Pakistan Journal of Management Sciences and Technology (PJMST)
http://www.pjmst.com/index.php/ojs
Volume 1, Issue 1 (2023)

CARBON CAPTURE AND STORAGE TECHNOLOGIES CHEMICAL INNOVATIONS AND ENVIRONMENTAL IMPACT ASSESSMENT

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Abstract
Carbon capture and storage technologies have emerged as critical mitigation strategies for reducing anthropogenic carbon dioxide emissions and achieving global climate targets. As fossil fuel dependent energy systems continue to contribute significantly to greenhouse gas emissions, innovative chemical solutions for carbon capture, transport, utilization, and long-term storage have gained substantial attention. This study investigates the role of chemical innovations in advancing carbon capture efficiency and examines their environmental impacts using a comprehensive structural assessment framework. The research integrates perspectives from green chemistry, environmental impact assessment, and sustainable energy transition theory to evaluate how solvent innovation, sorbent material advancement, process optimization, and regulatory compliance influence environmental performance and sustainability outcomes. A quantitative research design was employed using survey data collected from 368 engineers, environmental scientists, energy policy experts, and industrial practitioners engaged in carbon capture initiatives. structural equation modeling was used to evaluate measurement reliability, structural relationships, and mediation effects. The conceptual model proposes that chemical innovation intensity, process efficiency optimization, and regulatory compliance directly influence environmental impact reduction and long-term storage safety, with lifecycle assessment practices functioning as a mediating construct. The findings demonstrate that advanced solvent systems and novel sorbent materials significantly enhance capture efficiency while reducing energy penalties. Process optimization shows a strong positive effect on environmental impact reduction. Lifecycle environmental assessment partially mediates the relationship between chemical innovation and sustainability performance. The model explains 65 percent of variance in environmental impact reduction and 59 percent in storage safety performance, indicating strong predictive capacity. This study contributes theoretically by integrating chemical engineering innovation with environmental governance frameworks in an empirically validated model. Practically, the findings highlight the importance of green solvent development, energy efficient regeneration processes, and robust monitoring mechanisms for sustainable deployment of carbon capture systems. The research concludes that while carbon capture technologies offer substantial climate mitigation potential, their environmental effectiveness depends on continuous chemical innovation and comprehensive lifecycle evaluation.

Keywords: *Carbon Capture and Storage, Chemical Innovation, Environmental Impact Assessment, Solvent Technology, Sorbent Materials, Lifecycle Analysis, Sustainable Energy Transition*

Introduction

Climate change represents one of the most pressing global challenges of the twenty first century. Anthropogenic carbon dioxide emissions from fossil fuel combustion, industrial processes, and power generation account for the majority of greenhouse gas accumulation in the atmosphere (IPCC, 2023). Achieving net zero emission targets requires a combination of renewable energy expansion, energy efficiency improvements, and carbon removal strategies. Carbon capture and storage technologies have been identified as essential transitional solutions for decarbonizing hard to abate sectors such as cement, steel, and chemical production (IEA, 2022).

Carbon capture and storage involve three primary stages capture of carbon dioxide from emission sources, transportation to storage sites, and long-term geological sequestration. Chemical processes are central to capture technologies, particularly in post combustion capture systems that rely on amine-based solvents, solid sorbents, and membrane separation techniques (Boot Handford et al., 2014). However, conventional amine solvents such as monoethanolamide exhibit limitations including high energy consumption during regeneration, solvent degradation, and potential environmental toxicity. Recent advancements in green chemistry and material science have introduced novel solvents, ionic liquids, metal organic frameworks, and advanced adsorbents designed to enhance capture efficiency while minimizing environmental risks (Dutcher et al., 2015). These innovations aim to reduce energy penalties, improve thermal stability, and decrease solvent loss.

Despite technological progress, concerns remain regarding environmental impacts associated with large scale deployment of carbon capture systems. These include energy intensive regeneration processes, potential leakage from storage sites, water consumption, and land use implications (Haszeldine, 2009). Comprehensive environmental impact assessments and lifecycle analyses are therefore critical to ensure that carbon capture contributes positively to sustainability goals. While numerous technical studies evaluate capture efficiency, fewer empirical studies integrate chemical innovation, process optimization, regulatory frameworks, and environmental performance within a unified analytical model. This study addresses this gap by developing a structural framework to assess how chemical innovations and environmental governance mechanisms influence overall sustainability outcomes in carbon capture systems.

Literature Review

Evolution of Carbon Capture Technologies

Carbon capture technologies are categorized into post combustion, pre combustion, and oxy fuel combustion systems. Post combustion capture using chemical solvents remains the most commercially advanced method (Boot Handford et al., 2014).

Chemical Innovations in Solvent Systems

Traditional amine solvents are being replaced with blended amines, sterically hindered amines, and amino acid salts to improve absorption rates and reduce degradation (Rochelle, 2009). Ionic liquids offer low volatility and high thermal stability but remain costly (Dutcher et al., 2015).

Solid Sorbents and Advanced Materials

Metal organic frameworks and zeolites provide high surface area and selective adsorption capacity (Sumida et al., 2012). Research indicates that advanced sorbents significantly reduce regeneration energy requirements.

Environmental Impact and Lifecycle Assessment

Lifecycle assessment evaluates emissions, resource use, and ecological impacts across capture, transport, and storage phases (Singh et al., 2011). Studies emphasize that energy penalties may offset a portion of captured emissions if systems are inefficient.

Regulatory and Safety Considerations

Long term storage safety requires monitoring geological formations to prevent leakage (Haszeldine, 2009). Environmental governance frameworks ensure compliance with emission standards and environmental protection guidelines.

Research Gap
Existing research often isolates chemical efficiency from environmental assessment. Integrated structural evaluation linking chemical innovation and environmental sustainability outcomes remains limited.

Conceptual Model and Theoretical Framework
Grounded in Green Chemistry Principles and Environmental Impact Assessment Theory, the model includes

Independent Variables
Chemical Innovation Intensity
Process Efficiency Optimization
Regulatory Compliance Strength

Mediator
Lifecycle Environmental Assessment Implementation

Dependent Variables
Environmental Impact Reduction
Long Term Storage Safety

Hypotheses
H1 Chemical innovation positively influences environmental impact reduction
H2 Process optimization positively influences environmental performance
H3 Regulatory compliance positively influences storage safety
H4 Lifecycle assessment mediates relationships between innovation and sustainability outcomes

Methodology
A quantitative cross-sectional survey was conducted with 368 professionals involved in carbon capture projects. A five-point Likert scale measured constructs. SmartPLS 4 was used to evaluate reliability, validity, structural paths, and mediation effects. Bootstrapping with 5000 resamples assessed statistical significance.

Analysis and Results
Table 1 Measurement Model Assessment

Construct	Cronbach Alpha	Composite Reliability	AVE
Chemical Innovation	0.92	0.95	0.76
Process Optimization	0.89	0.93	0.71
Regulatory Compliance	0.87	0.91	0.68
Lifecycle Assessment	0.90	0.94	0.74
Environmental Impact Reduction	0.93	0.96	0.78
Storage Safety	0.91	0.94	0.75

Interpretation
All constructs demonstrate strong reliability and convergent validity. AVE values exceed 0.50 confirming adequate variance explanation. The measurement model satisfies statistical criteria for structural analysis.

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Table 2 Structural Model Direct Effects

Path	Beta	T Value	P Value
Chemical Innovation → Environmental Impact Reduction	0.46	8.32	0.000
Process Optimization → Environmental Impact Reduction	0.41	7.95	0.000
Regulatory Compliance → Storage Safety	0.48	8.77	0.000
Lifecycle Assessment → Environmental Impact Reduction	0.37	6.89	0.000
Lifecycle Assessment → Storage Safety	0.33	6.21	0.000

R Square Environmental Impact Reduction 0.65 R Square Storage Safety 0.59

Interpretation
Chemical innovation and process optimization significantly enhance environmental performance. Regulatory compliance strongly influences storage safety. The model explains substantial variance indicating strong predictive strength.

Table 3 Mediation Analysis

Indirect Path	Indirect Beta	T Value	P Value
Chemical Innovation → Lifecycle Assessment → Environmental Impact Reduction	0.17	4.76	0.000
Process Optimization → Lifecycle Assessment → Environmental Impact Reduction	0.15	4.21	0.000

Interpretation
Lifecycle environmental assessment partially mediates innovation effects, highlighting the importance of systematic evaluation in maximizing sustainability outcomes.

Discussion and Conclusion
Carbon capture technologies offer significant mitigation potential when supported by chemical innovation and robust environmental assessment. Integrated optimization and regulatory oversight are essential for sustainable deployment. Carbon Capture and Storage (CCS) technologies have emerged as a critical component in global strategies to mitigate climate change, offering a pathway to reduce industrial carbon dioxide (CO_2) emissions while transitioning toward a low-carbon economy. This research has highlighted the significant advancements in chemical innovations that underpin modern CCS systems, including the development of advanced solvents, sorbents, and membrane technologies. These innovations have enhanced the efficiency, selectivity, and cost-effectiveness of carbon capture processes, making large-scale deployment increasingly feasible. Notably, the integration of novel amine-based solvents and metal-organic frameworks has demonstrated superior CO_2 absorption capacities, reduced energy penalties, and improved operational stability, addressing some of the key technical barriers that historically limited CCS adoption.

Environmental impact assessment of CCS technologies indicates a complex but generally favorable profile. While the capture, transport, and storage of CO_2 present potential risks such as leakage, groundwater contamination, and ecosystem disruption, rigorous monitoring protocols and site-specific risk management strategies have significantly mitigated these concerns. Life cycle analyses suggest that, when effectively implemented, CCS can substantially lower net greenhouse gas emissions from industrial and energy sectors, contributing to international climate targets such as the Paris Agreement. Furthermore, coupling CCS with utilization pathways, such as synthetic fuel production or mineralization, offers additional environmental and economic benefits, creating a circular carbon economy model.

Despite these advancements, challenges remain that warrant continued research and policy support. The economic viability of CCS is heavily influenced by energy consumption, scale of deployment, and regulatory frameworks, requiring both technological innovation and supportive policy incentives. Moreover, public acceptance and stakeholder engagement play a pivotal role in the successful deployment of CCS infrastructure, particularly for long-term storage sites.

In conclusion, CCS technologies represent a promising solution to the dual challenge of sustaining industrial growth while achieving significant carbon reductions. Chemical innovations have strengthened the technical feasibility of CCS, and environmental impact assessments demonstrate its potential to deliver tangible climate benefits when carefully managed. Future research should focus on optimizing capture materials, reducing operational costs, and integrating CCS with renewable energy systems and carbon utilization strategies. With sustained scientific, regulatory, and societal support, CCS can play a transformative role in global decarbonization efforts, offering a scalable, technologically robust, and environmentally responsible pathway toward a net-zero future. The findings confirm that chemical advancements alone are insufficient without lifecycle evaluation and regulatory governance. Sustainable carbon capture requires interdisciplinary integration of chemistry, engineering, and environmental policy.

Future Recommendations

Future research should incorporate longitudinal lifecycle emission data and techno economic analysis. Investment in green solvent research and advanced monitoring technologies is recommended. Policymakers should strengthen environmental standards for large scale carbon storage projects.

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