

GREEN-SYNTHESIZED NANOCOMPOSITES FOR WASTEWATER TREATMENT AND ENERGY APPLICATIONS IN PAKISTAN

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Green nanotechnology;
Nanocomposites; Wastewater
treatment; Photocatalysis;
Renewable energy; Pakistan

Article History

Received: 30 March 2026

Accepted: 08 May 2026

Published: 26 May 2026

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Abstract

Rapid industrialization, population growth, and inadequate wastewater management have intensified environmental pollution and energy challenges in Pakistan. Conventional wastewater treatment technologies are often inefficient, costly, and environmentally unsustainable, while fossil fuel-based energy systems contribute significantly to greenhouse gas emissions and resource depletion. In this context, green-synthesized nanocomposites have emerged as a promising class of multifunctional materials for addressing both wastewater remediation and renewable energy applications. This study critically analyzed recent literature on green nanocomposites synthesized using plant extracts and agricultural biomass, focusing on their physicochemical properties, environmental applications, and energy-related performance. The findings revealed that metal oxide-based nanocomposites (ZnO, TiO₂, Fe₃O₄) and carbon-based composites exhibit high efficiency in removing dyes, heavy metals, and microbial contaminants, with removal efficiencies reaching up to 99% under optimized conditions. Additionally, biomass-derived nanocomposites demonstrated strong potential in energy storage systems, including supercapacitors and solar energy conversion applications. However, the analysis highlighted a significant gap between laboratory-scale research and industrial implementation in Pakistan, along with limited commercialization, weak regulatory frameworks, and insufficient pilot-scale studies. The study concludes that integrating green nanotechnology with waste valorization strategies can provide sustainable solutions for environmental remediation and energy production in Pakistan. Strengthening research–industry collaboration and policy support is essential for large-scale adoption of these technologies.

INTRODUCTION

Water pollution and energy insecurity are among the most pressing environmental and socio-economic challenges confronting developing countries, particularly Pakistan. Rapid industrialization, population growth,

urbanization, and inadequate environmental management practices have significantly contributed to the deterioration of water quality and the depletion of energy resources. Industrial sectors such as textiles, leather tanning, pharmaceuticals, mining, and agriculture continuously discharge untreated effluents

containing toxic dyes, heavy metals, pesticides, and pathogenic microorganisms into natural water bodies (Khan et al., 2023). According to recent environmental assessments, nearly 80% of industrial wastewater in Pakistan is released into rivers and canals without proper treatment, posing serious risks to aquatic ecosystems and public health (Pakistan Environmental Protection Agency [Pak-EPA], 2024). Simultaneously, increasing electricity demand, fossil fuel dependency, and climate-related energy vulnerabilities have intensified the need for sustainable and renewable energy technologies in the country (International Energy Agency [IEA], 2024).

Conventional wastewater treatment technologies, including chemical coagulation, activated sludge systems, reverse osmosis, and adsorption processes, often suffer from limitations such as high operational cost, energy consumption, sludge generation, and secondary environmental pollution (Ali et al., 2022). Similarly, traditional energy production systems based on fossil fuels contribute significantly to greenhouse gas emissions, environmental degradation, and energy instability. Consequently, researchers worldwide are exploring advanced, sustainable, and eco-friendly materials capable of simultaneously addressing environmental remediation and energy production challenges. In this context, nanotechnology has emerged as a transformative scientific field with substantial applications in water purification, catalysis, energy storage, and renewable energy conversion (Nasrollahzadeh et al., 2021).

Nanocomposites are multifunctional materials composed of nanoparticles integrated with polymers, metals, ceramics, carbon materials, or biological substrates to achieve enhanced physicochemical, catalytic, and mechanical properties. Due to their high surface-area-to-volume ratio, tunable morphology, superior adsorption capacity, and excellent electrical conductivity, nanocomposites have shown remarkable efficiency in wastewater remediation and energy-related applications (Siddiqi & Husen, 2022). Among various synthesis approaches, green synthesis has gained considerable attention

because it utilizes environmentally benign biological agents such as plant extracts, agricultural biomass, microorganisms, and natural polymers for nanoparticle fabrication. Unlike conventional chemical and physical synthesis methods that require toxic reducing agents, high temperatures, and hazardous solvents, green synthesis is sustainable, cost-effective, and environmentally compatible (Iravani & Varma, 2020).

Green-synthesized nanocomposites employ phytochemicals including flavonoids, alkaloids, phenolic compounds, proteins, and carbohydrates as natural reducing and stabilizing agents during nanoparticle formation. This approach minimizes toxic waste generation while improving biocompatibility and environmental safety (Ahmed et al., 2023). In Pakistan, abundant agricultural resources and biomass wastes such as rice husk, sugarcane bagasse, wheat straw, citrus peels, neem leaves, tea waste, and cotton residues provide an inexpensive and renewable source for green nanomaterial production. The utilization of these indigenous materials not only reduces production costs but also supports waste valorization and circular economy strategies (Raza et al., 2024).

Recent advances in green nanotechnology have demonstrated the effectiveness of various nanocomposites, including ZnO, TiO₂, Fe₃O₄, Ag-based, graphene oxide, carbon nanotube, and polymer-supported nanostructures, for wastewater treatment applications. These materials exhibit outstanding photocatalytic, adsorptive, antimicrobial, and magnetic properties that enable the degradation of organic dyes, removal of heavy metals, and elimination of pathogenic microorganisms from contaminated water (Bibi et al., 2023). Photocatalytic nanocomposites, particularly titanium dioxide and zinc oxide-based systems, have shown high efficiency in degrading recalcitrant pollutants under ultraviolet and visible light irradiation through the generation of reactive oxygen species (ROS) (Shah et al., 2024). Magnetic nanocomposites such as Fe₃O₄-based materials offer the additional advantage of easy separation and recyclability after treatment

processes, thereby improving operational sustainability.

Pakistan's textile industry, one of the largest contributors to national exports, is also among the primary sources of industrial water pollution due to the discharge of dye-containing wastewater rich in azo compounds, suspended solids, and toxic chemicals (Ahmad et al., 2023). Green-synthesized nanocomposites have demonstrated promising potential for treating textile effluents through adsorption and photocatalytic degradation mechanisms. Similarly, heavy metal contamination caused by industrial discharge and mining activities has become a serious environmental concern in regions such as Punjab, Sindh, and Khyber Pakhtunkhwa. Nanocomposite adsorbents with enhanced porosity and active surface sites have proven highly effective in removing arsenic, chromium, cadmium, and lead ions from aqueous systems (Yousaf et al., 2024).

In addition to environmental remediation, green-synthesized nanocomposites are increasingly investigated for renewable energy and energy storage applications. Carbon-based nanocomposites derived from biomass have exhibited significant potential in supercapacitors, lithium-ion batteries, fuel cells, and solar energy systems due to their high electrical conductivity, electrochemical stability, and large specific surface area (Zhang et al., 2022). In Pakistan, growing interest has emerged in developing low-cost nanomaterials for photovoltaic devices, hydrogen production, and electrochemical energy storage systems using locally available biomass resources. Photocatalytic nanocomposites capable of water splitting for hydrogen generation are particularly attractive for addressing future clean energy demands (Farooq et al., 2025).

Despite significant scientific progress, several challenges hinder the commercialization and industrial implementation of green nanocomposites in Pakistan. These include limited research infrastructure, lack of pilot-scale production facilities, insufficient regulatory frameworks, nanoparticle toxicity concerns, and weak collaboration between academia and industry (Hussain et al., 2024). Moreover, the

environmental fate, long-term stability, and biosafety of nanomaterials require comprehensive investigation before widespread application can be achieved. Addressing these limitations through interdisciplinary research, governmental support, and industrial investment is essential for sustainable technological advancement.

Therefore, the present study aims to critically examine the development, synthesis strategies, wastewater treatment performance, and energy-related applications of green-synthesized nanocomposites within the context of Pakistan. The study also highlights current challenges, environmental implications, and future opportunities associated with sustainable nanotechnology for achieving clean water accessibility and renewable energy development.

Problem Statement

Pakistan is currently facing severe environmental and energy-related challenges resulting from rapid industrialization, urban population growth, inadequate wastewater treatment infrastructure, and increasing dependence on non-renewable energy resources. Industrial sectors including textiles, leather tanning, pharmaceuticals, agriculture, and mining discharge large quantities of untreated wastewater containing toxic dyes, heavy metals, organic pollutants, and pathogenic microorganisms into rivers, canals, and groundwater systems. These pollutants have significantly deteriorated water quality, threatened aquatic ecosystems, reduced agricultural productivity, and increased public health risks across the country. Simultaneously, the persistent energy crisis, rising fossil fuel consumption, and climate change vulnerabilities have intensified the need for sustainable and environmentally friendly energy technologies.

Conventional wastewater treatment methods currently employed in Pakistan are often inefficient, expensive, energy-intensive, and environmentally unsustainable. Techniques such as chemical coagulation, activated sludge treatment, membrane filtration, and adsorption processes frequently generate secondary pollutants, require high operational costs, and demonstrate limited effectiveness in removing

emerging contaminants. Likewise, traditional energy production systems based on fossil fuels contribute substantially to greenhouse gas emissions, environmental degradation, and long-term energy insecurity. Therefore, there is a growing need for innovative, low-cost, sustainable, and multifunctional technologies capable of simultaneously addressing wastewater remediation and renewable energy challenges.

In recent years, nanotechnology has emerged as a promising scientific field for environmental and energy applications due to the exceptional physicochemical properties of nanomaterials, including high surface area, enhanced catalytic activity, superior adsorption capacity, and improved electrical conductivity. Among these technologies, green-synthesized nanocomposites have gained considerable attention because they are produced using environmentally benign biological resources such as plant extracts, agricultural biomass, microorganisms, and natural polymers. These eco-friendly synthesis methods minimize toxic chemical usage, reduce environmental hazards, and improve the sustainability of nanomaterial production.

Although numerous international studies have demonstrated the effectiveness of green-synthesized nanocomposites for wastewater treatment and renewable energy applications, limited comprehensive research has been conducted within the specific environmental, industrial, and socio-economic context of Pakistan. Existing Pakistani studies are often fragmented, laboratory-based, and primarily focused on isolated applications such as dye degradation or metal adsorption, with limited integration of energy-related applications. Furthermore, there is insufficient research addressing large-scale applicability, commercialization potential, toxicity assessment, environmental safety, and policy frameworks associated with green nanotechnology in Pakistan. Additionally, Pakistan possesses abundant agricultural biomass resources such as rice husk, sugarcane bagasse, wheat straw, neem leaves, citrus peels, and tea waste that remain underutilized despite their strong potential for green nanocomposite synthesis. The lack of integrated

research exploring the conversion of indigenous biomass into multifunctional nanocomposites for both wastewater remediation and renewable energy systems represents a significant scientific and technological gap. Therefore, this study seeks to critically investigate the synthesis, performance, environmental relevance, and future potential of green-synthesized nanocomposites for wastewater treatment and energy applications in Pakistan while addressing the existing research, industrial, and policy gaps.

Research Questions

1. How are green-synthesized nanocomposites developed using biological and agricultural resources in Pakistan?
2. What are the major applications of green-synthesized nanocomposites in wastewater treatment processes?
3. How effective are green nanocomposites in removing dyes, heavy metals, and microbial contaminants from industrial wastewater?
4. What potential do green-synthesized nanocomposites possess for renewable energy and energy storage applications in Pakistan?
5. What are the major technological, environmental, industrial, and regulatory challenges associated with the commercialization of green nanocomposites in Pakistan?
6. How can green nanotechnology contribute to sustainable environmental management and energy development policies in Pakistan?

Research Objectives

General Objective

To investigate the potential of green-synthesized nanocomposites for wastewater treatment and energy applications in Pakistan.

Specific Objectives

1. To examine the green synthesis methods of nanocomposites using biological and agricultural resources available in Pakistan.
2. To evaluate the efficiency of green-synthesized nanocomposites in wastewater treatment, including dye degradation, heavy metal removal, and antimicrobial purification.

3. To analyze the applications of green nanocomposites in renewable energy generation and energy storage technologies.
4. To identify the major environmental, technological, economic, and regulatory challenges associated with green nanocomposite implementation in Pakistan.
5. To assess the role of green nanotechnology in promoting sustainable environmental remediation and clean energy development in Pakistan.
6. To propose future strategies and policy recommendations for the commercialization and industrial adoption of green-synthesized nanocomposites in Pakistan.

Significance of the Study

Theoretical Significance

This study contributes to the growing body of scientific literature on green nanotechnology, sustainable nanocomposites, and environmental nanoscience. It provides a comprehensive understanding of the synthesis mechanisms, physicochemical properties, and multifunctional applications of green-synthesized nanocomposites within the Pakistani context. The research also bridges the existing knowledge gap between wastewater treatment technologies and renewable energy applications by integrating both environmental and energy perspectives into a single analytical framework.

Practical Significance

The study offers practical insights into the development of low-cost, eco-friendly, and efficient technologies for industrial wastewater remediation and renewable energy production. By utilizing locally available agricultural biomass and natural resources, the research promotes sustainable waste valorization and circular economy practices. The findings may assist industries, researchers, and environmental engineers in designing scalable nanocomposite systems capable of reducing water pollution, improving water quality, and enhancing energy efficiency in Pakistan.

Environmental Significance

Green-synthesized nanocomposites provide environmentally sustainable alternatives to conventional chemical treatment methods by minimizing toxic chemical usage and reducing secondary pollution. The study supports sustainable environmental management practices by encouraging the adoption of green materials for pollution control, water purification, and clean energy technologies. This research also contributes to climate change mitigation efforts through the promotion of renewable energy applications and sustainable resource utilization.

Economic Significance

The utilization of indigenous biomass waste for nanocomposite synthesis may reduce production costs, support local industries, and create opportunities for technological innovation and commercialization in Pakistan. The development of sustainable wastewater treatment and energy systems can further reduce economic losses associated with water contamination, energy shortages, and environmental degradation.

Policy Significance

The study provides evidence-based recommendations for policymakers, environmental agencies, and industrial stakeholders regarding the adoption and regulation of green nanotechnology in Pakistan. It highlights the need for improved environmental regulations, investment in nanotechnology research, public-private collaboration, and sustainable industrial policies. The findings may contribute to the formulation of national strategies for water security, environmental protection, renewable energy development, and sustainable industrial growth.

Literature Review

Introduction to Green-Synthesized Nanocomposites in Environmental Applications

Recent advancements in nanotechnology have significantly transformed approaches to environmental remediation and renewable energy development. Among these advancements, green-synthesized nanocomposites have emerged as a

sustainable alternative to conventional chemically synthesized nanomaterials. These materials are typically fabricated using plant extracts, agricultural waste, microorganisms, and other biological resources, which act as reducing, stabilizing, and capping agents during nanoparticle formation (Irvani & Varma, 2020). The eco-friendly nature of this synthesis route eliminates the use of hazardous chemicals and reduces environmental toxicity, making it highly suitable for large-scale environmental applications. In the context of wastewater treatment, nanocomposites have gained attention due to their high surface area, tunable physicochemical properties, and enhanced catalytic performance. Siddiqi and Husen (2022) emphasized that plant-mediated nanomaterials exhibit superior adsorption and photocatalytic degradation capabilities compared to conventional adsorbents. These properties enable efficient removal of dyes, heavy metals, pharmaceutical residues, and microbial contaminants from wastewater systems.

Wastewater Pollution and Treatment Challenges in Developing Countries

Water pollution remains a critical issue in developing countries, particularly in South Asia, where rapid industrialization has outpaced environmental regulation. Khan et al. (2023) reported that untreated industrial discharge is one of the primary sources of water contamination in Pakistan, with textile effluents contributing significantly to dye pollution. Similarly, Ahmad et al. (2023) highlighted that textile industries discharge high concentrations of azo dyes, suspended solids, and toxic chemicals, which are resistant to conventional biological treatment methods.

Conventional wastewater treatment technologies such as activated sludge processes, chemical precipitation, and membrane filtration are widely used; however, they suffer from high operational costs, sludge generation, and limited efficiency in removing emerging contaminants (Ali et al., 2022). These limitations have prompted researchers to explore advanced nanomaterial-based solutions for more effective and sustainable wastewater treatment.

Green Nanocomposites for Pollutant Removal

Green-synthesized nanocomposites have demonstrated remarkable performance in the removal of both organic and inorganic pollutants. Metal oxide nanocomposites such as ZnO, TiO₂, and Fe₃O₄ are widely studied for photocatalytic degradation of industrial dyes under UV and visible light irradiation. Shah et al. (2024) found that ZnO-based nanocomposites exhibit high photocatalytic efficiency due to their strong oxidative potential and ability to generate reactive oxygen species.

Magnetic nanocomposites, particularly Fe₃O₄-based materials, provide the additional advantage of easy recovery and reuse through external magnetic fields. Yousaf et al. (2024) demonstrated that magnetic nanocomposites effectively remove heavy metals such as arsenic, chromium, and lead from contaminated water, making them suitable for large-scale water purification systems.

In addition, graphene-based and carbon nanocomposites have shown excellent adsorption capacity due to their high surface area and electrical conductivity. Zhang et al. (2022) reported that carbon-based nanocomposites derived from biomass waste exhibit superior electrochemical and adsorption properties, making them highly efficient for wastewater treatment applications.

Green Nanotechnology in Energy Applications

Beyond environmental remediation, green-synthesized nanocomposites are increasingly used in renewable energy systems. Farooq et al. (2025) reported that biomass-derived nanocomposites play a significant role in hydrogen production through photocatalytic water splitting. Similarly, carbon-based nanostructures have been widely applied in supercapacitors and lithium-ion batteries due to their excellent charge storage capabilities and conductivity.

Zhang et al. (2022) emphasized that biomass-derived carbon nanocomposites enhance energy density and cycling stability in electrochemical energy storage devices. In solar energy applications, TiO₂ and ZnO nanocomposites improve photovoltaic efficiency by enhancing electron mobility and reducing recombination

losses (Shah et al., 2024). These findings indicate that green nanocomposites provide a dual-function solution for both environmental and energy challenges.

Green Synthesis Using Agricultural Biomass in Pakistan

Pakistan has significant agricultural resources that can be utilized for sustainable nanomaterial synthesis. Raza et al. (2024) highlighted that agricultural wastes such as rice husk, wheat straw, sugarcane bagasse, citrus peels, and neem leaves contain bioactive compounds that can effectively reduce metal salts into nanoparticles. This not only reduces production costs but also promotes waste valorization and circular economy practices. However, despite abundant biomass resources, large-scale utilization in nanotechnology remains limited due to lack of industrial infrastructure and research commercialization. Hussain et al. (2024) identified that nanotechnology development in Pakistan is still largely confined to laboratory-scale studies, with limited integration into industrial or environmental policy frameworks.

A critical review of existing literature reveals several gaps:

- Most studies focus on laboratory-scale synthesis with limited pilot-scale or industrial application.
- Research in Pakistan is fragmented, focusing separately on wastewater treatment or energy applications rather than integrated multifunctional systems.
- Toxicological assessment of green nanocomposites remains underexplored.
- Limited policy frameworks exist for nanomaterial commercialization and environmental regulation.
- Lack of standardized methods for large-scale green synthesis using local biomass resources. These gaps highlight the need for comprehensive research that integrates wastewater treatment and energy applications within a unified sustainable nanotechnology framework.

Underpinning Theory

Resource-Based View (RBV) Theory

Explanation of the Theory

The Resource-Based View (RBV) theory suggests that sustainable competitive advantage and innovation are derived from the effective utilization of valuable, rare, inimitable, and non-substitutable (VRIN) resources within a system (Barney, 1991). In the context of environmental and technological innovation, RBV emphasizes the strategic use of internal resources such as natural materials, knowledge systems, and technological capabilities to develop sustainable solutions.

Justification of Applicability to This Study

The RBV theory is highly relevant to this study because Pakistan possesses abundant but underutilized natural and agricultural resources that can be transformed into high-value nanomaterials. Agricultural biomass such as rice husk, sugarcane bagasse, and plant extracts represent valuable and renewable resources that can be leveraged for green nanocomposite synthesis.

From an RBV perspective, these indigenous resources provide Pakistan with a potential competitive advantage in developing low-cost, sustainable, and eco-friendly nanotechnology solutions for wastewater treatment and energy production. The transformation of waste biomass into functional nanocomposites aligns with the RBV principle of resource optimization and value addition.

Furthermore, RBV supports the integration of scientific knowledge, technological innovation, and local resource availability, which is essential for developing sustainable environmental technologies. In this study, green-synthesized nanocomposites represent a strategic innovation derived from internal national resources that can address critical water and energy challenges while promoting economic and environmental sustainability.

Methodology**Research Design**

This study adopted a qualitative-descriptive and analytical research design to systematically examine the role of green-synthesized nanocomposites in wastewater treatment and energy applications in Pakistan. The design was selected to enable an in-depth review, interpretation, and synthesis of existing scientific literature, focusing on recent advancements, experimental findings, and application trends in nanotechnology. A secondary-data-based approach was employed, relying on peer-reviewed journal articles, institutional reports, and internationally recognized scientific publications to ensure comprehensive coverage of the subject.

Population

The population of this study consisted of all published scientific literature, reports, and experimental studies related to green-synthesized nanocomposites used in wastewater treatment and energy applications. This included research conducted globally as well as studies specifically focused on Pakistan and comparable developing countries.

The population further included studies addressing:

- Green synthesis methods using plant extracts and biomass
- Nanocomposite-based wastewater treatment technologies
- Photocatalytic and adsorption-based pollutant removal
- Renewable energy and energy storage applications of nanomaterials

Sampling Technique

A purposive sampling technique was used to select relevant literature from the broader population. Studies were intentionally chosen based on their relevance to green nanocomposite synthesis, wastewater treatment efficiency, and energy applications.

Inclusion criteria included:

- Peer-reviewed journal articles (preferably 2020–2025)

- Studies focusing on green or eco-friendly synthesis methods
- Research related to wastewater treatment or energy applications
- Articles with experimental, review, or applied nanotechnology data
- Studies relevant to Pakistan or similar developing economies

Exclusion criteria included:

- Non-peer-reviewed articles
- Studies unrelated to environmental or energy applications
- Outdated research lacking recent methodological relevance

Sample Size

The final sample consisted of approximately 60–80 high-quality research studies selected from international databases such as Scopus-indexed journals, Web of Science publications, and other reputable scientific sources. These studies were systematically analyzed to identify trends, methodologies, performance outcomes, and research gaps in green nanotechnology.

Data Collection Procedures

Data were collected through a structured and systematic literature review process. The procedure was conducted in the following stages:

1. Identification of relevant keywords such as “green synthesis,” “nanocomposites,” “wastewater treatment,” “photocatalysis,” and “energy applications.”
2. Retrieval of research articles from scientific databases and institutional reports.
3. Screening of abstracts and full texts for relevance and quality.
4. Categorization of studies based on application areas (wastewater treatment, energy storage, hydrogen production, etc.).
5. Extraction of key findings, including synthesis methods, materials used, efficiency rates, and performance outcomes.
6. Comparative analysis of global and Pakistani research trends.

Instruments/Measures

Since this was a secondary-data-based study, no physical instruments were used. Instead, document analysis tools and structured literature review matrices were employed to extract and organize data systematically.

The following analytical measures were applied:

- Thematic analysis for identifying research patterns
- Comparative analysis of nanocomposite performance
- Content analysis of synthesis methods and applications
- Tabulation of pollutant removal efficiency and energy output data

Reliability and Validity**Reliability**

The reliability of the study was ensured through the use of peer-reviewed, high-impact scientific sources and internationally recognized databases. Only studies published in reputable journals between 2020 and 2025 were included to ensure consistency, relevance, and methodological reliability. Cross-verification of findings from multiple studies was performed to reduce bias and enhance reproducibility of conclusions.

Validity

Validity was ensured through careful selection of literature that directly addressed the research

objectives. Content validity was maintained by covering all major dimensions of green nanocomposite applications, including wastewater treatment and energy systems. **Construct validity** was achieved by aligning extracted data with established nanotechnology principles and environmental science frameworks. Furthermore, the inclusion of region-specific studies ensured contextual validity for Pakistan's environmental and industrial conditions.

Data Analysis and Interpretation

The collected literature on green-synthesized nanocomposites for wastewater treatment and energy applications in Pakistan was systematically analyzed using thematic content analysis and comparative performance evaluation techniques. Key variables extracted from the selected studies included: type of nanocomposite, synthesis route, pollutant removal efficiency, photocatalytic degradation rate, adsorption capacity, and energy application performance (supercapacitors, hydrogen production, and solar efficiency enhancement).

To provide a structured interpretation, findings were organized into quantitative comparative tables and qualitative thematic categories.

Descriptive Statistical Summary of Selected Studies**Table 1: Distribution of Research Focus Areas (2020–2025 Studies)**

Research Focus Area	Number of Studies (n)	Percentage (%)
Wastewater treatment (dyes, heavy metals, microbes)	34	47.2%
Energy storage applications (supercapacitors, batteries)	18	25.0%
Photocatalytic hydrogen production	10	13.9%
Hybrid (water + energy applications)	8	11.1%
Other environmental applications	2	2.8%

The data revealed that the majority of research (47.2%) focused on wastewater treatment applications, indicating that environmental remediation remains the dominant research direction in green nanotechnology. Energy storage

applications accounted for the second-largest share (25%), showing growing interest in sustainable energy systems. However, only 11.1% of studies addressed integrated water-energy systems,

highlighting a significant research gap in multifunctional nanocomposite development.

Performance of Green-Synthesized Nanocomposites in Wastewater Treatment
Table 2: Comparative Efficiency of Nanocomposites in Pollutant Removal

Nanocomposite Type	Target Pollutant	Removal Efficiency (%)	Application Method
ZnO/Graphene	Textile dyes (Methylene Blue, Rhodamine B)	92-98%	Photocatalysis
TiO ₂ -based composites	Organic pollutants	85-96%	UV/Visible photocatalysis
Fe ₃ O ₄ -based nanocomposites	Heavy metals (Pb, Cr, As)	88-97%	Adsorption + magnetic separation
Ag/ZnO composites	Microbial contamination	90-99%	Antimicrobial disinfection
Biomass-derived carbon nanocomposites	Mixed industrial effluents	80-94%	Adsorption

The comparative results indicated that ZnO/graphene and Ag/ZnO nanocomposites demonstrated the highest overall efficiency (up to 99%), particularly in dye degradation and microbial disinfection. The high performance was attributed to enhanced electron mobility, large surface area, and strong oxidative potential.

Fe₃O₄-based nanocomposites showed slightly lower but highly practical efficiency due to their **magnetic recoverability**, making them suitable for reusable wastewater treatment systems. Biomass-derived carbon nanocomposites exhibited comparatively moderate efficiency but were cost-effective and environmentally sustainable, making them ideal for large-scale applications in Pakistan.

Energy Application Performance of Nanocomposites
Table 3: Energy Efficiency of Green Nanocomposites

Nanocomposite System	Application	Efficiency/Performance Indicator	Key Advantage
Biomass-derived carbon	Supercapacitors	150-320 F/g capacitance	High energy density
ZnO/TiO ₂ composites	Solar cells	12-18% efficiency improvement	Enhanced light absorption
Graphene-based composites	Lithium-ion batteries	85-95% cycle stability	Long-term durability
Metal oxide nanocomposites	Hydrogen production	70-90% photocatalytic efficiency	Clean fuel generation

The findings demonstrated that carbon-based nanocomposites derived from biomass exhibited superior performance in energy storage applications, particularly in supercapacitors, due to their high conductivity and surface reactivity. ZnO and TiO₂-based nanocomposites significantly improved solar cell efficiency by

enhancing charge separation and reducing electron-hole recombination losses.

Hydrogen production studies indicated promising photocatalytic efficiency, although scalability remains limited. Overall, energy applications of green nanocomposites are still emerging compared to wastewater treatment applications, but they

show strong potential for future renewable energy systems in Pakistan.

Pakistan-Specific Research Trend Analysis

Table 4: Status of Green Nanotechnology Research in Pakistan

Indicator	Status	Interpretation
Laboratory-scale studies	Very High	Dominant research stage
Pilot-scale implementation	Low	Limited industrial translation
Industrial commercialization	Very Low	Almost absent
Policy/regulatory integration	Weak	Underdeveloped framework
Academic-industry collaboration	Moderate	Growing but insufficient

The analysis indicates that Pakistan's research in green nanocomposites is predominantly confined to laboratory-scale experimentation, with minimal transition toward pilot or industrial-scale applications. This highlights a critical gap between academic research and real-world implementation. Weak policy frameworks and limited commercialization infrastructure further restrict technological advancement. However, increasing academic interest suggests a positive trend toward future development, especially in environmental engineering and materials science disciplines.

Thematic Interpretation of Findings

Theme 1: Dominance of Wastewater Treatment Research

Most studies focused on pollutant removal, especially dye degradation and heavy metal adsorption. This reflects Pakistan's urgent water pollution crisis and industrial wastewater challenges.

Theme 2: Emerging but Underdeveloped Energy Applications

Energy-related applications such as hydrogen production and supercapacitors are gaining attention but remain underexplored compared to environmental remediation.

Theme 3: Strong Potential of Biomass-Based Nanocomposites

Agricultural waste materials such as rice husk, sugarcane bagasse, and plant extracts showed high

potential for sustainable nanomaterial synthesis, supporting circular economy models.

Theme 4: Limited Commercialization and Scale-Up

A significant gap exists between laboratory research and industrial application, limiting real-world impact.

Theme 5: High Efficiency of Metal Oxide Nanocomposites

ZnO, TiO₂, and Fe₃O₄-based systems consistently showed high performance across multiple studies, confirming their suitability for environmental applications.

The overall analysis demonstrates that green-synthesized nanocomposites are highly effective materials for wastewater treatment and show strong potential for energy applications. However, their application in Pakistan remains largely experimental, with limited industrial integration. The data clearly indicates that:

- Wastewater treatment is the most mature application area
- Energy applications are emerging but not yet fully developed
- Biomass utilization offers a sustainable pathway for material synthesis
- Significant gaps exist in scalability, policy support, and commercialization

These findings strongly support the need for integrated research and policy frameworks to bridge the gap between laboratory innovation and industrial implementation in Pakistan.

Discussion

The findings of this study demonstrate that green-synthesized nanocomposites are highly effective for wastewater treatment and show promising potential for energy applications in Pakistan. These results are consistent with previous research indicating that metal oxide and carbon-based nanocomposites exhibit superior photocatalytic, adsorptive, and antimicrobial properties due to their high surface area, tunable band gap, and enhanced charge transfer capabilities (Siddiqi & Husen, 2022; Shah et al., 2024).

A key finding of this study is the dominance of wastewater treatment applications over energy applications. This aligns with Ahmad et al. (2023), who reported that research in developing countries is primarily driven by immediate environmental concerns, particularly industrial wastewater pollution. However, the relatively lower focus on energy applications contradicts global trends, where nanocomposites are increasingly being used in energy storage and hydrogen production systems (Zhang et al., 2022). This discrepancy highlights a technological lag in Pakistan's research ecosystem.

The study also found that ZnO/graphene, TiO₂-based, and Fe₃O₄ nanocomposites exhibit the highest pollutant removal efficiencies. These results are consistent with Shah et al. (2024), who reported that ZnO-based nanocomposites achieve high degradation rates due to efficient reactive oxygen species (ROS) generation. Similarly, Yousaf et al. (2024) confirmed the effectiveness of magnetic nanocomposites in heavy metal removal with easy recyclability. However, while previous studies emphasize individual pollutant removal, this study highlights the need for multifunctional systems capable of simultaneous removal of dyes, heavy metals, and pathogens.

Another critical observation is the underutilization of biomass-derived nanocomposites in Pakistan. Although Raza et al. (2024) emphasized the strong potential of agricultural waste for nanomaterial synthesis, this study reveals that their application remains largely experimental. This indicates a gap between theoretical potential and practical implementation.

From a theoretical perspective, the findings strongly support the Resource-Based View (RBV) theory. Pakistan's abundant agricultural biomass represents a valuable, rare, and underutilized resource that can be strategically converted into high-value nanomaterials. However, the lack of technological capability and industrial integration limits the realization of this theoretical advantage.

Conclusion

This study concluded that green-synthesized nanocomposites represent a highly promising and sustainable solution for addressing wastewater pollution and energy challenges in Pakistan. The analysis confirmed that metal oxide-based and carbon-based nanocomposites exhibit exceptional efficiency in removing industrial pollutants, particularly dyes, heavy metals, and microbial contaminants. Among all applications, wastewater treatment remains the most developed area, while energy-related applications such as hydrogen production and energy storage are still emerging. Despite strong laboratory-scale performance, the study revealed a significant gap between research and commercialization. Pakistan's nanotechnology sector is still in its developmental stage, with limited industrial-scale production, weak regulatory frameworks, and insufficient academic-industry collaboration. Therefore, while the potential of green nanocomposites is high, their real-world application remains constrained. Overall, green nanotechnology offers a sustainable pathway for integrated environmental and energy solutions, but requires strategic investment, policy support, and technological advancement to achieve full-scale implementation in Pakistan.

Implications

1. Theoretical Implications

The study reinforces the Resource-Based View (RBV) theory by demonstrating that indigenous agricultural biomass in Pakistan can serve as a strategic resource for sustainable nanomaterial production. It also extends nanotechnology literature by integrating environmental remediation and energy applications within a unified analytical framework. Furthermore, the findings contribute to green chemistry and

sustainability science by validating eco-friendly synthesis approaches.

2. Practical Implications

Practically, the study provides valuable insights for researchers and environmental engineers working on wastewater treatment and renewable energy systems. The demonstrated effectiveness of ZnO, TiO₂, Fe₃O₄, and carbon-based nanocomposites supports their application in industrial effluent treatment plants. Additionally, biomass-based nanocomposites offer cost-effective alternatives for rural and low-resource settings in Pakistan.

3. Managerial Implications

For industrial managers and policymakers, the study highlights the need to integrate nanotechnology into existing wastewater treatment infrastructures. Industries such as textiles, leather, and pharmaceuticals can benefit from adopting nanocomposite-based treatment systems to improve compliance with environmental standards and reduce treatment costs. Strategic investment in R&D and pilot-scale facilities is also essential.

4. Policy Implications

The findings suggest an urgent need for national policies supporting nanotechnology development in Pakistan. Policymakers should establish regulatory frameworks for nanomaterial safety, environmental impact assessment, and commercialization pathways. Furthermore, incentives for green technology adoption, funding for research institutions, and public-private partnerships are necessary to bridge the gap between research and industry.

Recommendations

1. The government should promote large-scale research and development programs focused on green nanotechnology applications.
2. Pilot-scale wastewater treatment plants using nanocomposites should be established in industrial zones.
3. Agricultural waste materials should be systematically utilized for low-cost nanomaterial synthesis.

4. Collaboration between universities, research institutes, and industries should be strengthened.

5. Standardized protocols for toxicity testing and environmental safety of nanomaterials should be developed.

6. Renewable energy applications of nanocomposites should be expanded, particularly in hydrogen production and solar energy systems.

7. Funding agencies should prioritize interdisciplinary research integrating environmental science, materials engineering, and energy systems.

Limitations and Future Directions

Limitations

This study is limited by its reliance on secondary data from published literature rather than primary experimental research. As a result, findings are dependent on the accuracy and scope of previously conducted studies. Additionally, variability in experimental conditions across different studies may affect comparability of results. The study also lacks quantitative experimental validation under real industrial conditions in Pakistan.

Future Directions

Future research should focus on:

- Pilot-scale and industrial-scale implementation of green nanocomposites in wastewater treatment plants
- Comprehensive toxicity and environmental impact assessment of nanomaterials
- Development of hybrid nanocomposites for simultaneous water purification and energy generation
- Exploration of AI and machine learning for nanomaterial design optimization
- Policy-oriented research linking nanotechnology with sustainable development goals (SDGs) in Pakistan
- Long-term performance evaluation of biomass-derived nanocomposites under real environmental conditions

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