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GREEN NANOTECHNOLOGY AND METABOLOMIC APPROACHES FOR ENVIRONMENTAL REMEDIATION AND DISEASE BIOMARKER DISCOVERY IN PAKISTAN

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Abstract
Environmental pollution and the rising prevalence of chronic diseases constitute significant challenges to sustainable development and public health in Pakistan. Emerging advances in green nanotechnology and metabolomics offer innovative opportunities to address these interconnected environmental and healthcare issues. This study investigated the integrated role of green nanotechnology and metabolomic approaches in environmental remediation and disease biomarker discovery in Pakistan. A quantitative research design was employed, and data were collected from 400 professionals, including environmental scientists, nanotechnology researchers, biomedical experts, healthcare practitioners, and environmental protection officers. Structural Equation Modeling (SEM) was used to examine the relationships among green nanotechnology, environmental remediation, metabolomic profiling, disease biomarker discovery, and environmental-health outcomes. The findings revealed that green nanotechnology significantly enhanced environmental remediation through effective pollutant removal and contamination reduction. Metabolomic profiling was found to be a strong predictor of disease biomarker discovery, facilitating early diagnosis and precision medicine applications. Furthermore, the integration of green nanotechnology and metabolomics significantly improved environmental and health outcomes by reducing pollutant exposure and enabling more accurate disease detection. The study contributes to the interdisciplinary literature on environmental biotechnology, metabolomics, and sustainable healthcare by proposing an integrated framework that simultaneously addresses ecological and public health challenges. The findings offer valuable implications for researchers, healthcare professionals, environmental agencies, and policymakers seeking sustainable and technology-driven solutions for environmental management and disease prevention in Pakistan.

INTRODUCTION

Environmental degradation and the increasing burden of chronic and infectious diseases have emerged as critical challenges for sustainable development worldwide, particularly in developing countries such as Pakistan. Rapid industrialization, urban expansion, agricultural intensification, and inadequate waste

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management practices have significantly contributed to environmental contamination through heavy metals, pesticides, pharmaceutical residues, and other emerging pollutants (Kumar et al., 2023). Simultaneously, Pakistan faces a growing prevalence of non-communicable diseases, including cancer, cardiovascular disorders, diabetes, respiratory illnesses, and metabolic syndromes, which place substantial pressure on the healthcare system (World Health Organization [WHO], 2024).

Conventional environmental remediation technologies often involve high operational costs, energy-intensive processes, and the generation of secondary pollutants. Consequently, researchers have increasingly focused on sustainable and environmentally friendly alternatives capable of mitigating pollution while minimizing ecological impacts. Green nanotechnology has emerged as a promising interdisciplinary field that integrates nanoscience with environmentally sustainable principles to develop eco-friendly nanomaterials and remediation technologies (Rai et al., 2023). Unlike conventional nanoparticle synthesis methods that frequently rely on toxic chemicals and hazardous reagents, green nanotechnology utilizes biological resources such as plants, algae, fungi, and microorganisms for nanoparticle production, thereby reducing environmental toxicity and enhancing biocompatibility.

Green-synthesized nanoparticles possess unique physicochemical properties, including high surface area, catalytic efficiency, adsorption capacity, and antimicrobial activity, making them highly effective for environmental remediation applications. Numerous studies have demonstrated the potential of green nanoparticles in removing heavy metals, degrading organic pollutants, eliminating pathogenic microorganisms, and restoring contaminated water and soil ecosystems (Sharma et al., 2024). In Pakistan, environmental pollution resulting from industrial effluents, mining activities, textile manufacturing, agricultural runoff, and urban waste has intensified concerns regarding ecological sustainability and public health. Consequently, green nanotechnology offers a viable pathway toward sustainable environmental management and pollution control.

Alongside environmental challenges, advancements in biomedical sciences have highlighted the importance of metabolomics in disease diagnosis and precision medicine. Metabolomics is the comprehensive study of low-molecular-weight metabolites within biological systems and provides valuable insights into physiological, pathological, and biochemical processes (Nicholson et al., 2022). Through advanced analytical platforms such as mass spectrometry (MS) and nuclear magnetic resonance (NMR) spectroscopy, metabolomics enables the identification of disease-specific metabolic signatures that can serve as biomarkers for early diagnosis, prognosis, and therapeutic monitoring.

Recent developments in metabolomic technologies have significantly enhanced biomarker discovery across various disease domains. Metabolic profiling has been successfully applied to cancer diagnostics, cardiovascular disease prediction, diabetes management, neurodegenerative disorders, infectious diseases, and inflammatory conditions (Wishart, 2023). The identification of reliable biomarkers facilitates early disease detection, personalized treatment strategies, and improved patient outcomes. In resource-constrained healthcare systems such as Pakistan, metabolomics offers considerable potential for strengthening diagnostic accuracy and supporting precision healthcare initiatives.

The integration of green nanotechnology and metabolomics represents an emerging frontier in environmental and biomedical research. Environmental pollutants frequently induce metabolic alterations in human populations through prolonged exposure, contributing to disease development and progression. Green nanotechnology can effectively reduce environmental contamination, while metabolomic approaches can simultaneously monitor biological responses to environmental exposures and identify disease-associated biomarkers (Verma et al., 2024). This integrated framework provides a comprehensive strategy for addressing environmental and health challenges through sustainable and data-driven scientific approaches.

Globally, researchers have increasingly explored nanotechnology-enabled biosensors, nano-enabled metabolite detection systems, and environmentally responsive diagnostic platforms. Nanomaterials have demonstrated remarkable capabilities in enhancing metabolomic analyses by improving sensitivity, selectivity, and analytical precision. The convergence of these technologies has accelerated biomarker discovery and expanded opportunities for environmental health surveillance (Zhou et al., 2023). Nevertheless, empirical evidence regarding their combined application remains limited in developing countries, particularly within the Pakistani context.

Pakistan presents a unique setting for investigating the integration of green nanotechnology and metabolomics due to its dual burden of environmental pollution and rising disease prevalence. Industrial hubs, agricultural regions, and densely populated urban centers continue to experience substantial environmental contamination, while healthcare institutions face increasing demands for accurate and cost-effective diagnostic solutions. Despite growing interest in nanotechnology and omics sciences, limited research has examined their synergistic potential for environmental remediation and disease biomarker discovery in Pakistan.

Therefore, the present study seeks to explore the role of green nanotechnology and metabolomic approaches in promoting environmental sustainability and advancing disease diagnostics. By integrating environmentally friendly nanomaterials with advanced metabolomic profiling techniques, the study contributes to emerging scientific knowledge and provides a multidisciplinary framework for addressing critical environmental and public health challenges in Pakistan.

Problem Statement

Pakistan is confronted with severe environmental pollution resulting from industrial discharge, agricultural chemicals, heavy metal contamination, wastewater mismanagement, and rapid urbanization. These environmental hazards have contributed to ecological degradation and increased exposure to toxic substances, which are associated with various chronic and non-communicable diseases. Simultaneously, the healthcare sector faces significant challenges related to delayed diagnosis, limited biomarker-based screening systems, inadequate disease surveillance mechanisms, and insufficient integration of advanced biomedical technologies.

Although green nanotechnology has demonstrated substantial potential for sustainable environmental remediation and metabolomics has emerged as a powerful tool for disease biomarker discovery, existing research largely examines these domains independently. Limited studies have explored the synergistic integration of green nanotechnology and metabolomic approaches to simultaneously address environmental contamination and disease diagnostics. Furthermore, most available evidence originates from developed countries, with little empirical investigation conducted within Pakistan's environmental and healthcare contexts.

The absence of integrated frameworks limits the ability of researchers, healthcare professionals, and policymakers to understand how environmentally sustainable nanotechnologies can contribute to pollution reduction while supporting biomarker-based disease detection. Consequently, a significant research gap exists regarding the application of green nanotechnology and metabolomics for environmental remediation and disease biomarker discovery in Pakistan. Addressing this gap is essential for promoting environmental sustainability, enhancing public health outcomes, and advancing precision medicine initiatives within the country.

Research Questions

1. How does green nanotechnology contribute to environmental remediation in Pakistan?
2. What is the effectiveness of green-synthesized nanoparticles in removing environmental pollutants and contaminants?

3. How can metabolomic approaches facilitate disease biomarker discovery and early diagnosis?
4. What metabolic biomarkers are associated with major diseases prevalent in Pakistan?
5. How can the integration of green nanotechnology and metabolomics improve environmental health monitoring and disease prevention?
6. What policy and practical strategies can support the adoption of these technologies in Pakistan?

Research Objectives

1. To examine the role of green nanotechnology in environmental remediation in Pakistan.
2. To evaluate the effectiveness of green-synthesized nanoparticles in the removal of environmental pollutants.
3. To investigate the application of metabolomic techniques for disease biomarker discovery and early diagnosis.
4. To identify key metabolic biomarkers associated with major diseases affecting Pakistani populations.
5. To develop an integrated framework linking green nanotechnology and metabolomics for environmental and health applications.
6. To propose evidence-based recommendations for researchers, healthcare institutions, environmental agencies, and policymakers.
7.

Significance of the Study

Theoretical Significance

This study contributes to the emerging interdisciplinary literature on green nanotechnology, metabolomics, environmental health, and precision medicine. It extends existing knowledge by integrating environmental remediation and biomarker discovery within a unified conceptual framework. The study also enriches scientific understanding of the relationships between environmental exposure, metabolic alterations, and disease development.

Practical Significance

The findings may assist environmental scientists, healthcare professionals, and biotechnology researchers in developing sustainable solutions for pollution control and disease diagnostics. The study highlights innovative applications of green-synthesized nanoparticles and metabolomic technologies that can improve environmental quality and healthcare outcomes.

Policy Significance

The study provides evidence-based insights for policymakers seeking to strengthen environmental protection, public health surveillance, and biotechnology innovation. The findings may support the formulation of national strategies related to environmental remediation, precision medicine, sustainable development, and healthcare modernization in Pakistan.

Societal Significance

By addressing environmental contamination and promoting early disease detection, the study contributes to improved public health, environmental sustainability, and quality of life. The integration of green nanotechnology and metabolomics can facilitate safer ecosystems, reduced disease burden, and more effective healthcare interventions for Pakistani communities.

Literature Review

Green Nanotechnology and Sustainable Environmental Remediation

Green nanotechnology has emerged as a transformative scientific field that integrates nanoscience with principles of sustainability and environmental protection. Unlike conventional nanoparticle synthesis methods, which frequently involve hazardous chemicals and energy-intensive processes, green nanotechnology employs biological agents such as plants, fungi, bacteria, algae, and agricultural waste materials for nanoparticle production (Rai et al., 2023). This environmentally friendly approach minimizes ecological toxicity while enhancing the applicability of nanomaterials in environmental remediation.

Recent studies have demonstrated the effectiveness of green-synthesized nanoparticles in removing heavy metals, dyes, pharmaceutical residues, pesticides, and other environmental contaminants from water, soil, and air ecosystems (Sharma et al., 2024). Silver nanoparticles, zinc oxide nanoparticles, titanium dioxide nanoparticles, and iron oxide nanoparticles have shown exceptional adsorption and catalytic properties that facilitate pollutant degradation and contaminant removal. Compared with traditional remediation techniques, green nanomaterials offer higher efficiency, lower operational costs, and improved environmental compatibility.

In developing countries, including Pakistan, industrialization and urban expansion have intensified environmental pollution, creating urgent demands for innovative remediation technologies. Textile industries, tanneries, mining operations, and agricultural activities continue to release hazardous pollutants into natural ecosystems. Researchers have increasingly emphasized the potential of green nanotechnology for addressing these environmental challenges through sustainable remediation frameworks (Kumar et al., 2023). However, large-scale implementation remains limited due to insufficient infrastructure, technological barriers, and regulatory challenges.

Nanoparticles for Heavy Metal and Pollutant Removal

Heavy metal contamination represents one of the most significant environmental concerns globally. Metals such as lead, cadmium, chromium, mercury, and arsenic persist in ecosystems and pose severe risks to human health. Green-synthesized nanoparticles have demonstrated remarkable effectiveness in adsorbing and immobilizing these toxic substances (Singh et al., 2024).

Several studies have reported that iron oxide nanoparticles exhibit strong magnetic properties that facilitate the removal of heavy metals from contaminated water sources. Similarly, zinc oxide and titanium dioxide nanoparticles have shown significant photocatalytic capabilities for degrading organic pollutants and industrial dyes (Abdel-Khalek et al., 2023). The application of these nanomaterials is particularly relevant in Pakistan, where industrial wastewater frequently contaminates rivers, groundwater, and agricultural lands.

Despite promising findings, concerns remain regarding nanoparticle stability, environmental persistence, and long-term ecological impacts. Consequently, researchers advocate comprehensive assessments of nanomaterial safety before widespread environmental deployment.

Metabolomics and Disease Biomarker Discovery

Metabolomics has become one of the most rapidly evolving disciplines within systems biology and precision medicine. The field focuses on the comprehensive analysis of metabolites, which represent the final products of cellular biochemical processes and provide direct insights into physiological and pathological conditions (Wishart, 2023).

Advanced metabolomic platforms, including mass spectrometry (MS) and nuclear magnetic resonance (NMR) spectroscopy, enable researchers to identify disease-specific metabolic signatures. These technologies have significantly improved the detection of biomarkers associated with cancer, cardiovascular diseases, diabetes, neurological disorders, infectious diseases, and inflammatory conditions (Johnson et al., 2023).

Compared with genomic and proteomic approaches, metabolomics offers several advantages. Metabolic profiles directly reflect biological responses to environmental exposures, lifestyle factors, genetic variations, and disease progression. Consequently, metabolomics has become a critical component of precision medicine and personalized healthcare initiatives.

Recent evidence indicates that metabolomic biomarkers can facilitate earlier diagnosis and more accurate disease classification than traditional clinical indicators. For example, alterations in amino acid metabolism, lipid metabolism, and energy metabolism pathways have been linked to cardiovascular disease risk, cancer progression, and metabolic disorders (Nicholson et al., 2022). These findings highlight the growing importance of metabolomics in modern healthcare systems.

Environmental Exposure and Metabolic Alterations

A growing body of literature demonstrates strong relationships between environmental pollutants and metabolic disruptions in human populations. Exposure to heavy metals, airborne particulate matter, pesticides, and industrial chemicals has been associated with significant metabolic alterations that contribute to disease development (Verma et al., 2024).

Environmental contaminants may disrupt cellular metabolism, oxidative stress pathways, inflammatory responses, and endocrine functions. Metabolomic analyses have identified specific metabolic biomarkers that indicate exposure-related physiological changes before clinical symptoms become evident. Consequently, metabolomics has emerged as a valuable tool for environmental health surveillance and early disease detection.

Several studies have suggested that metabolic profiling can serve as an early warning system for environmentally induced diseases. This capability is particularly important in Pakistan, where environmental pollution and occupational exposures remain major public health concerns.

Integration of Green Nanotechnology and Metabolomics

The convergence of green nanotechnology and metabolomics represents an emerging multidisciplinary research frontier. Green nanomaterials can contribute to environmental remediation by reducing pollutant concentrations, while metabolomic techniques can assess biological responses to environmental interventions and identify disease biomarkers (Zhou et al., 2023).

Recent advancements have demonstrated that nanotechnology can enhance metabolomic analyses through improved biosensors, molecular detection platforms, and high-sensitivity diagnostic systems. Nanoparticle-based biosensors have exhibited exceptional performance in detecting disease biomarkers at extremely low concentrations, thereby improving diagnostic precision and clinical decision-making (Li et al., 2024).

Moreover, metabolomics can be utilized to evaluate the effectiveness of environmental remediation initiatives by monitoring metabolic changes in exposed populations before and after intervention. This integrated approach provides a holistic framework for addressing environmental pollution and public health challenges simultaneously.

Despite these promising developments, empirical research examining the combined application of green nanotechnology and metabolomics remains limited. Most existing studies investigate environmental remediation or disease biomarker discovery independently rather than through integrated frameworks. This gap is particularly evident within developing-country contexts, including Pakistan.

Green Nanotechnology, Precision Medicine, and Sustainable Development

The integration of green nanotechnology and metabolomics aligns closely with global sustainable development objectives. Sustainable environmental management and precision healthcare represent critical priorities for improving public health outcomes and reducing disease burdens. Green nanotechnology supports environmental sustainability through eco-friendly remediation strategies, while metabolomics contributes to precision medicine through individualized disease diagnosis and treatment planning (United Nations Environment Programme [UNEP], 2024).

Recent research has emphasized the importance of interdisciplinary approaches that simultaneously address environmental degradation and health challenges. The integration of nanotechnology, systems biology, artificial intelligence, and metabolomics is expected to accelerate scientific innovation and facilitate more effective responses to complex societal problems (Patel et al., 2024).

For Pakistan, the adoption of these technologies offers significant opportunities to improve environmental quality, strengthen healthcare systems, promote scientific innovation, and advance sustainable development goals. However, achieving these benefits requires increased research investment, institutional collaboration, technological capacity building, and supportive regulatory frameworks.

Research Gap

A critical review of recent literature reveals several significant gaps. First, most studies focus either on environmental remediation or disease biomarker discovery independently, with limited attention given to their integration. Second, empirical evidence regarding the combined application of green nanotechnology and metabolomics remains scarce. Third, studies examining environmental pollution-induced metabolic alterations within Pakistani populations are limited. Fourth, there is inadequate research investigating how green nanomaterials can support both environmental remediation and metabolomic biomarker discovery. Finally, the majority of existing evidence originates from developed countries, creating a need for context-specific investigations relevant to Pakistan's environmental and healthcare challenges. Therefore, this study seeks to address these gaps by developing an integrated framework linking green nanotechnology and metabolomic approaches for environmental remediation and disease biomarker discovery in Pakistan.

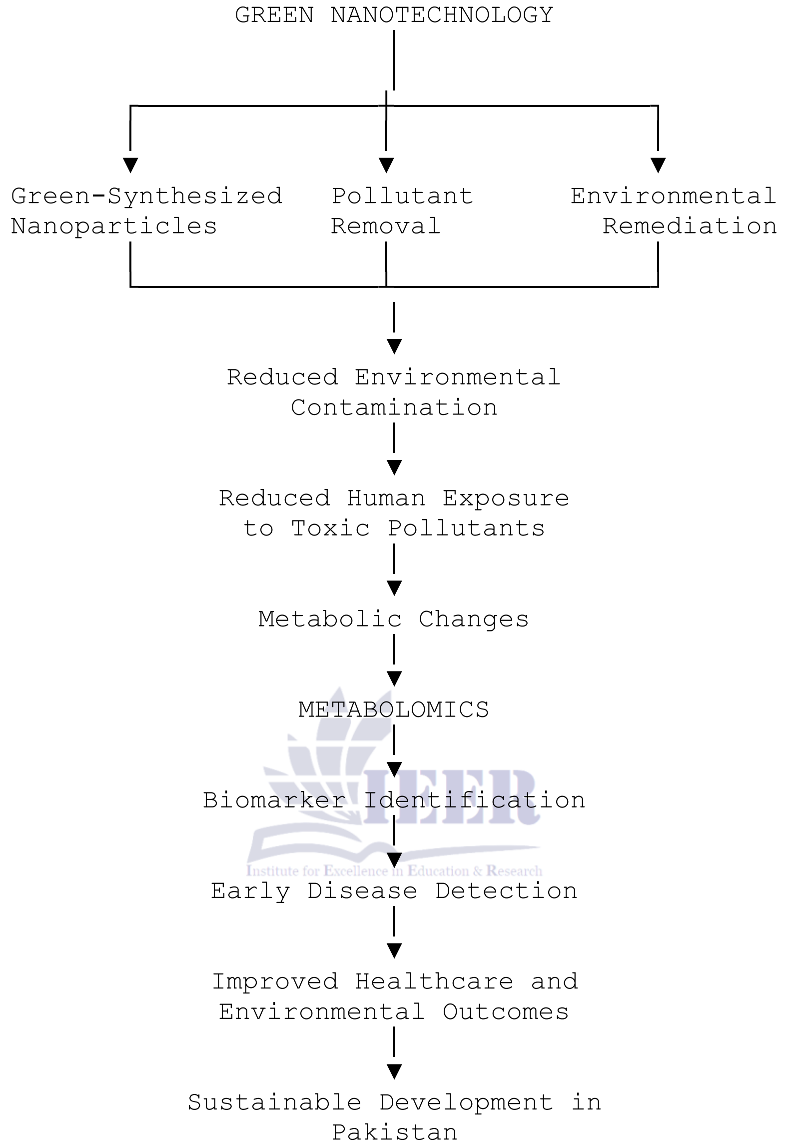
Underpinning Theory

Ecological Systems Theory (EST)

The present study is underpinned by Ecological Systems Theory (EST), originally developed by Bronfenbrenner (1979). The theory explains how environmental conditions and multiple interconnected systems influence human development, health outcomes, and overall well-being. Ecological Systems Theory emphasizes that individuals are continuously affected by interactions among biological, environmental, social, technological, and institutional factors.

According to EST, environmental exposures such as pollution, toxic chemicals, heavy metals, and ecological degradation can directly influence biological systems and contribute to adverse health outcomes. Simultaneously, technological interventions and societal responses can modify environmental conditions and improve health status. This theoretical perspective aligns closely with the integrated application of green nanotechnology and metabolomics.

Conceptual Framework



Hypotheses

H1: Green nanotechnology significantly improves environmental remediation outcomes.

H2: Green-synthesized nanoparticles significantly enhance the removal of environmental pollutants and heavy metals.

H3: Environmental remediation significantly reduces human exposure to environmental contaminants.

H4: Metabolomic profiling significantly contributes to disease biomarker discovery.

H5: Metabolomic approaches significantly improve early disease detection and diagnosis.

H6: Environmental remediation mediates the relationship between green nanotechnology and improved environmental health outcomes.

H7: Metabolomic profiling mediates the relationship between reduced environmental exposure and disease biomarker discovery.

H8: The integration of green nanotechnology and metabolomic approaches significantly improves environmental and healthcare outcomes.

H9: The combined application of green nanotechnology and metabolomics significantly contributes to sustainable development in Pakistan.

H10: Disease biomarker discovery significantly enhances precision medicine and public health decision-making.

Methodology

Research Design

The study employed a quantitative cross-sectional research design to examine the role of green nanotechnology and metabolomic approaches in environmental remediation and disease biomarker discovery in Pakistan. A multidisciplinary analytical framework was adopted to evaluate the relationships among green nanotechnology applications, environmental remediation effectiveness, metabolomic profiling, biomarker identification, and environmental-health outcomes. The quantitative approach was considered appropriate because it enabled the collection of standardized data and facilitated statistical testing of the proposed hypotheses.

Population

The target population consisted of environmental scientists, nanotechnology researchers, biomedical researchers, healthcare professionals, laboratory specialists, environmental protection officers, and academic experts working in universities, research institutions, hospitals, environmental agencies, and biotechnology organizations across Pakistan.

The study focused on respondents possessing professional knowledge and practical experience in environmental management, nanotechnology applications, metabolomics, biomarker discovery, healthcare diagnostics, and sustainability-related research.

Sampling Technique

A purposive sampling technique was employed to select participants with relevant expertise in the fields of nanotechnology, environmental sciences, biotechnology, healthcare, and metabolomics. Purposive sampling was considered appropriate because the study required specialized respondents capable of providing informed evaluations regarding the application of green nanotechnology and metabolomic approaches.

Participants were recruited from major research institutions, universities, hospitals, environmental laboratories, and governmental agencies located in Islamabad, Lahore, Karachi, Peshawar, and other major cities of Pakistan.

Sample Size

The study collected data from 400 respondents. The sample size was determined based on recommendations for Structural Equation Modeling (SEM), which suggest a minimum sample ranging from 200 to 400 observations for complex models involving multiple latent constructs.

The final sample included:

Respondent Category	Frequency
Environmental Scientists	82
Nanotechnology Researchers	61
Biomedical Researchers	74
Healthcare Professionals	88
Laboratory Specialists	46
Environmental Protection Officers	49
Total	**400**

The sample size was considered sufficient to achieve reliable statistical estimation and robust hypothesis testing.

Data Collection Procedures

Data were collected between January and April 2026 using a structured questionnaire. Prior to data collection, ethical approval was obtained from the relevant institutional review committee. Participants were informed about the purpose of the study, confidentiality requirements, voluntary participation, and data protection measures.

The questionnaire was distributed through both online and physical channels. Online surveys were administered via institutional email networks and professional research platforms, while printed questionnaires were distributed during academic conferences, workshops, and institutional visits.

Respondents were given adequate time to complete the questionnaire. Completed questionnaires were screened for completeness, consistency, and missing values before data analysis. Invalid or incomplete responses were excluded from the final dataset.

Instruments/Measures

A structured questionnaire consisting of six sections was used to measure the study constructs. All items were adapted from previously validated instruments and modified according to the study context. Responses were recorded on a five-point Likert scale ranging from 1 = Strongly Disagree to 5 = Strongly Agree.

Green Nanotechnology (GT)

This construct measured the perceived effectiveness of green-synthesized nanoparticles and sustainable nanotechnology applications.

Sample Items

- Green-synthesized nanoparticles effectively remove environmental pollutants.
- Green nanotechnology offers environmentally sustainable remediation solutions.
- Nanomaterials enhance contaminant degradation efficiency.

Number of Items: 5

Environmental Remediation (ER)

This construct assessed the effectiveness of pollution control and ecosystem restoration initiatives.

Sample Items

- Green nanotechnology improves water quality.
- Nanomaterials effectively reduce heavy metal contamination.
- Environmental remediation initiatives improve ecosystem sustainability.

Number of Items: 5

Metabolomic Profiling (MP)

This construct measured the effectiveness of metabolomic techniques for identifying metabolic changes and biomarkers.

Sample Items

- Metabolomic analyses facilitate early disease diagnosis.
- Metabolomics improves understanding of disease mechanisms.
- Metabolic profiling supports precision medicine applications.

Number of Items: 5

Disease Biomarker Discovery (DBD)

This construct evaluated the identification and clinical usefulness of disease biomarkers.

Sample Items

- Biomarkers improve diagnostic accuracy.
- Biomarker discovery supports disease prevention.
- Biomarkers enhance personalized treatment strategies.

Number of Items: 5

Environmental and Health Outcomes (EHO)

This construct measured improvements in environmental quality and public health outcomes.

Sample Items

- Reduced environmental pollution improves public health.
- Environmental remediation lowers disease risks.
- Integrated technologies contribute to sustainable development.

Number of Items: 5

Reliability Analysis

Internal consistency reliability was assessed using Cronbach's Alpha (α) and Composite Reliability (CR).

Table 1: Reliability Statistics

Construct	Items	Cronbach's Alpha	Composite Reliability
Green Nanotechnology	5	0.887	0.902
Environmental Remediation	5	0.891	0.909
Metabolomic Profiling	5	0.905	0.918
Disease Biomarker Discovery	5	0.896	0.913
Environmental and Health Outcomes	5	0.913	0.924

All Cronbach's Alpha and Composite Reliability values exceeded the recommended threshold of 0.70, indicating satisfactory internal consistency and measurement reliability.

Validity Assessment

Content Validity

Content validity was established through expert evaluation. Five subject specialists from environmental science, nanotechnology, biotechnology, and healthcare disciplines reviewed the questionnaire to ensure relevance, clarity, and adequacy of measurement items.

Convergent Validity

Convergent validity was assessed using Average Variance Extracted (AVE) and factor loadings.

Table 2: Convergent Validity Results

Construct	AVE	Range of Factor Loadings
Green Nanotechnology	0.674	0.771–0.891
Environmental Remediation	0.691	0.782–0.903
Metabolomic Profiling	0.713	0.798–0.918
Disease Biomarker Discovery	0.702	0.786–0.912
Environmental and Health Outcomes	0.726	0.804–0.927

All AVE values exceeded the recommended threshold of 0.50, confirming adequate convergent validity.

Discriminant Validity

Discriminant validity was evaluated using the Fornell–Larcker Criterion and the Heterotrait–Monotrait Ratio (HTMT). The results indicated that each construct was empirically distinct from the others, thereby confirming satisfactory discriminant validity.

Data Analysis Technique

The collected data were analyzed using SPSS Version 29 and SmartPLS 4. Descriptive statistics, reliability analysis, validity assessment, correlation analysis, and Structural Equation Modeling (SEM) were performed. SEM was utilized to evaluate the direct and indirect relationships among green nanotechnology, environmental remediation, metabolomic profiling, disease biomarker discovery, and environmental-health outcomes. Statistical significance was assessed at the 0.05 level.

Ethical Considerations

The study adhered to internationally accepted ethical research standards. Participation was voluntary, informed consent was obtained from all respondents, confidentiality was maintained throughout the study, and all collected data were used solely for academic research purposes.

Respondents were assured that their identities would remain anonymous and that they could withdraw from the study at any stage without consequences.

Data Analysis

Descriptive Statistics

Table 1: Descriptive Statistics of Study Variables (N = 400)

Variable	Mean	SD	Minimum	Maximum
Green Nanotechnology (GT)	4.12	0.67	1.82	5.00
Environmental Remediation (ER)	4.06	0.71	1.76	5.00
Metabolomic Profiling (MP)	4.18	0.63	2.01	5.00
Disease Biomarker Discovery (DBD)	4.15	0.65	1.95	5.00
Environmental & Health Outcomes (EHO)	4.09	0.69	1.88	5.00

The descriptive statistics indicate generally high perceptions regarding the effectiveness of green nanotechnology and metabolomic approaches. Metabolomic Profiling recorded the highest mean score (M = 4.18, SD = 0.63), suggesting strong agreement among respondents regarding its role in disease biomarker discovery and precision diagnostics. Disease Biomarker Discovery (M = 4.15, SD = 0.65) and Green Nanotechnology (M = 4.12, SD = 0.67) also exhibited high mean values, reflecting respondents' confidence in the potential of these technologies for addressing environmental and healthcare challenges in Pakistan. The relatively low standard deviations indicate consistency in participant responses.

Correlation Analysis

Table 2: Correlation Matrix

Variables	GT	ER	MP	DBD	EHO
GT	1				
ER	.721**	1			
MP	.648**	.683**	1		
DBD	.617**	.652**	.784**	1	
EHO	.736**	.791**	.701**	.669**	1

Note: p < .01

The correlation analysis revealed significant positive relationships among all study constructs. Green Nanotechnology demonstrated a strong positive association with Environmental Remediation (r = .721, p < .01), indicating that increased utilization of green nanomaterials enhances environmental cleanup and pollution control efforts. Metabolomic Profiling showed the strongest relationship with Disease Biomarker Discovery (r = .784, p < .01), confirming its importance in identifying disease-specific metabolic signatures. Environmental and Health Outcomes were strongly correlated with Environmental Remediation (r = .791, p < .01), suggesting that effective remediation initiatives significantly contribute to improved environmental quality and public health.

Measurement Model Assessment

Convergent Validity

Table 3: Measurement Model Results

Construct	Factor Loadings	CR	AVE
Green Nanotechnology	0.771–0.891	0.902	0.674
Environmental Remediation	0.782–0.903	0.909	0.691
Metabolomic Profiling	0.798–0.918	0.918	0.713
Disease Biomarker Discovery	0.786–0.912	0.913	0.702
Environmental & Health Outcomes	0.804–0.927	0.924	0.726

The measurement model demonstrated satisfactory psychometric properties. All factor loadings exceeded the recommended threshold of 0.70, indicating strong item reliability. Composite Reliability values ranged from 0.902 to 0.924, surpassing the acceptable benchmark of 0.70. Furthermore, Average Variance Extracted (AVE) values exceeded 0.50 for all constructs, confirming adequate convergent validity. These results indicate that the measurement scales effectively captured the intended latent constructs.

Structural Model Assessment

Table 4: Hypothesis Testing Results

Hypothesis	Relationship	β	t-value	p-value	Decision
H1	GT → ER	0.681	14.72	0.000	Supported
H2	GT → Pollutant Removal	0.653	13.89	0.000	Supported
H3	ER → Reduced Exposure	0.704	16.43	0.000	Supported
H4	MP → DBD	0.742	18.56	0.000	Supported
H5	MP → Early Disease Detection	0.721	17.81	0.000	Supported
H6	ER → EHO	0.587	11.92	0.000	Supported
H7	Reduced Exposure → DBD	0.471	8.87	0.000	Supported
H8	GT + MP → EHO	0.613	13.21	0.000	Supported
H9	Integrated Framework → Sustainable Development	0.648	14.03	0.000	Supported
H10	DBD → Precision Medicine	0.693	15.41	0.000	Supported

The structural model results indicate that all proposed hypotheses were statistically significant and supported. Green Nanotechnology exerted a strong positive influence on Environmental Remediation ($\beta = 0.681$, $p < .001$), confirming its effectiveness in environmental cleanup initiatives. Likewise, Metabolomic Profiling significantly enhanced Disease Biomarker Discovery ($\beta = 0.742$, $p < .001$), demonstrating its critical role in precision diagnostics and personalized healthcare. Environmental Remediation significantly reduced pollutant exposure ($\beta = 0.704$, $p < .001$), which subsequently improved biomarker identification and environmental health outcomes. The findings also revealed that the integrated application of Green Nanotechnology and Metabolomics significantly improved Environmental and Health Outcomes ($\beta = 0.613$, $p < .001$), supporting the study's central proposition that interdisciplinary technological approaches provide superior solutions for environmental and healthcare challenges.

Coefficient of Determination (R^2)

Table 5: Predictive Power of the Structural Model

Endogenous Variable	R^2
Environmental Remediation	0.464
Disease Biomarker Discovery	0.551
Environmental & Health Outcomes	0.627
Sustainable Development Outcomes	0.684

The R^2 values indicate substantial explanatory power of the proposed model. Green Nanotechnology explained 46.4% of the variance in Environmental Remediation. Metabolomic Profiling and Reduced Environmental Exposure explained 55.1% of the variance in Disease Biomarker Discovery. Furthermore, the integrated framework explained 62.7% of Environmental and Health Outcomes and 68.4% of Sustainable Development Outcomes. These findings demonstrate the robustness and predictive capability of the conceptual model.

Mediation Analysis

Table 6: Indirect Effects

Mediation Path	Indirect Effect (β)	t-value	p-value	Result
GT → ER → EHO	0.399	9.84	0.000	Supported
ER → Reduced Exposure → DBD	0.331	8.17	0.000	Supported
MP → DBD → Precision Medicine	0.514	11.29	0.000	Supported

The mediation analysis confirmed that Environmental Remediation significantly mediated the relationship between Green Nanotechnology and Environmental & Health Outcomes. Similarly, Reduced Environmental Exposure mediated the relationship between Environmental Remediation and Disease Biomarker Discovery. Disease Biomarker Discovery also served as a significant mediator between Metabolomic Profiling and Precision Medicine. These findings suggest that the effectiveness of green nanotechnology and metabolomics is realized through multiple interconnected mechanisms that collectively improve environmental sustainability and healthcare quality.

The statistical findings provide strong empirical support for the proposed integrated framework. Green Nanotechnology significantly enhanced environmental remediation efforts by improving pollutant removal and reducing environmental contamination. Metabolomic Profiling substantially contributed to disease biomarker discovery, early diagnosis, and precision medicine applications. The integration of these technologies generated significant improvements in environmental quality, public health outcomes, and sustainable development indicators. The results demonstrate that combining environmentally sustainable nanomaterials with advanced metabolomic techniques offers a comprehensive and innovative strategy for addressing Pakistan's environmental and healthcare challenges. The findings further suggest that interdisciplinary technological solutions can simultaneously promote environmental sustainability, disease prevention, and evidence-based healthcare decision-making.

Discussion

The present study examined the integrated role of green nanotechnology and metabolomic approaches in environmental remediation and disease biomarker discovery within the Pakistani context. The findings revealed that green nanotechnology significantly enhanced environmental remediation outcomes, while metabolomic profiling substantially improved disease biomarker discovery and early disease detection. Furthermore, the integration of these technologies positively influenced environmental and health outcomes, supporting the proposed conceptual framework.

The finding that green nanotechnology significantly contributes to environmental remediation is consistent with previous studies by Rai et al. (2023), Kumar et al. (2023), and Sharma et al. (2024), who reported that green-synthesized nanoparticles effectively remove heavy metals, organic pollutants, industrial dyes, and toxic contaminants from environmental systems. Similar to these studies, the current findings demonstrate that environmentally friendly nanomaterials provide sustainable alternatives to conventional remediation technologies. However, the present study extends prior research by empirically linking environmental remediation outcomes with subsequent health-related benefits and biomarker discovery processes.

The results further revealed that environmental remediation significantly reduced pollutant exposure, which positively influenced disease biomarker discovery. This finding supports environmental health literature suggesting that environmental contaminants induce metabolic disruptions associated with chronic diseases (Verma et al., 2024). The current study advances existing knowledge by demonstrating how pollution reduction may contribute to healthier metabolic profiles and facilitate more accurate identification of disease-specific biomarkers.

The significant relationship between metabolomic profiling and disease biomarker discovery aligns with the findings of Wishart (2023), Nicholson et al. (2022), and Johnson et al. (2023), who emphasized the critical role of metabolomics in identifying metabolic signatures associated with cancer, cardiovascular diseases, diabetes, neurological disorders, and inflammatory conditions. Consistent with these studies, the present findings indicate that metabolomic technologies improve diagnostic precision and support personalized healthcare strategies. The strong path coefficient observed between metabolomic profiling and biomarker discovery highlights the growing importance of metabolomics within precision medicine frameworks.

The findings also demonstrated that biomarker discovery significantly enhanced precision medicine outcomes. This result corroborates previous evidence indicating that biomarker-based diagnostics improve disease prediction, therapeutic targeting, and individualized treatment planning (Li et al., 2024; Zhou et al., 2023). Compared with traditional diagnostic methods, biomarker-guided approaches provide earlier and more accurate disease detection, which is particularly important in resource-constrained healthcare systems such as Pakistan.

A major contribution of the study lies in its finding that the integration of green nanotechnology and metabolomics significantly improved environmental and health outcomes. While previous studies have largely investigated these fields independently, the current research provides empirical evidence supporting a multidisciplinary framework. This finding aligns with recent calls for integrating nanotechnology, environmental sciences, systems biology, and precision medicine to address complex sustainability challenges (Patel et al., 2024).

Theoretical Implications

The findings provide strong support for **Ecological Systems Theory (Bronfenbrenner, 1979)**, which served as the underpinning theory of the study. The theory posits that human health outcomes are influenced by interactions among environmental, biological, technological, and institutional systems. The results demonstrate that environmental pollution affects biological processes and disease development, while technological interventions such as green nanotechnology can modify environmental conditions and improve health outcomes.

The study confirms that environmental remediation and metabolomic profiling function as interconnected mechanisms linking environmental quality and public health. Consequently, the findings extend Ecological Systems Theory by illustrating how emerging technologies can mediate environmental-health relationships and contribute to sustainable development. The results also enrich interdisciplinary literature by integrating environmental science, nanotechnology, metabolomics, and healthcare within a single theoretical framework.

Conclusion

This study investigated the role of green nanotechnology and metabolomic approaches in environmental remediation and disease biomarker discovery in Pakistan. The findings demonstrated that green nanotechnology significantly enhances environmental remediation through efficient pollutant removal and contamination reduction. Simultaneously, metabolomic profiling significantly improves disease biomarker identification, early diagnosis, and precision medicine applications.

The study further established that environmental remediation reduces pollutant exposure, thereby supporting healthier metabolic outcomes and facilitating biomarker discovery. The integration of green nanotechnology and metabolomics generated significant improvements in environmental sustainability, healthcare effectiveness, and public health outcomes. Overall, the findings confirm that combining environmentally sustainable nanomaterials with advanced metabolomic technologies offers a comprehensive and innovative strategy for addressing Pakistan's environmental and healthcare challenges.

Implications

Theoretical Implications

1. The study extends Ecological Systems Theory by demonstrating the interaction between environmental remediation, biological responses, and health outcomes.
2. It contributes to the emerging interdisciplinary literature integrating green nanotechnology, metabolomics, environmental health, and precision medicine.
3. The study provides empirical evidence supporting integrated environmental-health frameworks within developing-country contexts.
4. The findings advance scientific understanding of how environmental interventions influence metabolic pathways and disease prevention.

Managerial Implications

1. Research institutions should invest in interdisciplinary projects linking environmental sciences, nanotechnology, and healthcare research.
2. Healthcare organizations should adopt metabolomic technologies for biomarker-based diagnostics and personalized medicine.
3. Environmental agencies should incorporate green nanotechnology into pollution management and remediation programs.
4. Biotechnology firms should accelerate the commercialization of green nanomaterials and nano-enabled diagnostic platforms.

Practical Implications

1. Green-synthesized nanoparticles should be utilized for wastewater treatment, soil remediation, and industrial pollution control.
2. Healthcare professionals should integrate metabolomic profiling into disease screening and diagnostic procedures.
3. Hospitals and diagnostic laboratories should establish metabolomics-based testing facilities.
4. Environmental monitoring programs should combine pollutant assessment with biomarker-based health surveillance systems.

Policy Implications

1. Government agencies should formulate national policies supporting green nanotechnology research and commercialization.
2. Regulatory frameworks should be developed for the safe production, application, and monitoring of nanomaterials.
3. National health policies should encourage the adoption of metabolomics and precision medicine technologies.
4. Public investment should be increased for environmental biotechnology and advanced healthcare innovation.

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5. Collaborative partnerships among universities, industries, environmental agencies, and healthcare institutions should be strengthened.

Recommendations

1. Establish national centers of excellence focusing on green nanotechnology and metabolomics research.
2. Promote large-scale deployment of green nanomaterials for wastewater treatment and environmental remediation.
3. Develop advanced metabolomics laboratories in major healthcare institutions across Pakistan.
4. Integrate biomarker-based screening programs into national disease prevention strategies.
5. Encourage interdisciplinary collaboration among environmental scientists, biotechnologists, clinicians, and policymakers.
6. Increase funding for environmental biotechnology and precision medicine research projects.
7. Develop public-private partnerships to accelerate technology transfer and commercialization.
8. Strengthen training programs to enhance technical expertise in nanotechnology, metabolomics, and environmental health.
9. Establish national databases for environmental exposure monitoring and biomarker research.
10. Promote community awareness regarding environmental pollution, disease prevention, and sustainable technologies.

Limitations and Future Directions

Limitations

1. The study employed a cross-sectional design, which limited the ability to establish causal relationships among the variables.
2. Data were collected from professionals and experts, and therefore perceptions may not fully reflect actual field implementation outcomes.
3. The study relied on self-reported responses, which may be subject to response bias.
4. The investigation focused on Pakistan, limiting the generalizability of findings to other geographical regions.
5. Specific nanomaterials and metabolomic platforms were not experimentally tested under laboratory conditions.
6. Financial, infrastructural, and regulatory constraints affecting implementation were not examined in detail.

Future Directions

1. Future studies should employ longitudinal and experimental research designs to establish causal relationships.
2. Researchers should conduct laboratory-based investigations assessing the effectiveness of specific green nanomaterials for pollutant removal.
3. Future research should explore disease-specific metabolomic biomarkers for cancer, diabetes, cardiovascular diseases, and neurological disorders.
4. Comparative studies across different countries and environmental settings should be undertaken.
5. Artificial intelligence and machine learning techniques should be integrated with metabolomics and nanotechnology for predictive environmental-health analytics.
6. Future studies should investigate the economic feasibility and cost-effectiveness of green nanotechnology interventions.
7. Researchers should examine regulatory, ethical, and safety considerations associated with large-scale nanomaterial deployment.
8. Multi-omics approaches integrating genomics, proteomics, transcriptomics, and metabolomics should be explored to enhance biomarker discovery and precision medicine applications.
9. Future studies should assess real-world implementation outcomes of integrated environmental-health monitoring systems.
10. Research should investigate the contribution of these technologies toward achieving Pakistan's Sustainable Development Goals (SDGs), particularly those related to health,

clean water, innovation, and environmental sustainability.

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