$

where:

C_i = Initial pollutant concentration

C_f = Final pollutant concentration

Adsorption capacity was used to evaluate the amount of pollutant removed by the synthesized compounds.

Data Analysis and Statistical Techniques: To compare the performance of the synthesised compounds, descriptive statistical methods were applied to the acquired experimental data. Finding the most effective molecule based on catalytic and remedial results was the main goal of the analysis.

Among the statistical metrics were:

1. Mean efficiency analysis
2. Standard deviation analysis
3. Comparative performance ranking
4. Trend and consistency evaluation

The final interpretation was performed to identify the optimum eco-friendly compound exhibiting maximum catalytic efficiency, environmental remediation capability, and operational stability.

Result And Discussion : The analysis of experimental findings from the synthesis, characterisation, catalytic assessment, and environmental remediation investigations of the created environmentally friendly chemical compounds is presented in this section. The investigation focuses on evaluating the synthesised compounds' efficacy in terms of catalytic performance, pollutant removal capacity, synthesis efficiency, and overall environmental application. To determine which molecule performed best for sustainable catalytic and remedial applications, a comparative analysis was carried out.

Table 1 (see in last page)

Table 1 displays the physical properties and synthesis yield of the created environmentally friendly chemical compounds (EC-1 to EC-4). The results show that all compounds were successfully synthesised with yields ranging from 79.8% to 91.4%, proving the efficacy of the chosen green synthesis method. EC-3 had the lowest yield (79.8%) of the synthesised compounds, while EC-4 had the greatest synthesis yield (91.4%), indicating better reaction efficiency and product production. Physical property research showed that the compounds varied in terms of colour, water solubility, thermal stability, and pH resistance. Because of their high water solubility, EC-2 and EC-4 are better suited for environmental applications. EC-4 also showed the widest pH stability range (3–10), indicating greater environmental adaptability and operational stability. Thermal stability gradually increased from 210°C in EC-1 to 255°C in EC-4, demonstrating improved structural strength.

Table 2 (see in last page)

Table 2 shows the eco-friendly chemicals' catalytic performance based on energy consumption, reusability cycles, catalytic conversion efficiency, and reaction time. The findings show that the catalytic activity of all the produced compounds gradually improved. Compared to the other compounds, EC-4 exhibited the quickest catalytic action and improved reaction kinetics, as seen by its 35-minute reaction time. Better catalytic efficacy was demonstrated by the rise in catalytic conversion efficiency from 84.2% in EC-1 to 95.3% in EC-4. Concurrently, energy usage dropped from 2.8 kWh to 1.9 kWh, demonstrating increased energy efficiency. According to reusability analysis, EC-4 continued to operate effectively over six cycles, demonstrating increased sustainability and durability. Overall, the results indicate that of all the synthesised compounds, EC-4 had the best catalytic performance.

Table 3 (see in last page)

Figure 1 (see in last page)

Table 3 evaluates dye degradation, heavy metal removal, organic pollutant reduction, and adsorption capability to show how effective the synthesised compounds are at environmental remediation. The findings demonstrate a steady improvement in remediation performance between EC-1 and EC-4. With the highest dye degradation efficiency (94.2%), EC-4 showed a remarkable ability to remove dye pollutants from contaminated systems. The efficacy of EC-4 in various remediation methods was confirmed by the fact that heavy metal removal efficiency reached 91.4% and organic pollutant reduction reached 92.6%. EC-4 recorded the highest value of 53.7 mg/g, indicating increased availability of active sites for pollution collection. Adsorption capacity also gradually increased. Overall, the results show that the produced environmentally friendly chemicals have a great deal of remediation potential, with EC-4 offering the best environmental treatment performance.

Table 4 (see in last page)

Figure 2 (see in last page)

Table 4 offers a statistical comparison of the produced compounds based on standard deviation, overall performance ranking, mean catalytic efficiency, and mean remediation efficiency. The findings show that from EC-1 to EC-4, catalytic and remediation results gradually improved. EC-4 demonstrated excellent overall performance in both application areas, achieving the greatest mean catalytic efficiency (95.3%) and mean remediation efficiency (92.7%). From 3.24 in EC-1 to 1.74 in EC-4, the standard deviation numbers gradually dropped, indicating better consistency and less variability in the experimental results. The compounds were evaluated from IV to I based on the combined efficiency and stability characteristics; EC-4 was ranked highest overall. These findings demonstrate that EC-4 is the most dependable and efficient environmentally friendly substance for catalytic and environmental remediation applications.

Conclusion: The present study successfully demonstrated the development and evaluation of eco-friendly chemical compounds for catalytic and environmental remediation applications using sustainable and green chemistry approaches. The synthesised compounds (EC-1 to EC-4) demonstrated good environmental compatibility, favourable physical properties, and satisfactory synthesis yields, demonstrating the efficacy of the chosen synthesis approach. The developed compounds' catalytic and remediation performance gradually improved, according to comparative analysis, with EC-4 continuously outperforming the others in terms of synthesis yield, thermal stability, catalytic conversion efficiency, pollutant removal capability, adsorption capacity, and operational reusability. The discovered compounds' practical usefulness and sustainability were further demonstrated by the decrease in reaction time and energy usage. The highest mean efficiency values and lowest standard deviation in the statistical evaluation further supported the consistency and dependability of EC-4. Overall, the results show that environmentally friendly chemical compounds have great potential for sustainable catalysis, pollution control, and environmental remediation and can be useful substitutes for traditional chemical systems. To further improve their industrial and ecological uses, future research may concentrate on sophisticated characterisation methods, large-scale implementation, and long-term environmental performance evaluation.

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Table 1. Synthesis Yield and Physical Characteristics of Eco-Friendly Chemical Compounds

Compound Code	Synthesis Yield (%)	Color	Solubility in Water	Thermal Stability (°C)	pH Stability Range
EC-1	82.5	Light Brown	Moderate	210	5–8
EC-2	86.3	Pale Yellow	High	225	4–9
EC-3	79.8	Dark Brown	Moderate	240	5–10
EC-4	91.4	Yellowish White	High	255	3–10

Table 2. Catalytic Performance of Synthesized Eco-Friendly Compounds

Compound Code	Reaction Time (min)	Catalytic Conversion Efficiency (%)	Energy Consum -ption (kWh)	Reusability Cycles
EC-1	48	84.2	2.8	4
EC-2	42	88.5	2.4	5
EC-3	39	91.7	2.2	5
EC-4	35	95.3	1.9	6

Table 3. Pollutant Removal Efficiency in Environmental Remediation Studies

Compound Code	Dye Degra-dation (%)	Heavy Metal Removal (%)	Organic Pollutant Reduction (%)	Adsorption Capacity (mg/g)
EC-1	78.4	72.1	75.6	36.2
EC-2	84.7	79.3	81.5	42.8
EC-3	89.5	85.6	87.2	47.3
EC-4	94.2	91.4	92.6	53.7

Figure 1:Pollutant Removal Efficiency in Environmental Remediation Studies

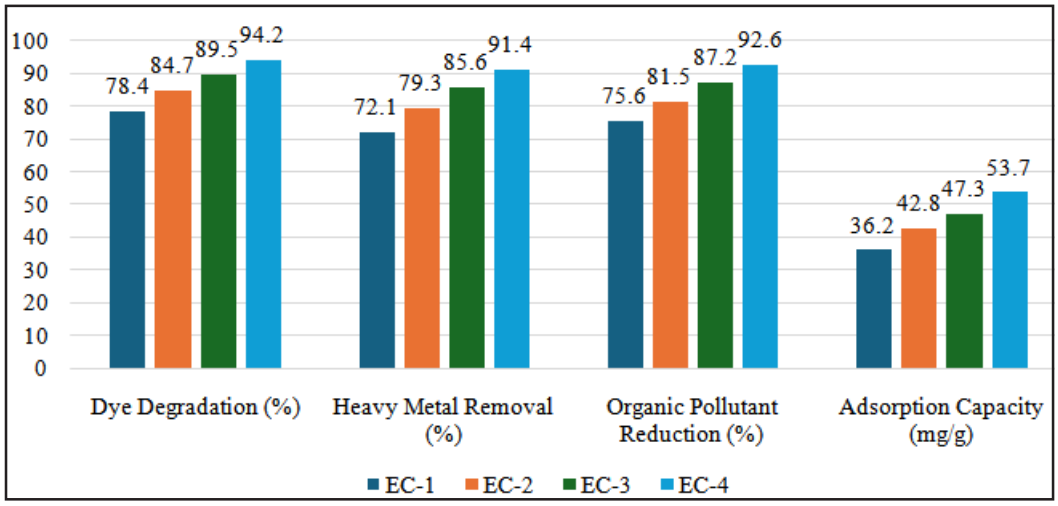
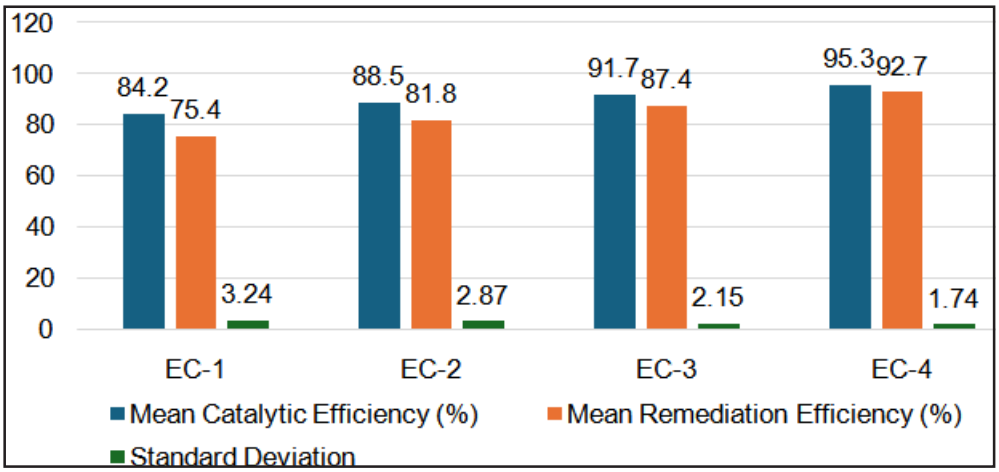


Table 4. Comparative Statistical Analysis of Catalytic and Remediation Efficiency

Parameter	EC-1	EC-2	EC-3	EC-4
Mean Catalytic Efficiency (%)	84.2	88.5	91.7	95.3
Mean Remediation Efficiency (%)	75.4	81.8	87.4	92.7
Standard Deviation	3.24	2.87	2.15	1.74
Overall Performance Rank	IV	III	II	I

Figure 2: Graphical Presentation ofComparative Statistical Analysis of Catalytic and Remediation Efficiency



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