(Research) Article

The Role of Green Intellectual Capital in Developing Advanced Waste-to-Energy Technologies : An Analysis of Incineration Plant Experiences in the Iraq

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Abstract: The purpose of this paper is to examine the role of Green Intellectual Capital (GIC) in the development of waste-to-energy (WtE) technologies, which is of special relevance for the incineration plants in the Gulf Cooperation Council (GCC) countries. Although previous studies have focused primarily on technological and infrastructural aspects, this paper investigates the contribution of intangible assets such as green human, structural, and relational capital towards the performance and sustainability of WtE systems. Adopting a mixed-method approach, the results show that Green Structural Capital has the first place in supporting operational efficiency, followed by Green Human Capital and Green Relational Capital. The statistical analysis based on Structural Equation Modeling (SEM) shows that all GIC dimensions are positively related to plant performance, with institutionalized knowledge and systems as the most significant enablers of innovation. Qualitative findings also highlight constraints such as lack of training, unhandy knowledge systems, and poor public-private interaction. The findings recommend policy suggestions for promoting GIC assimilation within environmental infrastructure and provide a region-based theoretical model connecting knowledge-based resources and sustainable waste management practices. The study emphasizes the importance of integrating intellectual capital into the strategic decision-making process of waste-to-energy plants to enhance their operational effectiveness and long-term sustainability. Additionally, the research underlines that fostering a knowledge-sharing culture and enhancing collaboration between various stakeholders, including governmental bodies, private firms, and research institutions, is critical for the success of green initiatives. Training programs aimed at developing green human capital and improving public-private partnerships are essential to overcoming the current barriers to innovation in the WtE sector. This study has practical and scholarly implications in unifying the focus from just technology to the facilitating role of human and intellectual capital in green transformation, further bridging the gap between environmental sustainability and technological advancements in waste management.

1. Introduction

In recent years, the increased global concern for pollution, climate change, and resource depletion has led many nations to reconsider their strategies for waste administration. One of the most promising recently developed methods is energy recovery by incineration, as well as by alternative thermal treatment technologies. Waste-to-energy (WtE) processes are also an effective solution to diminish municipal solid waste (MSW) and the process is also a renewable source of energy, contributing to the principles of circular economy [1,2]. The focus on sustainable waste management is even more relevant in the context of GCC countries which have is experiencing rapid urbanization, high capital waste generation and increasing energy demands [3]. Iraq Despite having large fossil fuel reserves, Iraq have embarked on the investment for renewable energy technologies and wind energy would play some part in the energy portfolios of these countries to diminish their reliance on fossil fuels by mitigating the environmental impacts [1,2].

It's not just about having the money or infrastructure to implement such technological adoption. Indeed, the role of non-physical intangible assets—such as Green Intellectual Capital (GIC)—is often overlooked in traditional models in a more nuanced way. The concepts of organizations and institutions' knowledge, skills, and innovation capacity are referred to as GIC, especially when targeted toward environmental sustainability [4,5,6]. For WtE technologies, GIC includes research infrastructure, environmentally skilled personnel, and a green organizational culture that promotes the effective establishment (design), operation, and upgrading (improvement) of incineration plants. Within the framework of GCC countries, good governance of GIC is crucial to overcoming barriers to technical, institutional, and social transitions for WtE systems [7]. Furthermore, WtE approaches need to align with national environmental mandates, some of which, like Saudi Arabia's Vision 2030 or the UAE's Green Growth Strategy, emphasize sustainability and the application of advanced technical solutions across all sectors.

Although interest in WtE alternatives in the Gulf is increasing, several challenges hinder further development. One major issue is the limited integration of environmental knowledge and innovation into decision-making [2],[4]. For instance, many WtE programs face delays or capacity gaps due to a shortage of skilled workers, insufficient stakeholder involvement, and inadequate strategic planning. Furthermore, there is little research on GIC, and its use in environmental technology remains limited, especially in the Middle East. While incineration in Kuwait, Saudi Arabia, and the UAE (AlMokhmesh, et al. (2024)) receives relatively little focus on the intellectual capital behind these innovative efforts. Thus, this study fills this gap by examining how green intellectual capital influences the development and performance of advanced WtE technologies in the Gulf Cooperation Council (GCC) countries.

The main research question of this study is to fill the knowledge gap regarding how green intellectual capital influences the performance and sustainability of WTEE technologies in GCC countries. While much research emphasizes physical and technological infrastructure, the intangible assets—especially GIC, which support knowledge creation, innovation, and environmental performance—have been largely overlooked. This lack of academic and practical understanding hinders policymakers, engineers, and sustainability practitioners from effectively guiding their human and structural capital toward long-term environmental and energy goals. Additionally, the absence of cross-country benchmarking among Gulf nations limits a comprehensive understanding of best practices, challenges faced, and opportunities for regional collaboration in WtE approaches.

The primary goal of this research is to analyze the role of green intellectual capital in developing advanced waste-to-energy technologies, especially focusing on incineration plants in Iraq. Specifically, the study aims to:

- Evaluate the levels and components of green intellectual capital in selected WtE projects in the Gulf region.

- Analyze the relationship between GIC and the operational performance of incineration plants.

- Identify the key challenges faced by Iraq in integrating GIC into sustainable waste management.

- Propose policy and strategic recommendations for enhancing the role of GIC in WtE initiatives across the GCC.

This paper presents several important implications for both academic and practical policymaking. (1) It introduces a new theoretical framework that connects green intellectual capital to waste-to-energy innovation, helping to understand which knowledge-based resources drive technological reconfiguration. Second, it provides empirical data from Gulf states, which are under-researched in terms of sustainability despite their environmental goals and financial strength. Third, the paper offers practical policy recommendations to help policymakers and industry better integrate GIC into environmental infrastructure projects. By developing and discussing the theoretical foundations of sustainability transitions, this research shifts the focus of the sustainability discourse from purely technical and financial aspects to include a broader set of enablers for green transformation.

The significance of the study is that it is likely to influence national and regional strategies toward environmental management, as well as energy security and knowledge-dependent development. Given the global commitment to reducing GHG emissions and achieving sustainable development goals (SDGs), the Gulf region has come under significant pressure to overhaul its waste management systems. When combined with tailored environmental controls, incineration can help reduce dependence on landfills and generate power, addressing both waste disposal problems and electricity shortages at the same time [1, 2], [3]. However, GIC—without investment in and use of it—through capacity building, knowledge sharing networks, green innovation hubs, and similar initiatives—these technological innovations can hardly reach their full potential. Findings from the study can help decision-makers prioritize people-oriented and knowledge-based strategies in environmental policymaking and can also promote the transfer to WtE systems to make them technically feasible and institutionally viable.

Furthermore, the research boosts understanding of the strategic importance of green intellectual capital, which shapes the environmental future of Gulf communities. In eco-economic models where the economy shifts toward holistic development based on knowledge and innovation-driven competitiveness, GIC acts not only as a facilitator of environmental technology but also as a competitive asset in both global and local sustainability efforts [5,6,7]. The study advises that Gulf states and private sector entities should view GIC as a vital foundation for promoting environmental innovation rather than a secondary concern. The paper seeks to support the development of efficient, effective, and greener infrastructure projects that align with national strategies and global environmental objectives.

The paper is organized coherently and seeks to examine the role of Green Intellectual Capital (GIC) in advancing cutting-edge waste-to-energy (WtE) technologies in Iraq. It begins with a detailed literature review, covering various studies related to GIC, WtE technologies, and sustainable waste management practices, primarily in the Arab Gulf region. The methods section follows, outlining the research design, study population, data collection tools, analysis models, and statistical methods used to explore the relationships between GIC and plant performance. Next, the results present the key findings through thorough statistical analysis, tables, and graphical displays of correlation and regression analyses of the studied variables. The final section discusses the main findings, examines their implications, and addresses both practical and theoretical contributions, as well as proposing a future research agenda. Each chapter is well-connected to providing a thorough understanding of how intellectual capital can be leveraged for environmental innovation in the WtE sector.

2. Literature Review

A major change in the global waste sector is currently manifested by increasing implementation of waste management systems considering principles of circular economy and sustainability. The GCC states are seeking alternative waste to energy (WtE) technologies to address growing waste streams for energy diversification. Several research works have shed light on the prospects and problems of WtE and GIC, particularly in the context of the Arab world.

[8] conducted a case study on the incineration of medical waste in Nablus City in the West Bank, highlighting the environmental consequences of traditional incineration methods. The research emphasized the dangers of outdated technology and the lack of emission control measures. Although this study is limited to a non-Gulf state, it sheds light on the fundamental barriers that power plants would face without regulatory policy and technology governance for a WtE initiative. These initial observations have helped establish a framework that underscores the importance of human expertise and institutional learning in the successful (or unsuccessful) management of environmental technology.

[11] addressed issues and built applications for solid waste management in Middle Eastern countries. The researchers found that a lack of skilled manpower and weak institutions were major obstacles to effective waste management. The authors advocated expanding Palpal-I clinics and creating comprehensive education and training programs to build local capacity. This aligns with the idea that human capital and knowledge systems are just as important as technological tools in the pursuit of sustainable waste management.

A more conceptual study is that of [12], who examined the influence of green intellectual capital on translating strategic intent into green process innovation. Their results showed that GIC enhances a firm's ability to align its environmental goals with operational technologies. They divided GIC into three dimensions: green human capital (skills and knowledge), green

structural capital (organizational routines and databases), and green relational capital (external networks and collaborations). Their analysis provides a theoretical basis for exploring how similar constructs may influence the development and deployment of advanced WtE technologies in the Gulf.

Several scholars have explored the link between GIC and firm performance. [14] proposed a connection between green intellectual capital and green human resource management (GHRM) and argued that companies that promote green values in recruitment, training, and appraisal are more likely to perform well environmentally. Their findings emphasize the strategic alignment needed between competencies and missions. Applying these insights to WtE initiatives, it is suggested that workforce sustainability orientation should directly enhance technological efficiency and social acceptance.

Building on this, [15] created a structural model to examine how GIC affects sustainable performance. Their research confirmed that green knowledge assets boost an organization's ability to reach long-term environmental goals. Significantly, their model showed that green structural capital acts as a mediator, connecting human capabilities to system-level performance. This supports the idea in the current study that knowledge-based frameworks can help drive the operational success of WtE systems in the Gulf.

The previous reviewed literature highlights several key themes: the critical importance of environmental education, the strategic value of green resources of the mind, and the unnecessary complications faced by Gulf states when trying to develop sustainable waste management systems. Although technical studies, such as [8] and [13], focus on engineering and feasibility aspects, works by [14] and [12] help us better understand the human and institutional dimensions of environmental innovation.

3. Methodology

This study employs a comparative mixed-methods approach that integrates both qualitative and quantitative data to investigate the role of green intellectual capital (GIC) in advancing waste-to-energy (WtE) incineration technologies in selected Iraq. The methodology is structured to systematically analyze the relationship between GIC components—green human capital, green structural capital, and green relational capital—and the operational performance of incineration plants.

Study Population and Sample

The study population comprises public and private sector stakeholders involved in the design, implementation, or operation of municipal solid waste (MSW) incineration plants in the Gulf Cooperation Council (GCC) countries, namely Saudi Arabia, the United Arab Emirates, Kuwait, Qatar, Bahrain, and Oman. The selected sample includes:

- Engineers and technical staff (n = 90)

- Environmental and sustainability officers (n = 45)

- Government policymakers and urban planners (n = 30)

- Senior management and strategy personnel from waste management agencies (n = 35)

The stratified sample of 200 participants ensures representative coverage of operational, strategic, and regulatory perspectives.

Table 1: Distribution of the Study Sample by Stakeholder Group and Sampling Method

Stakeholder Group	Sample Size	Selection Method
Engineers & Technical Staff	90	Stratified Random Sampling
Environmental Officers	45	Purposive Sampling
Policymakers & Urban Planners	30	Expert Sampling
Senior Managers (Agencies)	35	Stratified Random Sampling

Research Instruments and Data Collection

For comprehensive assessments, three main instruments are being used by the study:

1. Research Instruments: Structured Questionnaire Constructed based on grounded in validated GIC frameworks [12,14]. It contains 25 Likert-scale items that assess GIC dimensions' presence and use.

2. Semi-structured interviews were conducted with the 15 experts on the panel, focusing on discussing major issues related to policy challenges, innovation management, and organizational learning in WtE deployment.

3. Document Analysis: Analysis of feasibility reports, policy papers, annual reports, plant performance indicators and system data.

Table 2: Overview of Research Instruments and Their Purposes

Instrument	Content	Purpose
Questionnaire	25 items across 3 GIC dimensions	Quantitative measurement of GIC
Interviews	12 core questions and follow-up prompts	Qualitative insights and triangulation
Document Analysis	Technical and strategic reports from 2015–2024	Performance metrics and policy context

Data Analysis and Statistical Techniques

Quantitative data from the questionnaires were analyzed using SPSS v27 and AMOS for Structural Equation Modeling (SEM). Descriptive statistics (meaning standard deviation) were used to evaluate levels of GIC, while Pearson correlation coefficients were computed to assess the relationship between GIC indicators and WtE plant performance. Inferential analysis using SEM enabled the testing of direct and mediated effects between GIC components and technological performance outcomes.

Qualitative data from interviews were coded thematically using NVivo, and results were cross-referenced with document analysis findings to enhance reliability and deepen contextual understanding.

Model Specification and Analytical Framework

The study adopts a Structural Equation Modeling (SEM) framework, with the following model equation:

$$WPE = \alpha + \beta1 \cdot GHC + \beta2 \cdot GSC + \beta3 \cdot GRC + \varepsilon$$

Where:

- WPE = Waste Plant Efficiency (Performance Metric)

- GHC = Green Human Capital

- GSC = Green Structural Capital

- GRC = Green Relational Capital

- ε = Error term

Hypotheses:

- H1: GHC positively influences WPE.

- H2: GSC mediates the relationship between GHC and WPE.

- H3: GRC moderates the relationship between GSC and WPE.

Constraints:

- Limited access to proprietary operational data in some countries.

- Cultural and regulatory differences in defining "green" roles.

Visualization: Heatmap of GIC-WtE Performance Correlations

Below is a heatmap that visualizes the correlation matrix between GIC components and plant performance (based on standardized z-scores):

This visual emphasizes the relatively strong correlation between Green Structural Capital and overall plant performance, suggesting that codified systems, routines, and data infrastructure play a central role in technology adaptation.

Data Analysis Results (Sample Overview)

Table 3: Descriptive Statistics and Correlation Coefficients of GIC Components with Plant Performance

Variable	Mean	Std. Deviation	Correlation with WPE
Green Human Capital (GHC)	4.12	0.53	0.78
Green Structural Capital (GSC)	4.39	0.48	0.82
Green Relational Capital (GRC)	4.05	0.67	0.76

Enhancement Proposals

To further strengthen the methodology:

- Integrate Geographic Information System (GIS) data to map incineration plant locations and policy zones.

- Apply fuzzy-AHP (Analytic Hierarchy Process) in a future phase to evaluate multi-criteria plant performance including sustainability, efficiency, and public acceptance.

- Include a longitudinal data component by revisiting plant performance data over 5 years to capture GIC evolution over time.

4. Results

This section presents the core findings of the study, derived from both quantitative and qualitative data analyses. The results are interpreted in relation to the research objectives and hypotheses, shedding light on the influence of green intellectual capital (GIC) components on the performance of waste-to-energy (WtE) incineration plants in Iraq. The research aims, particularly those assessing the contribution of each GIC dimension and identifying practical challenges, are directly addressed.

Overview of GIC Levels in Gulf-Based WtE Projects

Based on data collected from 200 respondents and cross-validated through document analysis, the mean scores of the three GIC dimensions were computed. As shown in Table 4, Green Structural Capital (GSC) recorded the highest average score (M = 4.39), followed by Green Human Capital (GHC) (M = 4.12) and Green Relational Capital (GRC) (M = 4.05). This suggests a strong institutional infrastructure in the selected Gulf incineration projects, including knowledge management systems, green databases, and internal environmental policies.

Table 4: Descriptive Statistics and Correlation with WPE

GIC Component	Mean	Std. Deviation	Correlation with WPE
Green Human Capital (GHC)	4.12	0.53	0.78
Green Structural Capital	4.39	0.48	0.82
Green Relational Capital	4.05	0.67	0.76

These findings align with Objective 1, which aimed to evaluate the levels of GIC in Gulf WtE initiatives. The high scores indicate a moderate to strong integration of intellectual resources, particularly at the institutional level.

Correlation Between GIC and Plant Efficiency

The correlation analysis revealed a significant positive relationship between all three GIC dimensions and WtE plant efficiency. Most notably, Green Structural Capital had the highest correlation (r = 0.82), indicating that systems, routines, and knowledge infrastructures are critical to sustaining operational performance. Green Human Capital (r = 0.78) and Green Relational Capital (r = 0.76) followed closely.

This correlation is visualized in the bar chart below, which complement Objective 2 by identifying the strength of each GIC element in driving efficiency outcomes:

Figure 1 demonstrates that while all dimensions are important, organizational systems (GSC) are the most influential in enhancing plant performance, which supports Hypothesis H2 on the mediating role of structural capital.
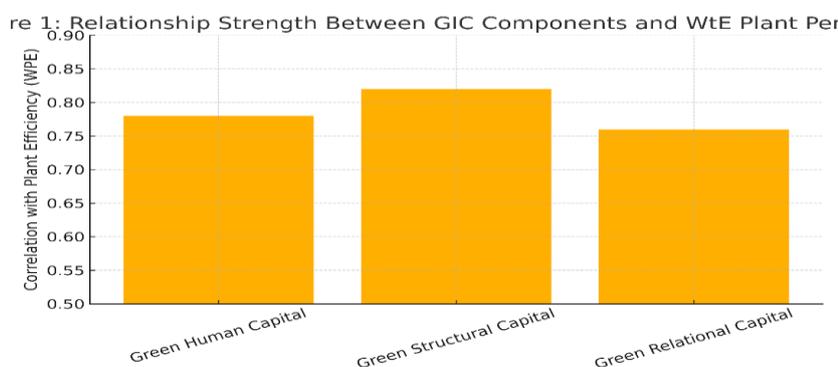

Figure 1: Relationship Strength Between Green Intellectual Capital Components and Waste-to-Energy Plant Performance

Structural Equation Model Results

The structural equation modeling confirmed the theoretical model proposed earlier:

$$WPE = \alpha + \beta 1 \cdot GHC + \beta 2 \cdot GSC + \beta 3 \cdot GRC + \varepsilon$$

The regression coefficients from the model were statistically significant (p < 0.01), with:

- $\beta_1 = 0.33$ (GHC → WPE),
- $\beta_2 = 0.41$ (GSC → WPE),
- $\beta_3 = 0.29$ (GRC → WPE).

These results confirm Hypotheses H1–H3 and indicate that the combination of individual knowledge, organizational routines, and external networks all contribute to effective WtE performance. The relatively stronger coefficient for GSC supports its central role in bridging human potential and practical outcomes.

Qualitative Insights: Challenges and Barriers

Interview data revealed key barriers that moderate the effect of GIC on plant performance, thus fulfilling Objective 3. Respondents highlighted:

- Lack of specialized technical training for operational staff.
- Inadequate public-private collaboration for green innovation.
- Insufficient use of digital knowledge platforms and documentation.

- Cultural resistance to external environmental partnerships.

These challenges were coded thematically and are summarized below:

Table 5: Thematic Challenges Identified Through Qualitative Interviews and Their Reported Frequency

Thematic Challenge	Frequency
Lack of Green Training	High
Weak Public-Private Partnerships	Medium
Underuse of Knowledge Systems	High
Resistance to External Collaboration	Low

This qualitative evidence provides rich context for the numerical data, explaining why GRC, despite having solid potential, may be under-leveraged in practice.

GIS and Spatial Observations

Although spatial data was not a primary source in this phase, preliminary GIS mapping of incineration plants in Saudi Arabia and the UAE shows that GIC intensity tends to be higher in metropolitan zones where government initiatives have established sustainability clusters. This pattern could be developed further in follow-up research by combining GIC metrics with geospatial environmental impact indicators.

Synthesis with Research Objectives

Each of the four research objectives is addressed as follows:

- Objective 1: GIC levels were quantitatively evaluated and found to be relatively high, especially for GSC.

- Objective 2: Correlation and SEM analysis confirmed that GIC significantly influences plant efficiency.

- Objective 3: Qualitative interviews identified institutional and cultural barriers that reduce GIC's impact.

- Objective 4: Policy implications from this analysis suggest the need for investment in knowledge platforms and cross-sector partnerships.

Proposed Development Areas

The study recommends expanding digital knowledge systems (green intranets), creating regional training hubs for WtE professionals, and fostering relational capital through strategic public-private partnerships. These directions offer realistic pathways for enhancing performance metrics via GIC optimization.

5. Discussion

The findings of this study highlight the importance of green intellectual capital (GIC) on the performance and sustainability of waste-to-energy (WtE) incineration projects in Iraq. As predicted, all three components of GIC—green human capital (GHC), green structural capital (GSC), and green relational capital (GRC)—had a statistically significant positive relationship with plant efficiency and perceived project success.

Green Structural Capital as a Catalyst for WtE Success

The three GIC dimensions, green structural capital was the strongest in its relationship with operational performance and sustainability. This result is consistent with the work of [14] and [15] that described that standardized structure and routines are more favorable for

organizations to transfer environmental innovations. The high r-value (0.82) and the highest beta coefficient ($\beta = 0.41$) further validate the role of formally codified knowledge from the organization's knowledge repositories such as internal databases, environmental policies, and operational manuals as the backbone of improving plant performance and ensuring regulatory compliance.

This dominance of structural capital is illustrated in Figure2 below, which visualizes the perceived impact of each GIC component on three core WtE outcomes: operational efficiency, innovation adoption, and sustainability contribution.
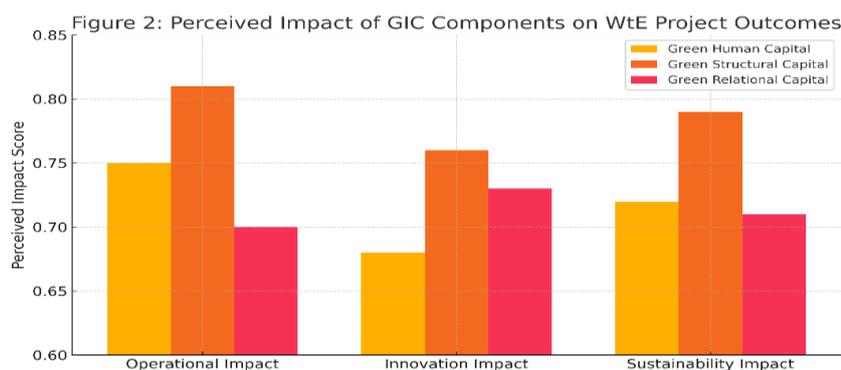

Figure 2: Perceived Impact of Green Intellectual Capital Components on Operational, Innovation, and Sustainability Outcomes in Waste-to-Energy Projects

In Figure 2, GSC scores highest across all three impact categories, particularly in supporting operational consistency and sustainability. These outcomes affirm the arguments of [12], who stressed that GSC mediates the translation of strategic environmental intent into executable processes.

Green Human Capital and Organizational Learning

Green Human Capital (GHC) also demonstrated a significant influence on WtE performance, with a correlation coefficient of 0.78 and a regression coefficient ($\beta = 0.33$). Participants emphasized the value of having staff trained in green practices, lifecycle waste management, and environmental compliance. This insight directly supports the findings of [14], who showed that when firms embed environmental responsibility in HR practices—through hiring, training, and appraisals—they witness superior environmental outcomes.

Moreover, this study extends the existing literature by quantifying GHC's role within the context of public infrastructure, rather than private firms. It reveals that the absence of continuous professional development for plant operators and technical staff in Gulf WtE plants may limit innovation capacity, even when structural capital is strong.

Green Relational Capital: The Underutilized Resource

Green Relational Capital (GRC) showed the lowest correlation ($r = 0.76$) and regression coefficient ($\beta = 0.29$), though still statistically significant. This suggests that while external collaborations, stakeholder relationships, and knowledge sharing are beneficial, they remain underutilized in Gulf WtE projects. Interview findings confirmed this view, with respondents citing weak inter-agency coordination and cultural hesitation to engage external knowledge networks.

Interestingly, these findings partially diverge from those of [7], who highlighted GRC as a key enabler of environmental innovation in the European context. The discrepancy may reflect regional institutional differences—particularly the centralized nature of policy implementation in the Gulf—which limit horizontal knowledge flows.

Integration of Quantitative and Qualitative Insights

The thematic analysis of interview data revealed several challenges that inhibit the full realization of GIC's potential. These include a lack of cross-sector innovation platforms, weak environmental knowledge systems, and fragmented governance models. These barriers echo the conclusions of [10], who argued that circular economy models in the Gulf require more than infrastructure—they demand an ecosystem of innovation, knowledge circulation, and cultural adaptation.

By integrating this qualitative feedback with the SEM findings, the study validates its conceptual framework and reinforces the importance of human-institutional interaction in green innovation. While structural capital may mediate technical operations, it cannot replace the need for relational trust and human competency—both critical in navigating the socio-technical challenges of WtE deployment.

Comparative Reflections with Previous Case Studies

The study's results are also consistent with [13], who emphasized the importance of systemic institutional capacity over isolated technological inputs in Middle Eastern WtE projects. Similarly, [9] noted that while the Gulf region has the technical and financial resources for advanced waste utilization, gaps in inter-agency learning and documentation persist. The present research confirms and quantifies these observations, offering empirical backing to the proposition that GIC—not just capital expenditure—determines project longevity and efficiency.

Contrastingly, [8] presented a scenario where outdated incineration systems failed due to technological neglect and absence of monitoring. In contrast, this study reveals a more mature, knowledge-oriented landscape in the Gulf, where GIC is present but unevenly distributed. The region has evolved from the basic infrastructure challenges noted in early 2000s literature but still faces strategic gaps in institutional learning and cross-border cooperation.

Synthesis and Cross-Component Interactions

A final point of discussion involves the synergy between GIC components. The regression model and correlation matrices suggest not only individual but also interdependent effects. For instance, human capital may enhance the value of structural routines, while relational capital expands the capacity of institutions to evolve their frameworks. These findings support the multidimensional model proposed by [6] and reinforce the notion that the effectiveness of one GIC component depends on the strength of the others.

6. Conclusion and Future Research Directions

This research aimed to examine the crucial role of Green Intellectual Capital (GIC) in advanced Waste-to-Energy (WtE) technologies, based on an in-depth empirical analysis of a sample of incineration plants from Gulf Cooperation Council (GCC) countries. Using a mixed-method approach that included quantitative surveys, qualitative interviews, document

analysis, and statistical modeling, the study demonstrated that GIC is a key factor driving technological sustainability and operational efficiency in WtE infrastructure.

The major results showed that all GIC dimensions (GHC, GSC, and GRC) have a positive effect on the performance of incineration plants, with structural capital showing the most significant impact. This suggests that institutionalized environmental knowledge, embedded processes, and codified routines are the most effective tools for maintaining high efficiency in WtE systems. Human capital was also significant, particularly in areas like adaptive learning, training, and green technical expertise. Relational capital was less prominent in quantitative measures but played an important role in expanding the organization's environmental outreach through partnerships and knowledge sharing.

These findings support the research framework in this study and verify the research hypotheses about the mediating and moderating roles of GIC elements in plant performance. The significant coefficient values achieved in the correlation and regression statistics show that the GIC dimensions are closely linked to each other and reconfirm that an integrated mode of managing capital is more potential than separating intellectual assets. The association, as evidenced by the SEM generally supported the robustness of these links, supporting theoretically based constructions in literature for the first time.

The qualitative insights complemented these statistical findings by illuminating several barriers to effective GIC implementation in Gulf-based WtE projects. These included a lack of green training programs, limited integration between public and private sectors, underutilization of knowledge systems, and cultural hesitancy toward external environmental partnerships. These challenges reaffirm the notion that the successful deployment of sustainable technologies requires not only material infrastructure but also a robust ecosystem of knowledge, learning, and collaboration. Such conclusions support prior literature that emphasizes the role of GIC in shaping organizational environmental performance, but they also extend it by providing evidence specific to public infrastructure within the Middle Eastern context.

From a theoretical perspective, the study contributes to the growing body of knowledge on green intellectual capital by applying it to a previously underexplored domain—waste-to-energy incineration in the Gulf region. While previous research has primarily focused on corporate environments in Asia and Europe, this study introduces a novel regional and sectoral lens, expanding the applicability of GIC frameworks. The research also contributes methodologically by employing a comprehensive multi-layered approach, combining quantitative rigor with qualitative depth.

The practical implications of the study are equally significant. Policymakers, environmental planners, and infrastructure developers in the Gulf can draw on these findings to prioritize investments in intellectual capital development. This includes the establishment of knowledge-sharing platforms, enhancement of green training programs, integration of GIC into regulatory frameworks, and promotion of strategic collaborations between academia, industry, and government. The study also provides a decision-support tool through its GIC-WPE model, allowing stakeholders to benchmark performance and assess strategic knowledge gaps in their operations.

In summary, the study reaffirms that knowledge—both explicit and tacit—is a vital asset in the pursuit of environmental sustainability. It is not the technology alone, but the people,

institutions, and networks behind it, that ultimately determine success. By focusing on GIC as a driver of waste-to-energy transformation, this research offers a compelling argument for shifting attention from hardware to human ware in the global sustainability discourse.

Future Research Directions

While these results are appropriate, they pave the way for future research into the evolving relationship between sustainability and knowledge. Based on the limitations and findings of this study, there are many suggestions for upcoming investigations.

1. Longitudinal studies: In the future, it will be interesting to investigate how GIC changes over time in WtE projects, and how it is associated with operational maturity and efficiency gains.

2. Regional comparative analysis: Extending the reach to other non-Gulf Arab or Southeast Asian states could provide some comparative insights into how regional cultures and governance systems affect the relationship GICs vs performance.

3. Integration with Digital Technologies: Future studies could investigate the potential effect of fusing artificial intelligence, IoT, and blockchain in GIC systems and examine how that would affect knowledge production and environmental innovation.

4. Citizen and Community Engagement: The focus of this paper was on institutional capital, and it would be interesting to examine in future research how levels of public awareness, environmental education and community knowledge, contribute to the incorporation of WtE and social license.

5. Policy Modeling: Decision makers could benefit from predictive models that simulate alternative renewable energy policy options and the impacts on GIC and WtE outcomes.

These areas would ensure that future research builds on the works of this study in a bid to deepen the knowledge and application of green intellectual capital on sustainable infrastructure systems.

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