

# GREEN SYNTHESIS OF FUNCTIONALIZED NANOCATALYSTS FROM INDIGENOUS BIOMASS FOR EFFICIENT DEGRADATION OF EMERGING PHARMACEUTICAL CONTAMINANTS IN PAKISTAN'S WASTEWATER SYSTEMS

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## Keywords

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## Abstract

The increasing prevalence of pharmaceutical contaminants in aquatic environments has emerged as a significant global environmental challenge, particularly in developing countries with limited wastewater treatment capacity. This study aimed to develop and evaluate green-synthesized functionalized nanocatalysts derived from indigenous biomass for the efficient degradation of emerging pharmaceutical pollutants in wastewater systems. A quantitative experimental design was employed, utilizing biomass sources such as rice husk, sugarcane bagasse, wheat straw, and citrus peels for nanocatalyst synthesis. Batch experiments were conducted to assess degradation efficiency under varying operational conditions. The results demonstrated that biomass-derived nanocatalysts achieved high degradation efficiencies, with citrus peel-based catalysts exhibiting the highest performance (up to 89.7%). Statistical analysis confirmed that biomass type, catalyst dosage, reaction time, and pH significantly influenced degradation efficiency ( $p < 0.05$ ). Compared to conventional wastewater treatment methods, green nanocatalysts showed superior efficiency, sustainability, and cost-effectiveness. The study concludes that indigenous biomass-based nanocatalysts provide a viable and eco-friendly solution for mitigating pharmaceutical pollution in wastewater systems. These findings support the integration of green nanotechnology into sustainable wastewater management strategies, particularly in resource-constrained settings such as Pakistan.

## INTRODUCTION

The rapid expansion of pharmaceutical production, population growth, and urbanization has led to a significant increase in the release of emerging contaminants into aquatic ecosystems.

Among these, pharmaceutical residues are considered one of the most persistent and biologically active pollutants due to their resistance to conventional wastewater treatment processes and their continuous introduction into

water bodies (Srivastava, 2024; Rocque et al., 2021). These contaminants, even at trace concentrations, pose serious ecological and human health risks, including endocrine disruption, antimicrobial resistance, and long-term toxicity in aquatic organisms (Xu et al., 2018; Semenza & Ebi, 2019).

In developing countries such as Pakistan, the situation is further exacerbated by inadequate wastewater treatment infrastructure, weak regulatory enforcement, and increasing discharge of untreated industrial and municipal effluents into freshwater systems. Consequently, pharmaceutical pollutants are increasingly detected in surface and groundwater resources, raising concerns about their cumulative environmental impact (Ahmad et al., 2024; Rasool et al., 2024). Traditional remediation techniques such as adsorption, chlorination, and biological degradation have shown limited efficiency in removing complex pharmaceutical compounds, particularly in mixed-contaminant environments (Chersich et al., 2020).

In recent years, nanotechnology-based remediation strategies have emerged as highly efficient alternatives for wastewater treatment. Nanocatalysts, due to their high surface area, tunable physicochemical properties, and enhanced reactivity, have demonstrated superior performance in degrading persistent organic pollutants (Basu & Ostro, 2008; Gasparrini et al., 2015). However, conventional nanoparticle synthesis methods often involve toxic chemicals and high energy consumption, raising concerns regarding secondary pollution and environmental sustainability.

To address these limitations, green synthesis approaches have gained significant attention. Green nanotechnology utilizes biological resources such as plant extracts, agricultural waste, and indigenous biomass to synthesize functionalized nanomaterials in an eco-friendly and cost-effective manner. These biomaterials act as reducing and stabilizing agents, enabling the formation of biocompatible nanocatalysts suitable for environmental applications (Malik et al., 2023; Shahzadi et al., 2025). Recent studies have highlighted the effectiveness of bio-based

nanocatalysts in degrading pharmaceutical pollutants through photocatalytic and adsorption mechanisms, offering a sustainable pathway for wastewater remediation (Quddus et al., 2023; Gaber et al., 2025).

Pakistan possesses abundant indigenous biomass resources, including agricultural residues such as rice husk, sugarcane bagasse, and fruit peels, which can be utilized for green synthesis of functional nanocatalysts. The valorization of these materials not only addresses waste management challenges but also contributes to the development of low-cost and scalable environmental technologies (Al-Gethami et al., 2024; Kumar et al., 2023).

Despite growing global research on green nanotechnology, there remains a significant research gap in the application of biomass-derived nanocatalysts for the degradation of pharmaceutical contaminants in Pakistan's wastewater systems. Limited studies have explored the integration of indigenous biomass with nanocatalytic systems under real environmental conditions. Therefore, there is a pressing need to develop efficient, sustainable, and locally adaptable green nanocatalysts for effective removal of pharmaceutical pollutants.

This study addresses this gap by investigating the green synthesis of functionalized nanocatalysts derived from indigenous biomass for the efficient degradation of emerging pharmaceutical contaminants in Pakistan's wastewater systems. The research contributes to advancing sustainable wastewater treatment technologies and supports the transition toward environmentally friendly nanoremediation strategies.

### Problem Statement

The increasing accumulation of pharmaceutical contaminants in aquatic environments has emerged as a critical global environmental and public health challenge. These emerging pollutants, including antibiotics, analgesics, hormones, and anti-inflammatory drugs, are continuously discharged into wastewater systems due to inefficient removal by conventional treatment technologies. In developing countries, particularly Pakistan, the situation is more severe due to rapid urbanization, inadequate wastewater

treatment infrastructure, weak environmental regulation, and unregulated pharmaceutical discharge into surface and groundwater systems. Conventional remediation techniques such as biological degradation, coagulation, and adsorption have demonstrated limited effectiveness in removing complex pharmaceutical compounds, especially those with high chemical stability and bioactivity. As a result, these contaminants persist in aquatic ecosystems, contributing to ecological toxicity, antimicrobial resistance, and long-term risks to human health. Although nanotechnology-based approaches have shown significant promise in degrading persistent organic pollutants, most conventional nanocatalyst synthesis methods rely on hazardous chemicals, high energy inputs, and non-renewable resources, which raise concerns regarding secondary pollution and sustainability. Moreover, their application in real wastewater systems in developing countries remains limited due to cost and environmental constraints.

In this context, green synthesis of nanocatalysts using indigenous biomass offers a sustainable and eco-friendly alternative. Pakistan possesses abundant agricultural residues such as rice husk, sugarcane bagasse, and fruit peels, which remain underutilized despite their potential as bio-reducing and stabilizing agents for nanomaterial synthesis. However, limited empirical research has explored the development and application of biomass-derived functionalized nanocatalysts for the degradation of pharmaceutical contaminants under real environmental conditions in Pakistan. Therefore, there exists a critical research gap in the development of cost-effective, sustainable, and high-efficiency green nanocatalysts derived from indigenous biomass for the treatment of pharmaceutical-contaminated wastewater. Addressing this gap is essential for advancing sustainable wastewater management technologies and mitigating emerging environmental health risks in Pakistan.

### Research Questions

1. What is the effectiveness of green-synthesized nanocatalysts derived from indigenous

biomass in degrading pharmaceutical contaminants in wastewater systems?

2. How do functionalized biomass-based nanocatalysts perform compared to conventional wastewater treatment methods in terms of degradation efficiency?

3. Which types of indigenous biomass materials are most effective for the green synthesis of nanocatalysts in Pakistan?

4. What are the key physicochemical mechanisms involved in the degradation of pharmaceutical contaminants using green nanocatalysts?

5. How can green nanocatalyst-based wastewater treatment systems be optimized for large-scale application in Pakistan?

### Research Objectives

#### General Objective

To develop and evaluate the efficiency of green-synthesized functionalized nanocatalysts derived from indigenous biomass for the degradation of emerging pharmaceutical contaminants in Pakistan's wastewater systems.

#### Specific Objectives

1. To synthesize functionalized nanocatalysts using selected indigenous biomass materials.

2. To characterize the structural, morphological, and chemical properties of the synthesized nanocatalysts.

3. To assess the degradation efficiency of nanocatalysts against selected pharmaceutical contaminants in wastewater.

4. To compare the performance of green-synthesized nanocatalysts with conventional wastewater treatment methods.

5. To analyze the underlying reaction mechanisms involved in the photocatalytic or catalytic degradation process.

6. To evaluate the feasibility of scaling up biomass-based nanocatalyst applications for wastewater treatment in Pakistan.

### Significance of the Study

This study is significant as it addresses one of the most pressing environmental and public health

challenges of the twenty-first century—the persistence of pharmaceutical contaminants in aquatic ecosystems—and proposes a sustainable, cost-effective, and locally adaptable solution through green nanotechnology. In developing countries such as Pakistan, where wastewater treatment infrastructure is limited and environmental regulations are weakly enforced, the continuous discharge of pharmaceutical residues into water bodies poses serious risks to ecological integrity and human health. This research contributes to filling a critical gap by developing green-synthesized nanocatalysts derived from indigenous biomass for efficient degradation of these emerging contaminants.

From an environmental science perspective, the study advances sustainable wastewater treatment technologies by introducing eco-friendly nanocatalysts that reduce reliance on hazardous chemical-based synthesis methods. The use of agricultural and biomass waste not only supports pollutant degradation but also promotes waste valorization, thereby contributing to circular economy principles and sustainable resource utilization.

From a scientific and technological perspective, the research contributes to the growing field of green nanotechnology by providing empirical insights into the synthesis, characterization, and catalytic efficiency of biomass-derived nanomaterials. It enhances understanding of the physicochemical mechanisms involved in the degradation of pharmaceutical pollutants and supports innovation in advanced oxidation and photocatalytic processes.

From a public health perspective, the study is highly relevant as pharmaceutical contaminants in water systems are associated with antimicrobial resistance, endocrine disruption, and chronic toxicity in humans. By improving the efficiency of wastewater purification, this research indirectly contributes to reducing exposure risks and improving overall environmental health outcomes.

From a policy and development perspective, the findings provide evidence-based support for integrating green nanotechnology into national wastewater management strategies. The study also

highlights the importance of utilizing locally available resources, such as agricultural biomass, to develop affordable and scalable environmental remediation technologies suitable for resource-constrained settings like Pakistan.

From a socioeconomic perspective, the proposed approach offers a low-cost and sustainable alternative to conventional treatment methods, potentially reducing infrastructure and operational costs while creating value-added uses for agricultural waste materials. This aligns with sustainable development goals, particularly those related to clean water and sanitation, responsible consumption and production, and climate action. Overall, this study is significant because it bridges environmental nanotechnology, waste valorization, and public health protection, offering a multidisciplinary framework for addressing pharmaceutical pollution in wastewater systems through sustainable innovation.

## Literature Review

### 1. Pharmaceutical Contaminants as Emerging Environmental Pollutants

The increasing presence of pharmaceutical contaminants in aquatic environments has emerged as a critical environmental and public health issue worldwide. Pharmaceuticals such as antibiotics, analgesics, antidepressants, and hormonal drugs are continuously introduced into water bodies through domestic wastewater, hospital effluents, pharmaceutical industries, and improper disposal practices. Due to their chemical stability and partial resistance to biodegradation, these compounds persist in aquatic ecosystems even after conventional wastewater treatment processes (Srivastava, 2024).

Numerous studies have shown that pharmaceutical residues, even at trace concentrations, can cause significant ecological disruptions, including endocrine system interference, toxicity in aquatic organisms, and the development of antimicrobial resistance (Xu et al., 2018; Rocque et al., 2021). The World Health Organization has also highlighted pharmaceutical pollution as an emerging global health threat due to its indirect impact on human health through

contaminated drinking water sources and food chains (WHO, 2023).

## 2. Limitations of Conventional Wastewater Treatment Technologies

Conventional wastewater treatment methods, including activated sludge processes, coagulation-flocculation, adsorption, and chlorination, have demonstrated limited efficiency in removing pharmaceutical contaminants. These methods are primarily designed for organic load reduction rather than micro-pollutant elimination, resulting in incomplete degradation and secondary pollutant formation in some cases (Chersich et al., 2020).

Moreover, advanced treatment technologies such as membrane filtration and ozonation, although more effective, are often associated with high operational costs, energy demands, and technical complexity, making them less feasible for developing countries like Pakistan. As a result, pharmaceutical contaminants continue to accumulate in receiving water bodies, posing long-term environmental risks (Rasool et al., 2024).

## 3. Nanotechnology-Based Wastewater Remediation

In recent years, nanotechnology has emerged as a promising solution for the removal of persistent organic pollutants, including pharmaceutical compounds. Nanomaterials, particularly metal and metal oxide nanoparticles, exhibit high surface area, enhanced reactivity, and catalytic efficiency, making them highly effective in adsorption and degradation processes (Basu & Ostro, 2008).

Nanocatalysts such as titanium dioxide (TiO<sub>2</sub>), zinc oxide (ZnO), and iron-based nanoparticles have demonstrated strong photocatalytic properties, enabling the breakdown of complex pharmaceutical molecules into less harmful by-products (Gasparrini et al., 2015). However, conventional nanoparticle synthesis methods often rely on toxic chemicals, high energy inputs, and non-renewable resources, which raise environmental sustainability concerns.

## 4. Green Synthesis of Nanocatalysts

To overcome the limitations of conventional synthesis methods, green nanotechnology has gained significant attention. Green synthesis involves the use of biological materials such as plant extracts, agricultural waste, microorganisms, and indigenous biomass as reducing and stabilizing agents for nanoparticle production. This approach is environmentally friendly, cost-effective, and scalable (Malik et al., 2023).

Recent studies have shown that bio-mediated nanocatalysts exhibit comparable or even superior catalytic efficiency compared to chemically synthesized nanoparticles. The presence of natural phytochemicals enhances stability and functionalization, improving pollutant degradation efficiency (Shahzadi et al., 2025). Additionally, green synthesis reduces secondary pollution risks, making it a sustainable alternative for environmental remediation.

## 5. Role of Indigenous Biomass in Nanocatalyst Development

Indigenous biomass such as rice husk, sugarcane bagasse, wheat straw, and fruit peels has been widely recognized as a valuable resource for sustainable nanomaterial synthesis. These agricultural wastes are rich in bioactive compounds, cellulose, lignin, and silica, which can act as natural reducing and capping agents in nanoparticle formation (Kumar et al., 2023).

In countries like Pakistan, where agriculture generates large volumes of biomass waste, these materials remain underutilized despite their potential for environmental applications. Recent research has demonstrated that biomass-derived nanocatalysts can effectively degrade organic pollutants through adsorption and photocatalytic mechanisms, offering a dual benefit of waste valorization and pollution control (Al-Gethami et al., 2024).

## 6. Mechanisms of Pharmaceutical Degradation Using Nanocatalysts

The degradation of pharmaceutical contaminants using nanocatalysts primarily occurs through advanced oxidation processes (AOPs), including photocatalysis, Fenton-like reactions, and reactive

oxygen species (ROS) generation. When exposed to light or chemical activators, nanocatalysts generate highly reactive radicals such as hydroxyl radicals ( $\bullet\text{OH}$ ) and superoxide radicals ( $\text{O}_2\bullet^-$ ), which break down complex pharmaceutical molecules into simpler, less toxic compounds (Quddus et al., 2023).

The efficiency of degradation depends on several factors, including catalyst surface area, particle size, pH, pollutant concentration, and reaction time. Functionalization of nanoparticles using biomass-derived compounds further enhances their catalytic activity and stability.

Despite significant advancements in nanotechnology-based wastewater treatment, there remains a substantial gap in the application of green-synthesized nanocatalysts derived from indigenous biomass in Pakistan. Most existing studies are laboratory-based, rely on non-local raw materials, or focus on single-pollutant systems rather than complex real wastewater conditions.

Furthermore, there is limited empirical research on the large-scale applicability, efficiency, and sustainability of biomass-derived nanocatalysts under real environmental conditions in developing countries. This highlights the urgent need for context-specific research that integrates local biomass resources with advanced nanotechnological approaches for effective pharmaceutical pollutant degradation.

The reviewed literature confirms that pharmaceutical contaminants represent a growing environmental challenge, while conventional treatment methods remain insufficient for their complete removal. Nanotechnology offers promising solutions; however, sustainability concerns necessitate a shift toward green synthesis approaches. Indigenous biomass presents a viable and underexplored resource for developing eco-friendly nanocatalysts. Therefore, further research is required to bridge the gap between green nanotechnology and real-world wastewater treatment applications in Pakistan.

### Underpinning Theory

#### Adsorption-Photocatalysis Coupled Reaction Theory

This study is underpinned by the Adsorption-Photocatalysis Coupled Reaction Theory, which explains the degradation of organic pollutants through a synergistic interaction between adsorption processes and photocatalytic reactions on nanocatalyst surfaces. This theory is widely applied in environmental nanotechnology to describe how nanomaterials facilitate the removal of persistent organic contaminants from aqueous systems.

The theory posits that pollutant degradation occurs in two interrelated stages. In the first stage, pharmaceutical contaminants are adsorbed onto the active surface sites of nanocatalysts due to high surface area, porosity, and surface functional groups. This adsorption step concentrates pollutants near reactive sites, enhancing contact efficiency and reaction probability.

In the second stage, under the influence of external energy sources such as light (UV or visible radiation), the nanocatalyst becomes photo-activated, generating electron-hole pairs. These charge carriers react with water and oxygen molecules to produce highly reactive oxygen species (ROS), including hydroxyl radicals ( $\bullet\text{OH}$ ) and superoxide radicals ( $\text{O}_2\bullet^-$ ). These reactive species are responsible for the oxidative breakdown of complex pharmaceutical molecules into simpler, non-toxic end products such as  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and inorganic ions.

Mathematically, the process can be simplified as:

$$\text{Pollutant degradation rate} \propto k_{\text{ads}} + k_{\text{photo}}$$

where ( $k_{\text{ads}}$ ) represents the adsorption rate constant and ( $k_{\text{photo}}$ ) represents the photocatalytic degradation rate constant.

In the context of this study, the theory is particularly relevant because green-synthesized nanocatalysts derived from indigenous biomass enhance both adsorption capacity and photocatalytic efficiency. Biomass-derived functional groups (such as hydroxyl, carboxyl, and phenolic compounds) improve surface reactivity, stability, and electron transfer efficiency, thereby accelerating degradation processes.

For Pakistan's wastewater systems, this theory provides a strong explanatory framework for understanding how sustainable nanocatalysts can simultaneously concentrate pharmaceutical pollutants and catalytically degrade them under environmental conditions. It also supports the development of low-cost, eco-friendly wastewater treatment strategies by integrating adsorption efficiency with photocatalytic oxidation mechanisms.

Overall, the Adsorption-Photocatalysis Coupled Reaction Theory offers a robust scientific foundation for this study, explaining both the mechanism and efficiency of green nanocatalyst-mediated degradation of pharmaceutical contaminants in aquatic environments.

### Hypotheses

**H1:** Green-synthesized nanocatalysts derived from indigenous biomass significantly enhance the degradation of pharmaceutical contaminants in wastewater.

**H2:** Functionalized biomass-based nanocatalysts show higher degradation efficiency of pharmaceutical pollutants compared to conventional wastewater treatment methods.

**H3:** The physicochemical properties of biomass-derived nanocatalysts significantly influence the rate of pharmaceutical contaminant degradation.

**H4:** Photocatalytic activity of green-synthesized nanocatalysts significantly improves the breakdown of pharmaceutical residues under light exposure.

**H5:** Reaction conditions (pH, catalyst dose, and contact time) significantly affect the efficiency of pharmaceutical contaminant degradation.

**H6:** Indigenous biomass type significantly influences the synthesis efficiency and catalytic performance of nanocatalysts.

### Methodology

#### Research Design

This study adopted a quantitative, experimental research design to evaluate the efficiency of green-synthesized functionalized nanocatalysts derived from indigenous biomass for the degradation of pharmaceutical contaminants in wastewater. The experimental approach was selected to establish

cause-and-effect relationships between nanocatalyst application and contaminant removal efficiency under controlled laboratory conditions.

#### Study Area and Setting

The study was conducted in laboratory settings of environmental and materials science research facilities in Pakistan. Wastewater samples were collected from selected urban drainage channels and municipal wastewater outlets representing pharmaceutical-contaminated effluents.

#### Population of the Study

The target population of the study comprised:

- Pharmaceutical-contaminated wastewater samples generated from municipal, hospital, and industrial discharge sources in Pakistan
- Indigenous biomass materials commonly available in Pakistan, including rice husk, sugarcane bagasse, wheat straw, and fruit peels
- Selected pharmaceutical contaminants frequently detected in wastewater systems, including antibiotics, analgesics, and anti-inflammatory drugs

#### Sample Size and Sampling Technique

A purposive sampling technique was used to select representative wastewater samples and biomass materials relevant to the study objectives.

The sample size included:

- 120 wastewater samples collected from different discharge points (municipal, hospital, and industrial effluents)
- 4 types of indigenous biomass materials (rice husk, sugarcane bagasse, wheat straw, and citrus peels)
- 10 commonly detected pharmaceutical contaminants used for degradation analysis (including antibiotics and analgesics)

Each experimental setup was replicated three times ( $n = 3$ ) to ensure reliability and reproducibility of results.

#### Synthesis of Nanocatalysts

Functionalized nanocatalysts were synthesized using a green synthesis approach, where aqueous extracts of indigenous biomass acted as reducing

and stabilizing agents. Metal precursors were introduced into the biomass extracts under controlled temperature and pH conditions, resulting in the formation of stable nanostructures without the use of toxic chemicals.

**Characterization of Nanocatalysts**

The synthesized nanocatalysts were characterized using standard analytical techniques:

- UV-Visible Spectroscopy for optical properties
- Scanning Electron Microscopy (SEM) for surface morphology
- X-ray Diffraction (XRD) for crystalline structure
- Fourier Transform Infrared Spectroscopy (FTIR) for functional group identification

**Experimental Procedure**

Batch experiments were conducted to evaluate the degradation efficiency of pharmaceutical contaminants. Wastewater samples were treated with varying doses of nanocatalysts under controlled conditions of pH, temperature, and reaction time. The influence of sunlight/UV exposure was also assessed to determine photocatalytic activity.

**Data Collection Tools**

**Data were collected using:**

- Spectrophotometric analysis for contaminant concentration reduction
- Chemical oxygen demand (COD) and biological oxygen demand (BOD) measurements
- Standard laboratory analytical instruments for pollutant quantification

**Data Analysis**

The collected data were analyzed using SPSS and OriginPro software. Descriptive statistics were used to summarize degradation efficiency, while inferential statistics (ANOVA and regression analysis) were applied to test the effect of nanocatalyst type, biomass source, and reaction conditions on degradation performance. A significance level of  $p < 0.05$  was applied throughout the analysis.

**Data Analysis**

The experimental data were analyzed using SPSS and OriginPro software. Descriptive statistics were used to evaluate degradation performance, while inferential statistics (one-way ANOVA and regression analysis) were applied to determine the effect of nanocatalyst type, biomass source, and reaction conditions on pharmaceutical degradation efficiency. Statistical significance was considered at  $p < 0.05$ .

**1. Characterization-Based Performance Overview**

**Table 1: Physicochemical Properties of Green-Synthesized Nanocatalysts**

Biomass Source	Particle Size (nm)	Surface Area (m <sup>2</sup> /g)	Functional Groups (FTIR Intensity)	Stability Index
Rice Husk	18.5	145.2	High	0.91
Sugarcane Bagasse	22.3	132.6	Moderate	0.87
Wheat Straw	25.1	118.4	Moderate	0.83
Citrus Peel Extract	16.8	158.7	Very High	0.94

The results indicate that nanocatalysts synthesized from citrus peel extract exhibited the smallest particle size and highest surface area, indicating superior catalytic potential. Higher FTIR intensity suggests the presence of abundant functional

groups, enhancing adsorption and reactivity. Overall, citrus peel-derived nanocatalysts demonstrated the highest structural stability and reactivity, making them most suitable for pollutant degradation.

2. Degradation Efficiency of Pharmaceutical Contaminants

Table 2: Overall Degradation Efficiency of Nanocatalysts

Biomass Source	Degradation Efficiency (%)	Reaction Time (min)	COD Reduction (%)
Rice Husk	82.4	90	76.3
Sugarcane Bagasse	78.6	90	71.8
Wheat Straw	74.2	90	68.5
Citrus Peel Extract	89.7	90	84.9

Citrus peel-based nanocatalysts achieved the highest degradation efficiency (89.7%), followed by rice husk (82.4%). Wheat straw showed comparatively lower performance. These findings

suggest that biochemical composition of biomass significantly influences catalytic activity, with citrus peel extracts providing stronger reducing and stabilizing capabilities.

3. Effect of Reaction Conditions on Degradation Efficiency

Table 3: Influence of Operational Parameters

Parameter	Condition Level	Degradation Efficiency (%)
pH	Acidic (5)	71.2
	Neutral (7)	86.5
	Basic (9)	79.8
Catalyst Dose	Low (0.5 g/L)	68.4
	Medium (1.0 g/L)	87.3
	High (1.5 g/L)	83.9
Contact Time	30 min	54.7
	60 min	78.2
	90 min	89.7

The highest degradation efficiency was observed under neutral pH conditions (pH 7), indicating optimal catalytic activity in near-neutral environments. Increasing catalyst dose improved

efficiency up to an optimal level (1.0 g/L), beyond which aggregation reduced effectiveness. Similarly, longer contact time significantly enhanced degradation, confirming that reaction kinetics are time-dependent.

4. Comparative Efficiency with Conventional Treatment Methods

Table 4: Performance Comparison of Treatment Techniques

Treatment Method	Degradation Efficiency (%)	Operational Cost	Environmental Impact
Conventional Biological Treatment	45.6	Low	Moderate
Chemical Oxidation	67.3	High	High
Adsorption (Activated Carbon)	72.8	Medium	Medium
Green Nanocatalysts (This Study)	89.7	Low	Low

Green-synthesized nanocatalysts significantly outperformed conventional treatment methods, achieving nearly 90% degradation efficiency,

compared to 45–73% for traditional techniques. Additionally, they offer lower environmental

impact and cost efficiency, making them a sustainable alternative for wastewater treatment.

### 5. Regression Analysis of Key Predictors

A multiple regression model was used to assess predictors of degradation efficiency.

- Biomass type ( $\beta = 0.42$ ,  $p < 0.01$ )
- Catalyst dose ( $\beta = 0.38$ ,  $p < 0.01$ )
- Reaction time ( $\beta = 0.45$ ,  $p < 0.001$ )
- pH level ( $\beta = 0.29$ ,  $p < 0.05$ )

Regression results confirm that reaction time and biomass type are the strongest predictors of pharmaceutical degradation efficiency. All variables showed statistically significant influence, validating the robustness of the green nanocatalyst system.

The analysis demonstrates that:

- Green nanocatalysts achieved high degradation efficiency (up to 89.7%)
- Biomass type significantly influenced catalytic performance
- Reaction conditions strongly affected degradation kinetics
- Green nanocatalysts outperformed conventional treatment methods

These findings confirm the effectiveness and sustainability of biomass-derived nanocatalysts for pharmaceutical wastewater remediation.

### Discussion

The findings of this study demonstrate that green-synthesized nanocatalysts derived from indigenous biomass exhibit high efficiency in the degradation of pharmaceutical contaminants in wastewater systems. The results revealed that citrus peel and rice husk-based nanocatalysts achieved the highest degradation performance, which can be attributed to their superior surface area, smaller particle size, and abundance of functional groups. These properties enhance adsorption capacity and catalytic reactivity, thereby accelerating the breakdown of complex pharmaceutical compounds.

The observed degradation efficiencies (up to 89.7%) confirm that biomass-derived nanocatalysts are highly effective compared to conventional wastewater treatment techniques such as biological treatment and adsorption. This

aligns with previous studies that have highlighted the limitations of traditional methods in removing micro-pollutants, particularly pharmaceuticals that are chemically stable and resistant to biodegradation. The enhanced performance of green nanocatalysts can be explained through the adsorption-photocatalysis coupled mechanism, where pollutants are first concentrated on the catalyst surface and subsequently degraded through reactive oxygen species generation.

Furthermore, the results indicate that operational parameters such as pH, catalyst dosage, and reaction time significantly influence degradation efficiency. Neutral pH conditions and optimal catalyst loading were found to maximize performance, while excessive catalyst concentration led to particle aggregation and reduced active surface availability. These findings highlight the importance of optimizing reaction conditions for large-scale applications.

Overall, the study confirms that indigenous biomass-based nanocatalysts provide a sustainable, efficient, and low-cost alternative for addressing pharmaceutical pollution in wastewater systems, particularly in resource-constrained countries like Pakistan.

### Conclusion

This study concludes that green-synthesized nanocatalysts derived from indigenous biomass are highly effective in degrading pharmaceutical contaminants in wastewater. Among the tested biomass sources, citrus peel and rice husk demonstrated the highest catalytic efficiency due to their favorable physicochemical properties. The study further confirms that reaction conditions and catalyst characteristics significantly influence degradation performance.

Importantly, the research establishes that green nanocatalysts outperform conventional wastewater treatment methods in terms of efficiency, sustainability, and environmental safety. Therefore, biomass-derived nanocatalysts represent a promising solution for addressing pharmaceutical pollution in aquatic environments.

### Implications of the Study

The findings of this study have several important theoretical, environmental, technological, and policy implications. Theoretically, the study contributes to the advancement of green nanotechnology by demonstrating the applicability of biomass-derived materials in environmental remediation processes. It strengthens the understanding of adsorption-photocatalysis mechanisms in pollutant degradation systems.

From an environmental perspective, the study provides a sustainable solution for mitigating pharmaceutical contamination in water bodies, thereby reducing ecological toxicity and risks associated with antimicrobial resistance and endocrine disruption.

Technologically, the research supports the development of cost-effective and scalable wastewater treatment systems based on locally available resources. The use of agricultural waste for nanocatalyst synthesis also promotes waste valorization and circular economy principles.

From a policy standpoint, the findings highlight the need for integrating green nanotechnology into national wastewater management strategies.

Policymakers can leverage these results to design environmentally sustainable and economically feasible water treatment frameworks, particularly in developing countries.

### Future Directions

Future research should focus on scaling up the application of biomass-derived nanocatalysts for industrial wastewater treatment under real environmental conditions. Long-term stability and reusability studies of nanocatalysts are also essential to evaluate their practical applicability.

Additionally, future studies should explore the integration of green nanocatalysts with hybrid treatment systems, such as membrane filtration and advanced oxidation processes, to enhance overall treatment efficiency. The application of computational modeling and artificial intelligence for optimizing catalyst design and reaction conditions also represents a promising research direction.

Further investigation into the toxicity and environmental fate of nanocatalysts after use is necessary to ensure their ecological safety and sustainability.

### Recommendations

Based on the findings, it is recommended that environmental agencies and wastewater management authorities adopt green nanotechnology-based treatment systems for pharmaceutical pollutant removal. Investment in research and development of biomass-derived nanocatalysts should be prioritized to support sustainable water treatment solutions.

It is also recommended that agricultural waste materials such as rice husk, sugarcane bagasse, and fruit peels be systematically utilized for environmental applications rather than being disposed of as waste. Public-private partnerships should be encouraged to scale up green nanotechnology solutions for industrial implementation.

Furthermore, regulatory frameworks should be strengthened to control pharmaceutical discharge into wastewater systems, thereby reducing environmental contamination at the source.

### Limitations of the Study

Despite its significant contributions, this study has certain limitations. First, the experiments were conducted under controlled laboratory conditions, which may not fully represent real-world wastewater environments with complex pollutant mixtures. Second, only a limited number of pharmaceutical compounds were tested, which may restrict the generalizability of the findings.

Third, long-term stability, reusability, and potential ecological toxicity of the synthesized nanocatalysts were not extensively evaluated. Additionally, the study did not incorporate large-scale field trials, which are necessary to assess industrial applicability.

Finally, variability in biomass composition due to seasonal and geographical differences may influence the reproducibility of nanocatalyst synthesis, which was not addressed in this study.

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