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Sustainable knowledge management: Driving green technology innovation and long-term performance in construction firms

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Abstract

This study aims to explore how sustainable knowledge management (SKM) influences green technology innovation (GTI) and enduring performance within construction companies. It further examines the impact of artificial intelligence (AI) on the relationship between SKM and green human capital (GHC). Data was collected through a survey of 309 construction companies in Pakistan, and hypothesis testing was conducted using AMOS-24 and SPSS PROCESS macro software. The results indicated that SKM positively affects both GTI and long-term performance. Key elements of green intellectual capital (GIC), such as green structural capital, green relational capital, and green human capital, were identified as important mediators in the relationship between SKM and GTI, as well as between SKM and sustainable performance. Additionally, AI was found to significantly affect the connection between SKM and GHC. These findings offer significant theoretical and practical insights for organizations and policymakers. The research contributes to the knowledge-based view of the firm by providing empirical evidence of how different GIC components mediate the relationships among SKM, GTI, and sustainable performance. Practically, the results suggest that investing in SKM and GIC can enhance GTI and long-term performance.

Keywords: Sustainable knowledge management; Artificial intelligence; Green intellectual capital; Green technology innovation; Long-term performance; Knowledge-based perspective

1. Introduction

In the nineteenth century, industrial advancements significantly improved living standards and lifted many out of poverty. However, this economic progress came at a cost, leading to environmental damage and resource depletion (Dahlquist, 2021). This situation prompts the question: Is environmental harm a necessary trade-off for economic stability? Despite the availability of natural resources, their susceptibility to climate change threatens the economic growth of developing nations. For years, governments have strived to implement regulations and standards to promote environmentally friendly production practices (Khan, 2022; Mehmood et al., 2022; Sana, 2020). The United Nations (UN) established Sustainable Development Goals (SDGs) to protect and improve social and environmental conditions (Ham et al., 2021). Consequently, businesses have increasingly recognized the importance of environmental stewardship, leading them to update their operational and managerial approaches. Research has highlighted the significance of business capabilities in fostering innovations that discover new applications for existing products, expertise, and resources (Hui & Khan, 2022; Khan & Khan, 2021). Since innovation often requires acquiring and applying new knowledge (Berraies & Zine El Abidine, 2019), knowledge assets are crucial for organizational success.

An organization's ability to acquire and retain knowledge is pivotal to its success or failure (Argote et al., 2000). Businesses leverage knowledge to enhance customer satisfaction and gain a competitive advantage (Dabbous & Tarhini,

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2019). In recent years, knowledge management (KM) has gained traction in the corporate sector (Caputo et al., 2019; Kianto, 2011), being recognized as a key component in strategic planning, product and service development, and operational management (Donate & de Pablo, 2015). An effective KM system can significantly improve a firm's performance (Brachos et al., 2007). With growing environmental concerns, many organizations have expanded KM to include environmental issues (Sahoo et al., 2022). As a result, green knowledge management (GKM) has become a vital strategic asset, offering firms a competitive edge by enabling them to achieve the UN SDGs (Sahoo et al., 2022). One of the SDG objectives is to facilitate green production processes through green innovation (Asiaei et al., 2022). To advance sustainability practices, companies must focus on both technological and managerial innovation and distinguish between two types of green innovation: green management innovation and green technology innovation (GTI). GTI combines advanced innovation with knowledge and expertise to foster a more sustainable world, helping firms develop new or improved products and processes that use fewer raw materials and resources while enhancing ecological, financial, and industrial outcomes (Aguilera-Caracuel & Ortiz-de-Mandojana, 2013).

While there has been extensive research on knowledge management (KM) and sustainable development (Choudri et al., 2016; Farrukh et al., 2022; Guo, 2019), there has been less focus on green knowledge management (GKM) and its impact on green technology innovation (GTI) and organizational environmental sustainability. Additionally, there is a lack of research on the contextual factors that affect the relationship between GKM and GTI. This study aims to fill these knowledge gaps by exploring how sustainable performance and GTI contribute to green practices. The knowledge-based view (KBV) of the firm considers knowledge as a vital operational resource (Revilla et al., 2016), as an organization's diverse knowledge bases and skills drive long-term competitive advantage, innovation, and performance; moreover, knowledge-based resources are often challenging to replicate and socially complex (Chowdhury et al., 2022). Green intellectual capital (GIC) is recognized as a crucial organizational resource for performance and sustainability (Haldorai et al., 2022a). GIC encompasses tangible resources or knowledge related to environmental conservation or innovation (Asiaei et al., 2022; Wang & Juo, 2021), including green human capital (GHC), green structural capital (GSC), and green relational capital (GRC) (Dang & Wang, 2022; Nisar et al., 2021). Research on GIC and GKM remains sparse (Martín-Rubio, 2021). Given the increasing environmental concerns, it is vital to understand the combined effects of GIC and GKM on GTI and sustainable performance. This study seeks to explore the relationship between GKM and GIC based on the KBV.

The study further investigates how GIC impacts organizations' sustainable performance and GTI, addressing another literature gap. GTI involves innovations that leverage advanced technology, systems, and control techniques to reduce the environmental impact of business activities (Gao et al., 2021; Liu et al., 2020). Its emphasis on minimizing ecological damage sets GTI apart from other technological innovations. GTI is grounded in the KBV, which posits that firms must adhere to environmental laws and policies to maintain credibility and access sustainable resources (Xie et al., 2019). Additionally, organizations often implement green initiatives like GKM to enhance GTI and performance. Understanding the role of GIC can clarify how GKM influences GTI and sustainable performance.

Several studies have examined the internal and external factors affecting GTI and sustainability. Research on intangible knowledge that drives green innovation indicates that GKM is a critical element of GTI (Sahoo et al., 2022; Su et al., 2020). However, few studies have explored how GKM fosters GTI and sustainable performance. Such research should consider the varying impacts of each GIC component on GTI and sustainable performance. This study contributes by first examining how GKM affects GTI and sustainable performance and then assessing the mediating role of GIC, thereby clarifying the connections between GKM, GTI, and sustainable performance.

The limited research in this area underscores the need for more detailed studies on how technological resources like artificial intelligence (AI) influence these relationships. Typically, firm resources are categorized into financial, technological, and managerial groups (Sahoo et al., 2022). AI is considered a firm's commitment to investing technological resources in GKM and GIC initiatives to enhance GTI and sustainable performance. This aligns with the KBV, which emphasizes that developing and managing key resources, including knowledge, helps firms achieve sustainable competitive advantages (Malik et al., 2022). AI is integrated into the study model due to its potential to improve KM and GIC projects. AI can assist firms in identifying and managing environmental risks, developing new green products and services, and enhancing overall sustainability performance by processing large volumes of data (Sahoo et al., 2022). Other advanced technological resources like big data, cloud computing, and robotics can also be utilized to enhance KM and GIC. However, AI stands out as particularly promising due to its ability to automate many KM and GIC processes, allowing human resources to focus on strategic tasks.

Research indicates that developing countries are particularly vulnerable to environmental risks (Adenle et al., 2015; Sharma et al., 2022), making it more challenging for firms in these regions to leverage organizational resources effectively. Thus, another objective of this study is to evaluate the applicability of the KBV framework within the

Pakistani construction industry. This sector is a major source of pollution, contributing to climate change through significant natural resource consumption and greenhouse gas emissions (Khan & Khan, 2021; Kinnunen et al., 2022; Li et al., 2022; Mehmood et al., 2023). KM, which involves creating, sharing, and utilizing knowledge within an organization, can help the construction industry mitigate its environmental impact by improving efficiency, optimizing resource use, and adopting innovative green technologies. Intellectual capital (IC), including employee knowledge, skills, and experience, can drive the development of new products, enhance efficiency, and create new business models. Green intellectual capital (GIC) focuses specifically on environmental sustainability (Mansoor et al., 2021), supporting the creation of green products and improving environmental performance. Effective KM can foster collaboration, learning, and innovation within the construction industry (Khan et al., 2023). Organizations that value IC attract talent and differentiate themselves. Green innovation reduces environmental impact, ensures regulatory compliance, and enhances organizational reputation. Knowledge-sharing platforms facilitate collaboration and continuous learning. Digital innovations such as building information modeling (BIM), the Internet of Things, and AI optimize resource allocation and support sustainable design and construction, enhancing project outcomes and industry competitiveness (Khan et al., 2021; Tam et al., 2004).

This study offers several significant contributions. First, it is the first to investigate how AI affects the relationship between GKM and GIC. Second, it provides new insights into how GIC influences sustainable performance and GTI. Third, it examines AI's mediating role in the GKM-GIC relationship. Finally, the study focuses on the Pakistani construction sector, a significant contributor to environmental pollution. The research questions guiding this study are:

- RQ1: What impact does GKM have on sustainable performance and GTI within the construction industry?
- RQ2: How does GIC mediate the relationships between GKM and sustainable performance, as well as between GKM and GTI?

The remainder of this paper is organized as follows: Section 2 reviews the literature and establishes a theoretical framework. Section 3 outlines the research methodology, including data collection and analysis methods. Section 4 presents the findings, supported by empirical data. Finally, Section 5 discusses the implications and significance of the results.

1.1. Theoretical Background and Hypothesis Development

1.1.1. Knowledge-Based View of the Firm

The knowledge-based view (KBV) of the firm builds upon traditional management theories, such as stakeholder theory, organizational theory, and the resource-based view (RBV). Often seen as an extension of the RBV, the KBV posits that knowledge generated within an organization is a critical resource for achieving a sustainable competitive advantage in dynamic environments. This is because (a) knowledge-based resources are challenging to interpret and integrate within the organization, (b) they are difficult for other firms to replicate, and (c) they continuously evolve and are co-created within the organization (Chowdhury et al., 2022; Grant, 1996). The KBV focuses on knowledge production and acceleration, and it is frequently integrated with the RBV and other theoretical frameworks in management literature. According to the KBV, firms are entities that integrate knowledge, with a key competency being the ability to coordinate procedures to adapt specialized knowledge to the organization's productive functions (Al Nuaimi et al., 2021). The KBV emphasizes that firms' systemic and structural characteristics enable them to develop the capacity to link specialized and complementary knowledge. As firms shift from producing knowledge to applying it, they require collaboration, cooperation, and adjustments in organizational hierarchies, job designs, guidelines, and decision-making processes. Knowledge, entrepreneurship, and innovation are established as fundamental drivers of competitiveness and economic growth (Yu et al., 2022). Recent research highlights the significant impact of integrating these factors on economic, environmental, and social goals, as represented in the United Nations Sustainable Development Goals (SDGs) (Srisathan et al., 2023; Ribeiro-Soriano & Pineiro-Chousa, 2021). Knowledge enhances innovation capabilities, which, in turn, improves organizational performance (Berraies & El Abidine, 2019; Brachos et al., 2007). According to Grant (1996), effective knowledge management (KM) involves how firms gather, maintain, communicate, and utilize knowledge to build resource-based strategies. The KBV views knowledge as the most crucial strategic resource, guiding this study to test the direct and indirect effects of green knowledge management (GKM) on green technology innovation (GTI) and sustainable performance through green intellectual capital (GIC). Additionally, AI is considered an organizational resource that enhances the GKM-GIC relationship, as illustrated in Fig. 1.

1.1.2. Green Knowledge Management, Green Technological Innovation, and Sustainable Performance

KM is often seen as essential for firms to thrive, survive, and grow in challenging environments (Shujahat et al., 2018). According to Revilla et al. (2016), KM distinguishes successful organizations from those that fail. KM is a key driver of firm growth (Chae & Bloodgood, 2006; Sahoo et al., 2022). In dynamic settings, creating and applying knowledge can

prevent failure and drive profitability. The KBV argues that firms exist to acquire knowledge and transform it into sustainable strategic advantages (Srivastava et al., 2006), emphasizing knowledge as a fundamental resource for enhancing performance and long-term survival (Malhotra, 2005). Knowledge is also the foundation of innovation, with continuous knowledge production leading to consistent innovation.

Green technology innovation (GTI) involves new technological advancements that enhance environmental standards, reduce energy consumption and pollution, and contribute to a more sustainable future (Liu et al., 2020; Rehman et al., 2018). Innovation is crucial for firm success and competitiveness, particularly in complex environments. The corporate environment influences a firm's ability to innovate (Brachos et al., 2007). With increasing pressure from stakeholders to adopt ethical and environmentally friendly practices, green competency is becoming more critical for success (Chen & Hung, 2016). The rise in pollution and resource depletion has led many governments and communities to advocate for broader GTI initiatives (Al Nuaimi et al., 2021). GTI includes all potential green consumption and eco-process innovations aimed at reducing energy use, pollution, and resource consumption. The motivations for implementing GKM and GTI can vary (Sahoo et al., 2022). As these topics are relatively new, research is just beginning to explore them, especially in business contexts where they are central to minimizing the environmental impact of economic activities (Su et al., 2020; Yu et al., 2022). GKM involves employees' understanding of their environment and insights into sustainability, facilitating shared participation in long-term development (Farrukh et al., 2022). Recent studies have questioned the connection between KM and innovation (Kianto et al., 2017; Sahoo et al., 2022; Su et al., 2020), leading to ambiguity in the relationship between GKM and GTI. This motivates the following hypothesis:

1.1.3. H1: GKM positively impacts GTI.

The relationship between sustainable performance and GKM is clear from the KBV perspective (Caputo et al., 2019). GKM, which involves managing environmental knowledge within an organization, aids in acquiring, integrating, innovating, and adopting sustainable practices (Wang et al., 2022). By obtaining relevant knowledge about sustainable technologies and regulations, integrating green knowledge into organizational processes, encouraging innovation and continuous improvement, and involving stakeholders, organizations can enhance their sustainable performance (Kakar & Khan, 2020; Sahoo et al., 2022). Utilizing GKM to align activities with sustainability goals, reduce waste, lower resource consumption, and promote environmental stewardship can provide a competitive advantage in sustainable development (Farrukh et al., 2022). Therefore, this study proposes the following hypothesis:

1.1.4. Green Intellectual Capital (GIC) and Its Components

Chen (2008) defines Green Intellectual Capital (GIC) as the comprehensive inventory of an organization's intangible resources, knowledge, capabilities, and interactions related to ecological sustainability and green innovation, encompassing both human and organizational levels. GIC is divided into three main components: Green Human Capital (GHC), Green Structural Capital (GSC), and Green Relational Capital (GRC) (Benevene et al., 2021; Delgado-Verde et al., 2014). The conceptualization of GIC stems from the recognition that knowledge is crucial to a firm's success (Giampaoli et al., 2021; Kianto et al., 2020; Rehman et al., 2021).

The roles of GIC and Green Knowledge Management (GKM) cover the entire spectrum of intellectual activity, from knowledge creation to its application (Martín-Rubio, 2021; Rehman et al., 2023). GKM acknowledges the relationship between GKM and GIC by representing the knowledge pool at a given time, produced through knowledge flow techniques (Al-Omoush et al., 2022; Hsu & Sabherwal, 2012). The connection between Intellectual Capital (IC) and KM is influenced by a firm's knowledge-based perspective, as developed through seminal research (Grant, 1996; Malik et al., 2022; Revilla et al., 2016).

- **Human Capital (GHC):** This refers to the knowledge, skills, expertise, creativity, and other attributes of employees related to ecological sustainability or innovation. Unlike structural capital, human capital is individual-based and can be lost if an employee leaves the organization (Nahapiet & Ghoshal, 1998). It is essential for generating green innovations and practices, supporting the firm's ability to meet external ecological challenges (Rehman et al., 2019; Wang & Juo, 2021).
- **Structural Capital (GSC):** This encompasses the firm's technological assets, databases, organizational processes, workplace culture, and management expertise related to ecological sustainability (Attar et al., 2019; Hsu & Sabherwal, 2012; Mansoor et al., 2021). Unlike human capital, structural capital is embedded in the organization and remains unaffected by employee turnover.
- **Relational Capital (GRC):** This includes the firm's relationships with customers, vendors, professional contacts, and other stakeholders concerning environmental sustainability and innovation (Mohan & Youndt, 2005; Rehman et al., 2020). Firms need to collaborate with external organizations and stakeholders to strengthen their green applications and mutual ecological concerns.

Each component of GIC is influenced by an organization's GKM practices, as GIC serves as a crucial organizational resource for managing environmental sustainability. KM strategies can enhance GHC, GSC, and GRC, with human capital sustainability aiding in recruiting and retaining intellectual capital (Asiaei et al., 2022; Yong et al., 2019). Technological advancements also impact individual careers and are integral to IC, as they enable individuals to leverage their accumulated knowledge and experience (Al-Omoush et al., 2022; Rehman et al., 2020). Based on this discussion, the following hypotheses are proposed:

- H3a: GKM positively impacts GHC.
- H3b: GKM positively impacts GSC.
- H3c: GKM positively impacts GRC.

1.1.5. Green Knowledge Management, Green Intellectual Capital, and Green Technological Innovation

Human capital is a vital resource for organizational innovation, with employee knowledge being crucial for sustaining organizations amid rapidly advancing technologies (Lepak & Snell, 2002). Employees motivated to apply green knowledge can drive green technology innovation (GTI) (Nisar et al., 2021). Firms with high GHC are likely to achieve more successful GTI compared to those with low GHC (Haldorai et al., 2022b). GHC acts as a bridge between employee GKM and GTI, with firms leveraging their GHC capacity to enhance GTI.

Sustainability initiatives, including green innovations and practices, reflect an organization's commitment to improving the natural ecosystem (Hart, 1995). Integrating sustainability knowledge and experience into business processes enhances joint knowledge and GTI outcomes. Organizations with strong GRC can collaborate effectively with partners to develop new green technologies and initiatives (Asiaei et al., 2022). GTI may be challenging to achieve in organizations with poor green practices and negative environmental attitudes. Firms that absorb and codify environmental knowledge into their processes can better promote and utilize it for GTI (Asiaei et al., 2022; Liu et al., 2020; Sahoo et al., 2022; Wang & Juo, 2021). The KBV emphasizes the significance of organizational knowledge-based resources in managing innovation (Grant, 1996). Hence, this study assumes that GKM enhances GHC, which in turn, improves GTI. Therefore, the following hypotheses are proposed:

- H4a: GHC mediates the relationship between GKM and GTI.
- H4b: GSC mediates the relationship between GKM and GTI.
- H4c: GRC mediates the relationship between GKM and GTI.

1.1.6. Green Knowledge Management, Green Intellectual Capital, and Sustainable Performance

The integration of GKM, GIC, and GTI is vital for enhancing sustainable performance. By leveraging GKM and GIC, firms can drive innovations that align with sustainability goals, thus improving their overall sustainable performance.

1.2. Sustainable Performance, Green Knowledge Management, and Green Intellectual Capital

Sustainable Performance refers to the integration of financial and environmental goals in corporate operations to enhance returns while addressing ecological sustainability (Dey et al., 2022). According to the Knowledge-Based View (KBV) framework, competitive advantage arises from a firm's strategic use of its strengths. Firms adhering to strict environmental regulations increasingly recognize the significance of Green Knowledge Management (GKM). Those that effectively utilize GKM, including the knowledge, skills, and creativity of their employees, are more likely to adopt green policies that improve their sustainability performance (Sami et al., 2020).

GKM helps firms identify and leverage their intangible resources, such as Green Human Capital (GHC), thereby supporting the successful implementation of green initiatives and enhancing green performance. Additionally, Relational Capital (GRC) plays a role in fostering external collaborations, which can reduce transactional and negotiation costs associated with green improvements. By implementing GRC strategies, firms can achieve more successful sustainability initiatives and engage customers interested in sustainability (Asiaei et al., 2022; Yong et al., 2022). Effective collaboration based on GKM–GRC-generated knowledge helps firms develop sustainable business models and enhances green performance.

Structural Capital (GSC) is crucial for organizing systems and practices to develop and identify critical technological expertise. GKM, as part of the KBV framework, helps firms ensure employee access to essential information in an environmentally friendly manner (Wang et al., 2022). Under significant ecological pressure, Green Intellectual Capital (GIC) is vital for a firm's green performance (Wang & Juo, 2021). The study hypothesizes that GIC mediates the relationship between GKM and sustainable performance:

- H5a: GHC mediates the relationship between GKM and sustainable performance.
- H5b: GSC mediates the relationship between GKM and sustainable performance.
- H5c: GRC mediates the relationship between GKM and sustainable performance.

1.3. Moderating Role of Artificial Intelligence (AI)

AI is a transformative tool that enhances performance across sectors by leveraging human intellect to boost efficiency and productivity (Nishant et al., 2020). As a significant technological advancement, AI influences business innovation, process modernization, and environmental sustainability (Chowdhury et al., 2022). Although AI's role in organizational sustainability is gaining recognition, there is limited research on how AI impacts Green Intellectual Capital (GIC) or the relationships between GKM and GIC.

AI can potentially strengthen or weaken the link between GKM and GIC. For example, AI might automate GKM processes, allowing employees to focus on strategic tasks, thus increasing GHC. AI can also enhance GSC by improving data collection, storage, and analysis, helping organizations better understand and manage their environmental impact. Additionally, AI can facilitate stakeholder collaboration, strengthening GRC.

Based on these considerations, the study proposes the following hypotheses:

- **H6a: AI moderates the link between GKM and GHC.** AI could enhance GHC by automating GKM processes and enabling employees to focus on green technologies and practices.
- **H6b: AI moderates the link between GKM and GSC.** AI might improve GSC through better data management and environmental impact analysis.
- **H6c: AI moderates the link between GKM and GRC.** AI may promote stakeholder collaboration and strengthen GRC.

These hypotheses underscore the potential of AI to impact the effectiveness of GKM in fostering Green Intellectual Capital and achieving sustainable performance. Further research is needed to validate these relationships and the moderating role of AI.

2. Methodology

2.1. Sample and Data Collection

This study focuses on the construction sector in Pakistan, which is a significant contributor to the country's GDP but also a major consumer of energy and emitter of greenhouse gases (GHGs). Improving energy efficiency in buildings is crucial for addressing climate change, aligning with the Sustainable Development Goals (SDGs) of the 2030 Agenda.

2.2. Data Collection Process:

- **Data Source**: A questionnaire was used to collect data, a common method for obtaining large-scale quantitative data on industrial practices (Bahadur et al., 2020; Khan et al., 2021; Xiongfei et al., 2020).
- **Geographic Scope**: Data were gathered from construction firms across Pakistan, with no restriction on firm size to ensure a diverse sample.
- **Sample Size**: The initial sample consisted of 900 randomly selected construction firms. The survey was distributed electronically.
- **Participants**: The survey targeted individuals with sufficient knowledge of the firm's operations, including managing directors, procurement directors, site engineers, and construction managers, rather than focusing solely on sustainability or eco-innovation executives.
- **Response Rate**: Out of the 900 surveys sent, 309 completed and valid responses were received, yielding a 34.33% response rate. This is consistent with response rates found in similar empirical studies (Ali et al., 2020; Khan et al., 2023; Moin et al., 2021).

2.3. Survey Instruments:

- **Green Knowledge Management (GKM)**: Measured using a five-item scale (Mao et al., 2016; Sahoo et al., 2022). Example item: "Employees and partners at our organization have easy access to information on best-in-class environmentally friendly practices."
- **Green Intellectual Capital (GIC)**: Composed of three components:

  - **Green Human Capital (GHC)**: Measured using items from Chen (2008) and Chang and Chen (2012). Example item: "The employees' competence in environmental protection in the company is better than that of its major competitors."
  - **Green Relational Capital (GRC)**: Measured using items from Chen (2008). Example item: "The company designs its products or services in compliance with the environmental desires of its customers."
  - **Green Structural Capital (GSC)**: Measured using items from Chen (2008). Example item: "The management system of environmental protection in the company is better than that of its major competitors."
- **Artificial Intelligence (AI)**: Assessed with five items adapted from Belhadi et al. (2021) and Chen et al. (2022). Example item: "We use AI techniques to forecast and predict environmental behavior."
- **Sustainable Performance**: Measured using a scale from Dey et al. (2022), with components for financial, environmental, and social performance. Example item: "Our firm has a policy to improve its energy efficiency."
- **Green Technological Innovation (GTI)**: Measured using a scale adapted from Huang and Li (2017) and Sahoo et al. (2022). Example item: "Our organization is actively involved in the redesign and improvement of products or services in order to comply with existing environmental or regulatory requirements."

This methodology aims to capture a comprehensive view of how green knowledge management practices influence various aspects of green intellectual capital and performance in the construction sector.

3. Data Analysis and Results

3.1. Test of Method Bias and Endogeneity

- **Non-Response Bias**: To evaluate non-response bias, comparisons were made between early and late respondents. The p-values for construct means ranged from 0.514 to 0.880, indicating that non-response bias did not affect the study's findings.
- **Common Method Bias (CMB)**
  - Mitigation Strategies: To address CMB, participants were motivated to respond honestly and allowed to remain anonymous. Questionnaire items were carefully crafted based on previous studies and reviewed by a group of academics in digital technology and service businesses.
  - Marker Variable (MV) Method: A marker variable was included to assess CMB's influence. No significant difference was found between the baseline model and the alternative model, suggesting that CMB did not affect the conceptual model's relationships.
- **Endogeneity**
  - Reverse Causality: The study's theoretical model, based on the Knowledge-Based View (KBV), avoids the possibility of reverse causality. The use of cross-sectional data further reduces the risk of endogeneity.
  - Control Variables: Control variables were employed as recommended by Antonakis and House (2014) to minimize endogeneity issues.

3.2. Reliability and Validity Testing

- **Reliability and Validity**
  - Measures: Reliability and validity of the measures were evaluated using Cronbach's alpha, composite reliability (CR), and average variance extracted (AVE). The recommended cut-offs were:
    - Cronbach's alpha: ≥ 0.70
    - Composite reliability: ≥ 0.70
    - Average variance extracted: ≥ 0.50
  - Factor Loadings: Should exceed 0.60 (Bagozzi & Yi, 1988).
  - Discriminant Validity: Confirmed by ensuring the AVE of the variables was greater than their squared correlation (Fornell & Larcker, 1981).
- **Collinearity**
  - Variance Inflation Factors (VIF): Calculated using a different predictive model, showing relatively low magnitudes (between 1.14 and 1.21), indicating minimal collinearity.
- **Model Fit**
  - Confirmatory Factor Analysis (CFA): Measures included chi-square/df, CFI, IFI, TLI, and RMSEA. The model fit metrics were:
    - CMIN/DF = 1.783
    - p = 0.00
    - IFI = 0.934

- CFI = 0.927
- TLI = 0.933
- SRMR = 0.0452
- RMSEA = 0.050

- Fit Assessment: All values were within the recommended ranges, indicating a good fit for the measurement model.

The analysis confirmed that the data were reliable and valid, and the model fit well. With these assessments complete, hypothesis testing was conducted next.

3.2.1. Hypothesis Testing

Direct Effects

- **Impact of GKM on GTI**
  - Result: GKM positively impacted GTI ($b = 0.37$, $p < 0.001$), supporting Hypothesis H1.
- **Impact of GKM on Sustainable Performance:**
  - Result: GKM positively influenced sustainable performance ($b = 0.39$, $p < 0.001$), supporting Hypothesis H2.
- **Impact of GKM on GHC, GSC, and GRC**
  - Result:
    - GHC: GKM had a significant impact on GHC ($b = 0.52$, $p < 0.001$), supporting Hypothesis H3a.
    - GSC: GKM positively influenced GSC ($b = 0.35$, $p < 0.001$), supporting Hypothesis H3b.
    - GRC: GKM had a significant impact on GRC ($b = 0.39$, $p < 0.001$), supporting Hypothesis H3c.

Mediating Effects

- **Mediators of GKM and GTI**
  - Results:
    - GHC: GHC mediated the link between GKM and GTI ($b = 0.17$, CI = [0.085, 0.273]), supporting Hypothesis H4a.
    - GSC: GSC also mediated this link ($b = 0.09$, CI = [0.039, 0.162]), supporting Hypothesis H4b.
    - GRC: GRC mediated the relationship ($b = 0.08$, CI = [0.032, 0.144]), supporting Hypothesis H4c.
- **Mediators of GKM and Sustainable Performance**
  - Results
    - GHC: GHC mediated the relationship between GKM and sustainable performance ($b = 0.27$, CI = [0.171, 0.369]), supporting Hypothesis H5a.
    - GSC: GSC mediated this relationship ($b = 0.15$, CI = [0.077, 0.238]), supporting Hypothesis H5b.
    - GRC: GRC also mediated the relationship ($b = 0.12$, CI = [0.060, 0.193]), supporting Hypothesis H5c.

Moderating Effects

- **Moderating Role of AI**
  - GKM and GHC
    - Result: The interaction term (GKM*AI) was significant and positive for GHC ($b = 0.19$, $p < 0.01$), supporting Hypothesis H6a.
  - GKM and GSC, GKM and GRC:
    - Result: The interaction terms for GSC and GRC were not significant, leading to the rejection of Hypotheses H6b and H6c.
  - Interaction Effects: Higher AI levels strengthened the effect of GKM on GHC, as shown in Figure 2.
- **Moderated Mediation**
  - Moderation of AI: The PROCESS macro was used to test whether AI moderated the indirect effects of GKM on GTI and sustainable performance through GHC.
    - Results:
      - ✓ **GTI**: Conditional indirect effect was significant (0.06, 95% CI = [0.029, 0.104]).
      - ✓ **Sustainable Performance**: Conditional indirect effect was significant (0.10, 95% CI = [0.049, 0.167]).
- **Control Variables**
  - Impact: Control variables did not have a significant impact on the outcome variables.

This comprehensive analysis confirms that GKM positively affects both GTI and sustainable performance through various mediators, with AI enhancing the relationship between GKM and GHC but not significantly affecting GKM's relationships with GSC and GRC.

4. Discussion

This study applied a Knowledge-Based View (KBV) framework to explore the relationships between Green Knowledge Management (GKM), Green Technological Innovation (GTI), and sustainable performance through Green Innovation Capabilities (GIC), with a focus on the moderating effects of Artificial Intelligence (AI). The findings offer significant contributions to the literature on KM, innovation, sustainability, and AI, particularly within the context of the construction industry.

4.1. Key Findings

4.1.1. Impact of GKM on GTI and Sustainable Performance

- The study found that GKM positively influences both GTI and sustainable performance, consistent with previous research indicating that organizational resources are positively associated with green innovation (Su et al., 2020; Wang et al., 2022). This supports the notion that GKM can enhance GTI and improve sustainable performance in Pakistani construction firms. These results align with findings from Sahoo et al. (2022) and highlight the value of GKM in promoting green innovation and performance.

4.1.2. Role of GIC

- GIC was found to mediate the relationships between GKM and both GTI and sustainable performance. This supports earlier studies that have identified GIC as a key mediator in similar contexts (Asiaei et al., 2022; Martín-Rubio, 2021). The mediation effect underscores the importance of GIC in translating GKM into tangible outcomes such as improved green innovation and sustainability.

4.1.3. Moderating Effects of AI

- The study revealed that AI significantly moderates the relationship between GKM and Green Human Capital (GHC), enhancing the positive impact of GKM. This finding suggests that AI can strengthen the effect of GKM on GHC by facilitating access to and use of technical resources, which can improve employees' knowledge and performance (Chowdhury et al., 2022). However, AI did not significantly moderate the relationships between GKM and Green Supply Chain (GSC) or Green Research and Development (GRC), indicating that the impact of AI may be more pronounced in specific areas such as GHC.

4.1.4. Implications for Practice

- For practitioners, particularly in the construction sector, these findings suggest that investing in GKM practices and AI technologies can lead to substantial improvements in green innovation and sustainable performance. Companies can benefit from integrating AI into their GKM strategies to enhance GHC and leverage technical resources more effectively.

4.1.5. Future Research Directions

- This study highlights several areas for future research, including exploring the reasons behind AI's varying impact on different components of GIC and further investigating how AI can be leveraged to support GKM in diverse contexts. Additionally, examining the long-term effects of GKM and AI on organizational sustainability could provide deeper insights into their roles in driving green innovation and performance.

Overall, this study provides valuable insights into the relationships between GKM, GTI, and sustainable performance, with a focus on the moderating effects of AI, contributing to the growing body of knowledge in these fields.

4.2. Theoretical Contributions

This study makes several significant theoretical contributions, enriching the existing literature on Knowledge-Based View (KBV), Knowledge Management (KM), Innovation Capabilities (IC), and Artificial Intelligence (AI):

4.2.1. Advancing KBV Theory

- **Integration of GKM, GTI, and Sustainable Performance**: By examining the relationships between Green Knowledge Management (GKM), Green Technological Innovation (GTI), and sustainable performance, this research supports the KBV theory. The KBV posits that organizations can enhance their performance and competitiveness through effective use of intangible resources (Grant, 1996). The study's findings align with this theory, showing that firms focusing on GKM can improve their GTI capabilities and, consequently, their overall performance. This supports earlier research by Sahoo et al. (2022), which identified GKM as a precursor to both green innovation and sustainability.

4.2.2. Contributing to KM and IC Literature

- **Direct Effects of GKM on GIC**: The study's finding that GKM directly impacts Green Innovation Capabilities (GIC) challenges previous literature suggesting that Intellectual Capital (IC) influences KM (Hsu & Sabherwal, 2012). This discrepancy may arise from the specific context of the construction industry, where updated and relevant knowledge significantly enhances intangible resources (Zhang & Sun, 2020). This contributes to a nuanced understanding of how GKM influences IC and highlights the importance of context in KM research.

4.2.3. Highlighting the Role of GIC as a Mediator

- **GIC as a Mediator in Emerging Economies**: The study provides new theoretical insights by emphasizing GIC as a critical mediator between GKM, GTI, and sustainable performance. This perspective is particularly novel in the context of developing countries, where the role of GIC in mediating these relationships has been underexplored (Al-Hakimi et al., 2022). GIC is presented as a catalyst for innovation and sustainable practices, crucial for firms in emerging economies like Pakistan, where environmental challenges are significant. By demonstrating the importance of GIC in enhancing sustainable performance, this research contributes to the KBV literature from the perspective of emerging markets.

4.2.4. Exploring AI's Moderating Role

- **AI's Influence on GKM and GHC**: This study sheds light on AI's moderating role in the relationship between GKM and Green Human Capital (GHC). This finding adds a significant contribution to AI literature by highlighting AI's role in leveraging technical resources to enhance intangible resources' capabilities. However, it also underscores that AI alone is insufficient; firms must combine AI with GKM practices to improve collaboration and coordination among employees (Rahman et al., 2023). This dual approach enriches the understanding of how AI can be integrated into organizational practices to support green innovation and sustainable performance.

In summary, this research extends theoretical knowledge in multiple domains by clarifying the relationships between GKM, GTI, and GIC, emphasizing the role of GIC in emerging economies, and exploring AI's moderating effects. These contributions provide valuable insights for both academics and practitioners seeking to understand and leverage intangible resources for enhanced performance and sustainability.

4.3. Practical Contributions

The findings of this study offer valuable practical insights for policymakers, managers, and practitioners, particularly in the context of promoting Green Technological Innovation (GTI) and enhancing sustainable performance. Here are the key practical contributions:

4.3.1. Investment in Information Technology

- **Enhancing GKM and GTI**: The results highlight the importance of developing cutting-edge IT infrastructures to support Green Knowledge Management (GKM) and GTI. Managers should align these technological investments with the firm's strategic mission and vision, ensuring that they integrate seamlessly with existing management approaches. Effective IT infrastructure supports the efficient management of knowledge and technological innovation, thereby improving overall sustainability efforts (Sahoo et al., 2022).

4.3.2. Strategic Management of Technology Resources

- **Compatibility and Coordination**: In engineering and construction contexts, it is crucial for managers to oversee the compatibility of all technological resources. By managing these resources effectively, firms can

enhance their technological capabilities and achieve better sustainability outcomes. This approach fosters a cooperative green mindset across organizational teams and business allies (Asiaei et al., 2022; Xie et al., 2019).

4.3.3. Balancing Financial and Environmental Goals

- **Beyond Financial Success**: While improving financial performance is essential, firms must also focus on sustainability and environmental protection. The study underscores the need for firms to take additional steps to minimize their environmental impact and protect natural resources. This involves investing in green technologies, enhancing knowledge bases, and adopting practices that contribute to sustainable development (Algarni et al., 2022).

4.3.4. Investing in Green Innovation and Marketing

- **Promoting Eco-Innovation**: For construction firms aiming to enhance their sustainable performance, it is crucial to invest in Green Innovation Capabilities (GIC) and GKM. This includes implementing processes that facilitate the creation of innovative environmental solutions and adopting green marketing strategies. Effective green marketing can boost firm performance by promoting sustainable products and solutions, as well as strengthening the firm's eco-friendly reputation (Kinnunen et al., 2022).

4.3.5. Role of AI in Enhancing GHC

- **Integrating AI for Better Outcomes**: The study highlights AI's role as a moderator in the relationship between GKM and Green Human Capital (GHC). Organizations should develop clear strategies for incorporating AI to improve sustainability and process performance. This involves investing in AI technologies, training staff to work effectively with AI systems, and addressing ethical concerns related to AI. Establishing internal and external control mechanisms can help manage privacy issues and ensure that AI contributes positively to organizational goals (Chowdhury et al., 2022; Rahman et al., 2023).

In summary, the practical implications of this study suggest that firms, particularly in the construction sector, should focus on integrating advanced IT infrastructure, managing technology resources strategically, balancing financial and environmental goals, investing in green innovation, and effectively utilizing AI to enhance their sustainability and performance. These measures will help organizations achieve their sustainability objectives and improve their overall performance.

5. Conclusion

This study examined the impact of Green Knowledge Management (GKM) on Green Technological Innovation (GTI) and sustainable performance within the construction industry, and assessed the role of Artificial Intelligence (AI) in these relationships. The key findings are:

- **Positive Impact of GKM**: GKM positively affects both GTI and sustainable performance.
- **Mediating Role of GIC**: Green Innovation Capabilities (GIC) mediate the relationships between GKM and both GTI and sustainable performance.
- **AI's Influence**: AI significantly moderates the relationship between GKM and Green Human Capital (GHC).

These findings underscore the importance of leveraging GKM and GIC to enhance GTI and sustainability performance, and highlight AI's role in strengthening GKM's impact on GHC.

Limitations and Implications for Future Research

While the study offers valuable insights, it also has several limitations that should be addressed in future research:

- **Sample Size and Generalizability**
    - The study's findings are based on a sample of 309 participants, which may limit the generalizability of the results. Future research should consider increasing the sample size to enhance the robustness of the findings. Additionally, examining different sectors and countries, and employing longitudinal or time-wave designs could provide a broader understanding of the relationships studied.

2.

- **Scope of AI Moderation**
    - The study focused on the moderating impact of AI on the relationship between GKM and GHC in the context of Pakistan. Future research could explore other factors that might influence this relationship, such as leadership styles, organizational support, or varying contexts within different industries.
- **Control Variables**
    - Although some control variables were considered, future studies could further investigate the direct impacts of additional control variables, such as gender and industry type, on the outcome variables. This could provide deeper insights into how these factors affect GKM, GTI, and sustainable performance.
- **Environmental Dynamism**
    - Future research should examine how environmental dynamism—i.e., the rate of change in the external environment—affects the relationships between GKM and GTI and sustainable performance. Understanding how dynamic environmental conditions influence these relationships can offer valuable perspectives for managing sustainability in varying contexts.

Overall, these suggestions aim to build on the current findings and address the study's limitations, contributing to a more comprehensive understanding of GKM, GTI, sustainability, and AI in different settings.

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