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The Influence of Green Intellectual Capital on Green Product and Process Innovation: The Mediating Role of Green Knowledge Sharing in the Pakistani SMEs

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ABSTRACT

The present study is undertaken to investigate the underlying mechanism of the relationship between three dimensions of Green Intellectual Capital (GIC), which include Green Human Capital (GHC), Green Structural Capital (GSC), and Green Relational Capital (GRC), with green product innovation (GPDI) and green process innovation (GPRI) within the context of Pakistani manufacturing Small and Medium Enterprises (SMEs). This investigation aims to elucidate the function of green knowledge sharing (GKS) as a mediating mechanism among GHC, GSC, GRC, GPDI, and GPRI by incorporating concepts from the natural resource based view (NRBV) and the knowledge based view (KBV) theories. A quantitative study design was used, with survey data collected from 381 owners and managers of manufacturing SMEs in Pakistan. Structural Equation Modeling (SEM) techniques were used to examine the proposed relationships among these variables. Results show that all components of GIC considerably influence both GPDI and GPRI, directly and indirectly through GKS. GKS has a significant impact on the development of intangible green competencies, resulting in innovative outcomes. This research contributes to the literature by applying NRBV and KBV theories in the context of green innovation within resource constrained SMEs. The study found that these firms can enhance their green innovation performance by leveraging green intellectual capital and cultivating a culture of green knowledge sharing. The study has significant implications for policymakers and business leaders in developing regions, promoting and encouraging the adoption of sustainable approaches.

Introduction

The combination of air pollution, energy consumption, and climate change is severely exacerbating environmental issues (Dźwigoł et al., 2023). It is estimated that the total volume of material waste is expected to reach 2.59 billion tonnes by the year 2030, underscoring the need for action to mitigate waste and reduce the harmful effects of climate change (Peng et al., 2023). Every year, the world generates more than two billion tons of municipal solid waste and at least one third of this waste is not managed adequately (Kaza et al., 2018). Kalagy et al. (2025) estimated that the global solid waste will reach 3.88 billion tons by 2050 due to ongoing urbanization and rising populations which is a 73% increase from 2020. These ecological concerns have caused a great deal of apprehension among people all over the world. According to Ullah et al. (2021) and Xu et al. (2022), sustainable development objectives such as decreasing carbon emissions, promoting the use of renewable energy, and sustaining global environmental protection have been established by the societies worldwide. The Eco-Innovation Action Plan 2011 by European Commission, the 2030 Agenda of the United Nations General Assembly for sustainable development, and the Glasgow Climate Pact 2021 have all adopted this consensus.

According to the Environmental Performance Index 2024, Pakistan is placed on 179th position out of 180 countries and is among the developing nations struggling to uphold environmental sustainability. Pakistan, with a population of 220 million and ranking 19th in greenhouse gas emissions, is projected to release 2.9 tonnes of CO2 per capita by 2025 and 5.4 tonnes per capita by 2050 (Iftikhar et al., 2024). Manufacturing operations have a considerable and frequently negative influence on the environment due to their excessive use of natural resources, huge energy consumption, greenhouse gas emissions, and production of hazardous waste (Alinda et al., 2024; Andersén, 2021; Li et al, 2020). 98% of manufacturing firms are SMEs in Pakistan and 80% of these firms are located in urban areas. Many enterprises lack sufficient controls for managing greenhouse gas emissions, leading to significant waste (Ishaq et al., 2024). Approximately 5.2 million SMEs operate in Pakistan, including service providers, manufacturing entities, and diverse startups across several sectors (Qamar et al., 2024). SMEs constitute approximately 80 percent of the non-agricultural labor population, providing nearly 40 percent of Pakistan's annual GDP (Khan et al., 2024k; Qamar et al., 2024). The manufacturing industry must implement policies that enhance environmental quality to reduce emissions (Ren & Mia, 2025).

According to sustainability scholars, green innovation (GRI) can help SMEs control environmental degradation, minimize environmental pollution, and improve a company's performance (Huang & Li, 2017; Zhang et al. 2023). The SMEs can gain substantial benefits by taking initiatives to promote GRI that enable them to meet stakeholder expectations while dealing with environmental degradation (Singh et al., 2022). GRI can promote high quality economic development by attaining a balance of environmental, financial, and social benefits (Asadi et al., 2020). Earlier studies have frequently concentrated on the outcomes of GRI (Ahmar & Astuti, 2023; Cheng et al., 2023; Ji et al., 2024; Rahmani et al., 2024; Ta'Amnha, 2024; Niazi et al., 2023). However, relatively few researchers have examined the underlying drivers of GRI, leaving significant gaps in understanding of the factors that predict GRI within SMEs (Ahmed et al., 2023; Yadegaridehkordi et al., 2023; Ta'Amnha et al., 2024). The current study presents Green Intellectual Capital (GIC) as a strategic organizational asset to mitigate ecological degradation by advancing GRI. Prior research suggests that GIC enhances a firm's ecological performance (Jirakraisiri et al., 2021; Li, et al., 2023; Ahmar & Astuti, 2023). GIC stems from the broader concept of Intellectual Capital (IC) which refers to intangible organizational assets such as information, knowledge, and data that contribute to increased sustainable corporate value (Chen, 2008a).

Traditionally, intellectual capital has been categorized into three forms: Human, Structural, and Relational Capital (Edvinsson & Malone, 1997). Human Capital includes the talents, competencies, and creative capacities of personnel that contribute to environmental goals (Stewart, 2001). Structural Capital denotes the organizational infrastructure encompassing sustainable practices, databases, intellectual property, and environmental management systems (Bontis et al., 2002). Relational Capital refers to the trust, loyalty, and long term affiliations established with customers, suppliers, and external regulatory bodies (Stewart, 2001; Bontis et al., 2002). Recent researches have advanced the concept by incorporating the environmental aspect of intellectual resources and introduced Green Human Capital (GHC), Green Structural Capital (GSC), and Green Relational Capital (GRC) (Chen, 2008a).

Empirical studies on GIC as a strategic intangible capital are scarce in developing countries like Pakistan despite the growing global interest in this topic. Conversely, studies conducted in numerous countries have broadly examined the effect of GIC on environment performance, competitive advantage, green innovation performance and sustainability (Marco-Lajaraet al., 2023; Asiaeiet al., 2023; Martínez-Falcó et al., 2024; Buhaya & Metwally, 2024). These results confirm the strategic significance of GIC in global contexts. However, there is a considerable gap in the SME sectors of Pakistan, where the impact of the three elements of GIC on GPDI and GPRI is not sufficiently investigated. The present research address this gap by offering empirical evidence of the specific impact of each dimension of GIC on two forms of GRI separately in Pakistani manufacturing SMEs. The SME sector in Pakistan is increasingly becoming one of the key contributors to environmental damage owing to unsustainable industrial activities and a lack of effective environmental policies (ud Din et al., 2025; Mehboob & Zaidi, 2024). Earlier studies have proven that GRI which includes both GPDI and GPRI has strong potential for fostering sustainable development, particularly in SMEs (Saleem et al., 2024; Ishaq et al., 2024; Zhang et al., 2023). The study concentrates on GHC, GSC, and GRC as strategic drivers for achieving GPDI and GPRI within Pakistani manufacturing SMEs. This research focuses on the role of Green Knowledge Sharing (GKS) in transforming three dimensions of GIC into successful innovation outcomes (Li et al., 2023). The research investigates these relationships as well as their collective impact on GRI. The study will provide numerous strategic pathways for SMEs to improve their ecological sustainability. This work contributes to the conceptual gaps in the literature which intertwine sustainability with environment knowledge sharing. Moreover, this research provides significant findings that can be employed by practitioners, policymakers, and professionals seeking to enforce green initiatives in the manufacturing SME landscape.

Research Objectives and Questions

This study seeks to address the following research questions:

1. What is the impact of GHC, GSC, and GRC on GPDI and GPRI in Pakistani manufacturing SMEs?
2. Do GHC, GSC, and GRC influence GKS in these firms?
3. Does GKS mediate the relationship between GHC, GSC, and GRC and both GPDI and GPRI in Pakistani SMEs?

Significance of the Study

This research contributes to the literature by analyzing the impact of three specific dimensions of GIC on GPDI and GPRI (Chen, 2008; Yusliza et al., 2020). It deepens our understanding of how GIC's components affect particular green innovation results (Shahzad et al., 2020; Abbas et al.,

2021). Secondly, this study offers a new insight distinct from other studies by explaining GKS as a mediating variable between GIC and GRIC under the Knowledge Based View (KBV) of the firm (Grant, 1996), thus showing more clearly how components of GIC influence GPDI and GPRI. Third, the research fills an important gap in the literature pertaining to manufacturing SMEs in Pakistan. This sector is frequently disregarded in sustainability studies despite its substantial environmental impact (Qamar et al., 2024). In conclusion, the study argues that internal green capabilities of the firms including GIC can serve as strategic resources that generate an environmentally sustainable competitive advantage by incorporating the NRBV (Hart, 1995). This theoretical incorporation enhances the study's contribution by conceptualizing green innovation as a resource based approach for enduring sustainability and a knowledge driven process. The findings supports the decision makers to strategically invest in the most effective green intellectual resources for specific innovation outcomes.

The paper is organized into five primary sections. The literature review section synthesizes existing research and generates hypotheses. The methodology section delineates the utilization of a quantitative, cross sectional, and descriptive research design which is predicated on simple random sampling of respondents from Pakistan's manufacturing SME sector and a structured questionnaire. SmartPLS was employed to analyze the data using Structural Equation Modeling (SEM). The hypotheses are tested in the results section, and the results primarily support both direct and indirect effects. These are addressed in accordance with the current body of literature, and a conclusion is provided that encompasses future research directions and limitations.

Theoretical background and hypotheses development

Theoretical background

The natural resource based view (NRBV) and knowledge based view (KBV) theories are combined to form the basic theoretical framework of the present study. This dual perspective leverages GIC and green knowledge to navigate the complex dynamics of green assets and innovation within the corporate environment.

According to the NRBV proposed by Hart and Dowell in 2011, businesses can secure sustainable competitive advantages by obtaining and managing environmentally benign, rare, and valuable resources through proper stewardship. This approach enriches the traditional resource based view by introducing the environment as a significant element of the company's strategic portfolio (Mishra & Yadav, 2021). This research envisions these capabilities within a dynamic framework, proposing that strategically structured capabilities, especially via GKS, augment a firm's capacity for GRI and fortify its market position.

At the same time, KBV theory considers information to be the most strategically pertinent resource for attaining and maintaining a competitive advantage (Grant, 1996). Based on this perspective, an organization's ability to acquire, integrate, and mobilize green knowledge is central to its capacity to innovate, particularly in terms of long term performance (Eisenhardt & Santos, 2006). This method not only enhances the application of intellectual capital but also strengthens the company's culture of sustainability, fostering GRI in both products and processes (Sahoo et al., 2023; Zhang, 2024).

The theoretical framework outlines how companies utilize intellectual and green knowledge capabilities to enhance their green performance, highlighting the combined NRBV and KBV approach to develop the theory further and foster GRI. The following sections specify the primary constructs and detail the proposed connections among them.

Green Intellectual Capital

The concept of GIC was first introduced by Chen in 2008 and refers to the collection of intangible resources and capabilities connected with innovation that protect the environment (Chen, 2008a; Chang & Chen, 2012). The contribution of GIC toward sustainable performance is noticeable because it equally integrates components such as knowledge, abilities, and skills which help organizations and firms to improve environmental, financial, and social performance (Chen, 2008a). However, there is still a debate on how companies use the different intangible assets to improve their performance to gain a competitive advantage (Haldorai et al., 2022). The literature commonly divided GIC into three key components: Green Human Capital (GHC), Green Structural Capital (GSC), and Green Relational Capital (GRC) (Li et al., 2023; Ahmar & Astuti 2023; Asiaei et al., 2023; Chen, 2008a). GHC refers to the environmental knowledge, skills, competencies, experiences, attitudes, and creative capabilities that employees bring to the organization (Chen & Chang, 2013; Wang & Juo, 2021). According to Irfan et al. (2022), GSC is the repository of organizational capability, culture, knowledge management systems, trademarks, patents, copyrights, and other components relevant to a corporation's environmental preservation or ecological innovation. GRC prioritizes strategic alliance with external parties on environmental development (Chen, 2008a, Yusoff et al., 2019; Ahmar & Astuti, 2023). Yu and Huo (2019) ultimately articulate the concept of GRC, which integrates the interactions by stakeholders about business environmental control and green improvement.

Green Innovation (GRI)

GRI is defined as an innovation that intentionally or unintentionally reduces negative environmental impacts (Kraus et al., 2020). It is critical for ensuring business continuity and an enduring competitive advantage (Ishaq et al., 2024). GRI supports organizations in transitioning towards green manufacturing practices, thereby minimizing environmental damage (Huang & Li, 2017). Companies can enhance their corporate image, expand market share, and expand new business opportunities by demonstrating environmental stewardship (Shah & Soomro, 2021). Chen (2008b) classified green innovations into “green product innovation” and “green process innovation.” In this study, we adopted this classification which is also consistent with the investigative framework of Ullah et al. (2022).

GIC and GRI

As outlined in NRBV, the foundation of competitive advantage lies in capabilities that are rare, valuable, and difficult to replicate, particularly when they are in harmony with ecological considerations (Hart, 1995). GIC aligns with this framework by cultivating internal skills that empower organizations to innovate environmentally, oversee green knowledge, and build sustainable relationships with stakeholders (Yusliza et al., 2020). Hart and Dowell (2011) indicate that when GIC is nurtured and aligned with NRBV principles, it serves as a foundational capability that assists firms in reducing environmental impact while attaining differentiation and cost advantages through green innovation. Nonetheless, limited research investigates the precise mechanism through which three dimensions of GIC influences GPDI and GPRI in firms.

GHC and GPDI & GPRI

GHC is a valuable resource for organizational innovation as environmental preservation and sustainable development become increasingly significant (Chien et al. 2022, 2023b). GHC acts as a platform that facilitates the integration of green innovation with the environmental awareness of employees (Asiaei et al., 2023). Companies can boost their operation efficiency in terms of GPDI and GPRI by utilizing their GHC potential. Empirical studies indicate that SMEs investing more effort in GHC tend to achieve better environmental outcomes, along with enhanced business

performance (Li et al., 2023; Ullah et al., 2021; Singh et al., 2020). Therefore, a firm's green performance depends significantly on the effective utilization of its GHC (Yusoff et al., 2019). Hence, it is proposed that

H1a: GHC has a positive impact on GRPDI.

H1b: GHC has a positive influence on GRPDI.

GSC and GRPDI & GRPRI

In contrast to GHC, the GSC operates with little reliance on staff. GSC enables managers to assess the potential for reducing pollution by redesigning processes and enhancing eco-productivity (Asiaei et al., 2023). Malik et al. (2020) argue that leaders must invest in robust green systems to acquire environmental knowledge and sustain innovation. Other scholars argue that companies with strong GSC roots are more inclined to adopt new tools and practices that reduce harm to nature (Yong et al., 2022; Xi et al., 2022). A wide range of studies thus shows that GSC serves as a powerful driver of GRI in the industrial sector. Hence, it is proposed that

H2a: GSC has a positive effect on GPDI.

H2b: GSC has a positive impact on GPRI.

GRC and GPDI & GPRI

Yusliza et al. (2020) highlight that adequate GRC enables managers to establish eco-conscious relationships with strategic partners, disseminate knowledge about environmental issues, and guide the firm toward new green innovations. Networks backed by GRC tend to generate fresh, creative, and clean technologies, ideas, and business opportunities (Wang & Juo, 2021). Through these joint efforts, participants gain clearer insight into how specific practices, resources, and workflows impact the environment, a knowledge that fuels further green innovation (Ali et al., 2021; Tran et al., 2023). Based on these studies, the following hypotheses are put forth:

H3a: GRC has a positive influence on GPDI.

H3b: GRC has a positive effect on GPRI.

Green Knowledge Sharing (GKS)

Knowledge sharing can be enhanced by establishing a structure that prioritizes social interaction among employees inside an organization (Wang et al., 2022). GKS is characterized as the process of instructing personnel about environmental matters to advance an organization's sustainability objectives (Zhang, 2024). GKS refers to the process by which employees exchange environmental information to help their workplace achieve sustainability targets (Ahmed et al., 2023). To work effectively, a company must foster a climate that encourages employees to share their knowledge. When sharing becomes the norm, colleagues tend to imitate it, and many staff members go beyond their baseline duties to help achieve the firm's green objectives (Abbas & Khan, 2023). GKS thus measures how broadly team members disseminate ecological insights, thereby improving the organization’s overall environmental performance (Lin & Chen, 2017).

Green Intellectual Capital and Green Knowledge Sharing

According to the KBV, companies are perceived as dynamic systems for integrating and applying knowledge (Grant, 1996). Chuang and Huang (2018) propose that an organization's level of active participation in acquiring green-related knowledge and resources is a key factor in determining its environmental performance. Given the internal ramifications, GIC and GKS might contribute to

reducing environmental expenses and advancing staff members' professional expertise and understanding of eco-friendly concepts and energy-saving technologies.

GHC and GKS

GHC refers to human resource attributes such as expertise, knowledge, capabilities, wisdom, creativity, skills, and qualifications related to environment awareness and GRI (Chen, 2008l Asiaei et al., 2018). Similarly, organizations have increasingly recognized the importance of imparting environmental knowledge in their employees to foster GRI and management in response to external environmental pressure (Chang & Chen, 2012). Previous studies have identified that the cultivation of GHC fosters a positive relationship between GKS and green relationship learning, resulting in better green innovation performance (Chang & Chen, 2012; Asiaei et al., 2022). Consequently, Song et al. (2020) demonstrates that GHC fosters employees' environmentally conscious behaviors, consequently boosting their readiness to engage in GKS initiatives. Thus it is proposed that

H4: GHC has a positive impact on GKS.

GSC and GKS

The firm's KBV argues that the routines, structures, systems, and culture a company embeds over time form a strategic asset that supports lasting competitive advantage (Grant, 1996). Within this framework, GSC plays a crucial role by enabling firms to disseminate environmental information effectively. GSC encompasses all the capabilities, knowledge-management networks, incentive schemes, databases, IT platforms, managerial tools, daily procedures, leadership outlooks, corporate culture, public reputation, intellectual property, copyrights, and trademarks that relate to GRI or environmental protection (Chen, 2008a). GSC offers the infrastructure, information systems and strategies to efficiently gather, preserve, and share green knowledge (Inkinen, 2015; Jardon & Dasilva, 2017). According to Shahbaz et al. (2024), the firms possessing robust structural support, such as green databases, sustainable workflows, and employee training systems, foster a supportive environment for knowledge exchange. Hence, it is postulated that

H5: GSC has a positive effect on GKS.

GRC and GKS

Under the KBV of the firm, external and internal relationships are seen as crucial conduits for knowledge acquisition, diffusion, and application (Grant, 1996). GRC functions as a relational knowledge infrastructure, facilitating the flow of green tacit and explicit knowledge across organizational boundaries (Inkinen, 2015). Shahbaz et al. (2024) empirically confirm the significance of GRC in enhancing GKS and green process innovation, highlighting how organizations with strong external environmental ties are better positioned to leverage external knowledge for internal sustainability improvement. GRC asserted that collaboration with external partners can foster GRI by facilitating creativity and encouraging the exchange of fresh knowledge and ideas (Wang & Juo, 2021). In the KBV framework, the firm is not viewed as an isolated entity but as a node in a knowledge network. Thus, GRC serves as a strategic channel for importing, sharing, and internalizing green knowledge. Thus, it is offered that

H6: GRC has a positive effect on GKS.

GKS and GRI

GKS enables firms to tap into the innovative skills required to develop new products and improve existing processes. By circulating internal ideas and borrowing external insights, an organization

can advance its green innovations (Ghisetti et al., 2015). Such open exchange enables the firm to combine resources and expertise creatively, resulting in solutions that reduce environmental harm (Lin & Chen, 2017). GKS significantly contributes to the improvement of green innovation performance by cultivating a sustainability oriented culture throughout all organizational tiers (Shafait and Huang, 2024). Disseminating knowledge on green technologies, sustainability policies, and eco-efficient practices markedly enhances innovation in both green products and processes (Makhloufi, 2024; Frempong et al., 2021).

H7a: GKS has a positive and significant impact on GPDI.

H7b: GKS has a positive and significant impact on GPRI.

GKS as a Mediating Mechanism

Lin and Chen (2017) argue that knowledge sharing disseminates information and expertise, creating learning opportunities and encouraging others to acquire new skills. However, the heart of knowledge always rests with individual people. Within any organization, these people are the crucial link that moves information from one place to another. From a KBV, Grant (1996) holds that knowledge is a firm's top resource and that a company exists mainly to collect, share, and put that knowledge to work for a lasting competitive edge. When it comes to GRI, this perspective emphasizes the production, dissemination, and application of environmental knowledge as the key drivers of eco-creative outcomes (Song et al., 2020).

The KBV posits that a firm's GIC represents a stock of environmental knowledge that only yields innovative output when it is actively shared and applied (Nonaka et al., 1996). When internal or external channels for sharing this knowledge are weak, much of the GIC remains dormant, significantly curbing its potential to drive green innovation. Effective sharing enables environmental practices, technologies, and problem-solving tools to flow freely throughout the firm, converting static knowledge into practical green solutions (Abbas & Khan, 2023). Consequently, the link between GIC and green innovation is not only direct; it is also mediated by the firm's capacity to mobilize and circulate its environmental knowledge. The study comes up with the following hypotheses:

H8a: GKS mediates the relationship between GHC and GPDI.

H8b: GKS mediates the relationship between GHC and GPRI.

H9a: GKS mediates the relationship between GSC and GPDI.

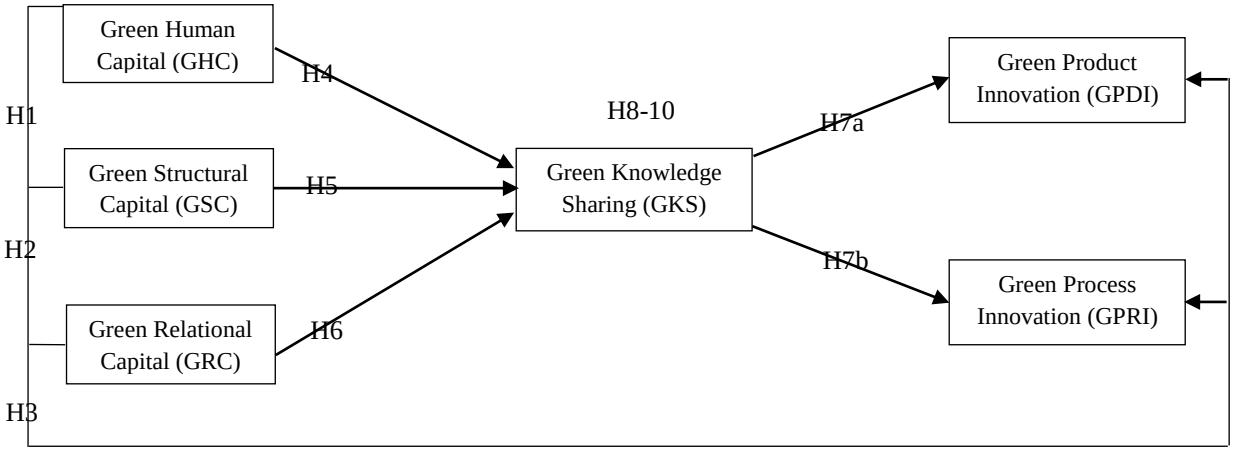
H9b: GKS mediates the relationship between GSC and GPRI.

H10a: GKS mediates the relationship between GRC and GPDI.

H10b: GKS mediates the relationship between GRC and GPRI.

The integration of GHC, GSC, GRC and GKS within the NRBV and KBV provides a comprehensive model for achieving GPDI and GPRI. The proposed research model, illustrated in Figure 1, demonstrates how GKS mediates the effects of each dimension of GIC between GPDI and GPRI.

Figure 1: ***Research Model***



Methodology

Research Design, Sampling and Data Collection

Research philosophy constitutes the foundational principles guiding all stages of the research process from data collection and analysis to interpretation (Sekaran & Bougie, 2016). The positivist paradigm employed in this study posits that reality is something that can be observed, is objective, and is quantifiable through reliable data. In line with this perspective, the researchers employ a quantitative survey design and collect data through a well-structured questionnaire.

Data were collected from manufacturing SMEs located in key industrial cities of the Punjab, Pakistan. These cities included Faisalabad, Lahore, Sialkot, Multan, and Gujranwala. These areas represent the most concentrated manufacturing hubs in the province. According to the definition by the Small and Medium Enterprises Development Authority (SMEDA), an SME in Pakistan has fewer than 250 employees and generates annual revenue of less than PKR 800 million. The lists of SMEs working in various industries were obtained from the Chambers of Commerce in each target region. We used a simple random sampling technique to draw sample from the target population. This sampling technique ensure a representative and unbiased sample for the study Creswell et al. (2003). Data were collected using a cross sectional method which is appropriate for analyzing interactions between variables. According to Creswell and Poth (2016) and Creswell et al. (2003), a quantitative research approach is most reliable for investigating statistical relationships between variables. The sample size for this study was calculated by using G*Power 3.1.9.7 software to ensure adequate power for a multiple linear regression model featuring four predictors. The calculation employed a medium effect size ($f^2 = 0.15$), a 0.05 level of significance, and a 0.95 desired power. According to the G*Power output, a minimum of 129 participants is required to detect statistically meaningful relationships. The researchers followed Sekaran and Bougie (2016) to minimize the risk of a low response rate and possible bias by focusing a larger sample size. A larger sample size improve response rate and minimize error, so increases the generalizability of the results (Taherdoost, 2017). Hair et al. (2019) recommended a sample size from 100 to 400 responses to apply SEM. The researchers calculated sample size by keeping with these criteria and followed the advised range of 100 to 400 responses. SMEs were targeted as the unit of analysis in the present study. The CEOs or owners of these enterprises were requested to complete the questionnaire because they had extensive knowledge about the green innovation policies and programs in the firms. They were assured that their responses would be kept confidential and used only for the research and academic purposes. A total of 650 questionnaires were distributed via personal visits, WhatsApp, and email during September 2024. Participants are required to

complete and submit the questionnaires by October 2024. A total of 393 responses were received and response rate was 60.46%. After scrutiny, a total of 381 valid responses were selected for subsequent analysis for the study variables. SmartPLS software was used to investigate the interactions between the variables by apply PLS-SEM approach as this software is designed to study such complex research models (Hair et al., 2019).

Measures

A structured questionnaire was developed to measure the study variables. Reponses were recorded on a Likert scale from 1 to 5 (Dou & Ishaq, 2024), with 1 denoting “strongly disagree” and 5 representing “strongly agree” about the items of the respective variable. The research utilized established and validated instrument used in the past studies. GHC, GSC, and GRC were measured using scales from the study of Chen (2008) and Yusliza et al. (2020). The GHC was determined using a five items scale (CR = 0.90, α = 0.87). One sample item is "Employee competence concerning environmental protection in our firm is better than that of our major competitors". GSC was measured with nine items (CR = 0.94, α = 0.93). One of the items was "The overall operational processes for environmental protection in our firm work smoothly." Similarly, GRC comprised five items (CR = 0.9, α = 0.86) including "Our firm has well-cooperative relationships concerning environmental protection with our strategic partners." The GKS was evaluated utilizing a six items scale developed by Yu et al. (2022). A sample item was "We are provided with the latest equipment and technology to obtain and share knowledge." The scale indicated substantial reliability in this study (CR = 0.96, α = 0.95). GPDI and GPRI were measured using scales adapted from the studies of Chen et al. (2016) and Begum et al. (2022). The GPDI scale comprised four items (CR = 0.97, α = 0.97) and a sample item was "Our firm uses the fewest number of materials to comprise the product for conducting product development or design." A four items scale was utilized to measure GPRI (CR = 0.98, α = 0.97) with one sample item "The manufacturing process of the company reduces the consumption of water, electricity, coal, or oil." All these scale demonstrated high reliability and validity in the present study (Dijkstra & Henseler, 2015).

Data Analysis and Results

Demographic Information

The survey results present a diverse participant profile across age, education, industry, geographic location, professional experience, and gender. The largest age group was 31–35 years with 33.8%, followed by participants aged 25–30 (26.3%), 36–40 (19.5%), 20–25 (13.2%), and those aged 41 and above with 7.2%. In terms of education, 33.9% of respondents hold a matriculation qualification, followed by those with master's degrees (29.5%), high school education (24.5%), and graduate-level qualifications (12.1%). 73.8% were male and 26.2% were female respondents. Geographically, responses were concentrated in major industrial cities, including Faisalabad (25.3%), Sialkot (24.1%), Gujranwala (18.2%), Lahore (17.3%), and Multan (15.1%), reflecting the prominence of these regions in Pakistan's manufacturing sector. In terms of professional experience, the majority of participants have 16–20 years of experience (46.8%), while only 10.9% reported having over 21 years of experience. Industry wise, the textile sector was most represented (29.7%), followed by iron and steel (19%), pharmaceuticals (19%), home appliances (16.2%), automotive (12.7%), and food processing (3.5%).

Common Method Bias

In survey based research, common method variance (CMV) bias is a serious issue. The CMV was evaluated in the present investigation applying Harman's single factor test (Podsakoff et al., 2003). Harman (1976) developed this test to assess the probability of CMV among constructs. The

findings demonstrated that there were numerous components within the sample items, with the main factor explaining 43.809% of the variation, which is less than the suggested minimum of 50%. In addition, we implemented a comprehensive collinearity evaluation employing Smart-PLS, as advised by Kock (2015) and other social science researchers. This method is considered precise and effective for computing CMV. The results exhibited that CMV is not a significant concern in our model, as evidenced by Variance Inflation Factor (VIF) values that are less than the suggested threshold of 5.

Results

This study employs PLS-SEM to analyze the data by the sample and the theorized model, accounting for intense mediation effects (Hair et al., 2019). PLS-SEM suits complicated frameworks that include latent variables because it does not rely on the assumption of multivariate normality (Chin, 1998). SmartPLS is commonly used in multivariate work to estimate these elaborate structural equation models, especially when the data is skewed or when researchers are still in the exploratory phase (Hair et al., 2019; Benitez et al., 2020). For that reason, the analysis here follows the PLS-SEM tradition. The researcher executed all tests through SmartPLS 4.0. First, the measurement model was checked and thereafter, the structural model was examined (Sarstedt et al., 2021). Only constructs that passed indicator loading, convergent validity, composite reliability, and discriminant validity then entered the structural model. Finally, bootstrapping was used to estimate the size and significance of each path coefficient.

Measurement Model

The authors utilized a reflective framework to study the relationship between latent and manifest variables. The evaluation of the measurement model started with assessing discriminant validity, convergent validity, and reliability. Reliability concerns were evaluated through Cronbach's Alpha and composite reliability (CR) as was delineated by Hair et al. (2018). Chin (1998) deemed these measures acceptable if values lie from 0.70 to 0.95. Values presented in Table 1 indicate that all Cronbach’s Alpha and CR values are within these limits which support the scales' reliability. Convergent validity was evaluated using average variance extracted (AVE) alongside outer loadings per recommendations from Hair et al., 2018. These must exceed the threshold of 0.50 as suggested by Hair et al., 2018. The information contained in Table 1 validates all values that satisfy this requirement, thus affirming the constructs' convergent validity.

Figure 2: ***Measurement Model***

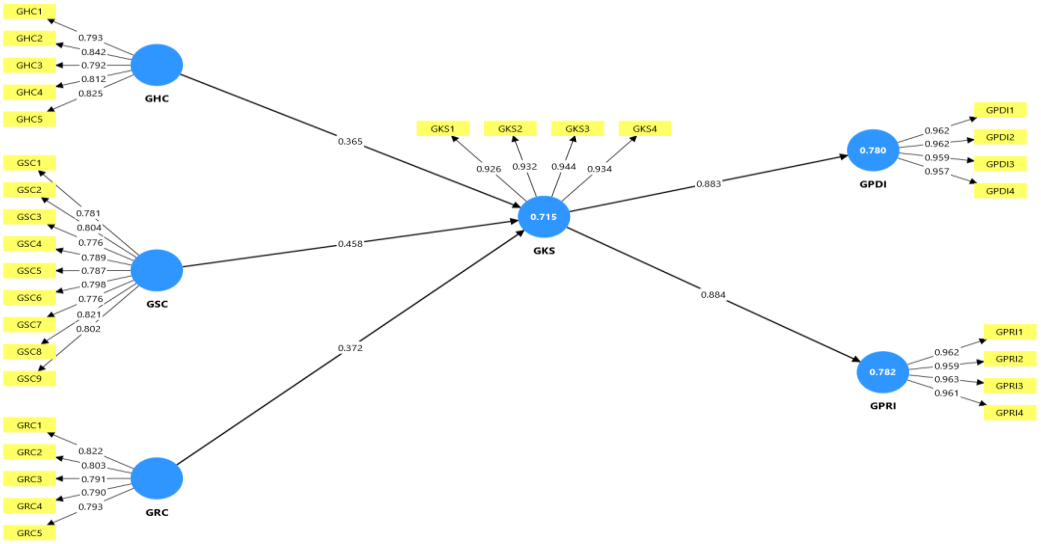


Table 1: ***Reliability and validity testing***

Variable and constructs	Items	FL	VIF	CA	CR (rho_a)	CR (rho_c)	AVE
Green Human Capital				0.872	0.876	0.907	0.661
	GHC1	0.793	1.854				
	GHC2	0.842	2.105				
	GHC3	0.792	1.837				
	GHC4	0.812	2.006				
	GHC5	0.825	2.075				
Green Structural Capital				0.926	0.927	0.938	0.628
	GSC1	0.781	2.096				
	GSC2	0.804	2.300				
	GSC3	0.776	2.079				
	GSC4	0.789	2.143				
	GSC5	0.787	2.139				
	GSC6	0.798	2.242				
	GSC7	0.776	2.049				
	GSC8	0.821	2.390				
	GSC9	0.802	2.260				
Green Relational Capital				0.859	0.860	0.899	0.640
	GRC1	0.822	2.067				
	GRC2	0.803	1.910				
	GRC3	0.791	1.772				
	GRC4	0.790	1.789				
	GRC5	0.793	1.806				
Green Knowledge Sharing				0.951	0.951	0.965	0.872
	GKS1	0.926	4.128				
	GKS2	0.932	4.386				
	GKS3	0.944	3.121				
	GKS4	0.934	4.450				
Green Product Innovation				0.972	0.972	0.979	0.922
	GPDI1	0.962	3.588				
	GPDI2	0.962	4.598				
	GPDI3	0.959	4.071				
	GPDI4	0.957	2.851				
Green Process Innovation				0.972	0.972	0.980	0.924
	GPRI1	0.962	2.665				
	GPRI2	0.959	2.125				
	GPRI3	0.963	2.757				
	GPRI4	0.961	1.427				

Note: *CA* Cronbach's alpha, *CR* composite reliability, *AVE* average variance extracted

The study used the Fornell-Larcker criterion and HTMT ratio to measure discriminant validity because they are well recognized and highly accepted methods (Hair et al., 2018). The authors calculated the square root of the AVE for each construct with Fornell-Larcker criterion. The results confirmed that all constructs had greater variance with their respective indicators as opposed to other constructs, thus confirming satisfactory discriminant validity (Hair et al., 2018).

Based on the HTMT criteria, it is recommended that values stay under 0.85 and anything above 0.90 may raise some questions about discriminant validity issues. In the present study, all HTMT metrics stayed below 0.80 indicating that the constructs are empirically distinct as shown in Table 2.

Table 2: ***Heterotrait-monotrait ratio (HTMT)***

	GHC	GSC	GRC	GKS	GPDI	GPRI
Green Human Capital	-					
Green Structural Capital	0.288	-				
Green Relational Capital	0.187	0.329	-			
Green Knowledge Sharing	0.598	0.706	0.626	-		
Green Product Innovation	0.543	0.659	0.585	0.818	-	
Green Process Innovation	0.548	0.647	0.578	0.819	.897	-

Note: *GHC* green human capital, *GSC* green structural capital, *GRC* green relational capital, *GKS* green knowledge sharing, *GPDI* green product innovation, *GPDI* green process innovation

Moreover, validity was assessed following Fornell & Larcker's (1981) criteria for discriminant validity. The results presented in Table 3 also support the model's discriminant validity in that the square roots of the AVE for each construct are greater than its inter-construct correlations.

Table 3: ***Fornell-Larcker criterion***

	GHC	GSC	GRC	GKS	GPDI	GPRI
Green Human Capital	0.813					
Green Structural Capital	0.261	0.793				
Green Relational Capital	0.165	0.295	0.800			
Green Knowledge Sharing	0.546	0.664	0.567	0.934		
Green Product Innovation	0.502	0.626	0.535	0.883	0.960	
Green Process Innovation	0.507	0.615	0.529	0.884	0.873	0.961

Note: *GHC* green human capital, *GSC* green structural capital, *GRC* green relational capital, *GKS* green knowledge sharing, *GPDI* green product innovation, *GPDI* green process innovation

Structural Model

Bootstrapping was performed with 5,000 subsamples to assess the structural model in SmartPLS 4. Hair et al. (2011) have noted that R^2 measures the degree of explanatory power a model has by describing how much variance is accounted for in each endogenous construct. As noted by Henseler et al., 2015, Table 4 provides R^2 values showing significant levels of explained variance along with relevant predictive value for certain constructs within the model. Also, as highlighted in Table 4, Q^2 conveys relevance sufficing predictive accuracy for those regression outcomes deemed endogenous within the structure and provided by Henseler et al., (2015) as a measure of model predictive relevance. To validate its hypothesis and confirm predictive relevance, the Smart-PLS blindfolding procedure was conducted on Q^2, where values above zero were deemed as confirming adequate prediction (Hair et al., 2019). GPDI's R^2 stands at 0.780 suggesting that 78% of its variance is captured presenting moderately strong explanatory power level per given range between low moderate high ranges.

The adjusted R^2 of 0.779 strengthens the conclusion of a well-fitted model while the Q^2 value of 0.541 suggests good predictive relevance. Also, the f^2 value of 0.351 indicates a large effect size,

meaning that the predictors greatly influence GPDI. Regarding GPRI, its R^2 of 0.782 indicates approximately similar explanatory power to GPDI and the adjusted R^2 of 0.781 also confirms the model's fit. Equally important are the Q^2 value of 0.532, suggesting good predictive relevance, and the f^2 value of 0.358, which corroborates the large effect size confirming the significant impact of predictors on GPRI. Concerning GKS, its R^2 value of 0.715 reflects moderate explanatory power and is further supported by an adjusted R^2 of 0.712 showing minimal loss in explanatory power: The Q^2 value of .636 indicates very good predictive relevance and f^2 value of .397 demonstrating large effect size illustrating strong dependence from predictors on variance in GKS. Furthermore, all VIF values being far below the cutoff point of five suggests no multicollinearity issues and satisfactory structural model fit (Sarstedt et al., 2021).

Figure 3: ***Structural Model***

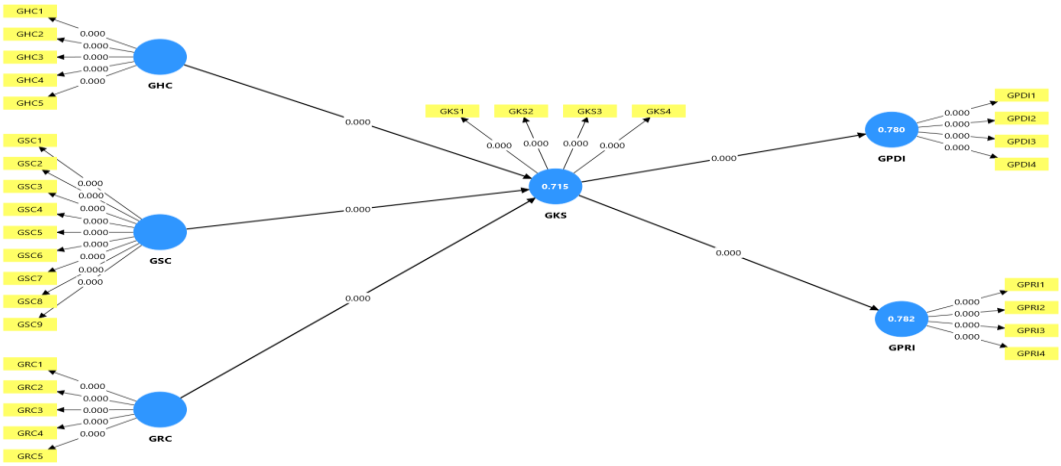


Table 4: ***Coefficient of determination and predictive relevance***

Endogenous Constructs	R^2	R^{2Adj}	Q^2	F^2
GPDI	0.780	0.779	0.541	0.351
GPRI	0.782	0.781	0.532	0.358
GKS	0.715	0..712	0.636	0.397

Note: *GKS* green knowledge sharing, *GPDI* green product innovation, *GPDI* green process innovation

Hypothesis Testing

Subsequently, the path coefficients of the structural model and their significance levels were examined. In accordance with the guidelines of Ringle et al. (2020), a bootstrapping process with 5,000 subsamples was implemented to derive t-values and p-values for assessing the significance of the proposed hypotheses. A total of eleven hypotheses were formulated to investigate direct impact. The results of the regression analysis in Table 5 support Hypotheses H1a and H1b, showing that GHC has a significant and positive effect on both GPDI ($\beta = 0.313$, $t = 11.737$) and GPRI ($\beta = 0.314$, $t = 11.706$). These findings suggest that employees' green knowledge, skills, and awareness play a vital role in fostering environmentally friendly innovation within organizations. Hypotheses H2a and H2b are also supported. GSC positively influences both GPDI ($\beta = 0.395$, $t = 13.587$) and GPRI ($\beta = 0.396$, $t = 13.631$). These results indicate that internal organizational structures, processes, and routines that support green initiatives are instrumental in driving both product and process based environmental innovations. The analysis confirms H3a and H3b as well.

GRC significantly impacts GPDI (β = 0.337, t = 12.294) and GPRI (β = 0.338, t = 12.199). This shows that the relationships and collaborations with external stakeholders such as customers and partners are important enablers of green innovation strategies. The findings further reveal that all three components of GIC positively affect GKS. GHC has a significant positive relationship with GKS (β = 0.355, t = 11.922) supporting H4. GSC has the strongest effect on GKS (β = 0.448, t = 14.041), confirming H5, while GRC also significantly impacts GKS (β = 0.382, t = 12.380) supporting H6. These results highlight the crucial role of intellectual capital in enhancing the exchange and dissemination of green knowledge within organizations. Lastly, Hypotheses H7a and H7b are strongly supported. GKS significantly influences both GPDI (β = 0.883, t = 10.923) and GPRI (β = 0.884, t = 11.361). These values suggest that effective knowledge sharing is a key mechanism through which organizations can translate their green intellectual resources into innovative outcomes. In summary the regression analysis confirms all proposed direct paths indicating that GHC, GSC and GRC significantly contribute to both GPDI and GPRI directly and indirectly through GKS. The results underscore the strategic importance of nurturing green intellectual resources and promoting a culture of knowledge sharing to drive sustainable innovation within organizations.

Table 5: ***Regression Analysis Direct path***

Hypothesis	**Relationships**	**Beta**	**Standard Deviation**	***T* statistics**	***P* values**
H1a	GHC→GPDI	0.313	0.027	11.737	0.000
H1b	GHC→GPRI	0.314	0.027	11.706	0.000
H2a	GSC→GPDI	0.395	0.029	13.587	0.000
H2b	GSC→GPRI	0.396	0.029	13.631	0.000
H3a	GRC→GPDI	0.337	0.027	12.294	0.000
H3b	GRC→GPRI	0.338	0.028	12.199	0.000
H4	GHC→GKS	0.355	0.030	11.922	0.000
H5	GSC→GKS	0.448	0.032	14.041	0.000
H6	GRC→GKS	0.382	0.031	12.380	0.000
H7a	GKS→GPDI	0.883	0.015	10.923	0.000
H7b	GKS→GPDI	0.884	0.015	11.361	0.000

Note: *GHC* Green Human Capital, *GSC* Green Structural Capital, *GRC* Green Relational Capital, *GKS* Green Knowledge Sharing, *GPDI* Green Product Innovation, *GPRI* Green Process Innovation

This study examined the mediating role of GKS between GHC, GSC, GRC and GRI, which includes GPDI and GPRI. The findings in Table 6 provide empirical evidence for most of the hypothesized relationships. The findings show that GKS strongly mediates the links between all three aspects of GIC and both dimensions of GRI, providing full support for hypotheses H8a–H10b. Specifically, GKS significantly mediates the effect of GHC on GPDI (β = 0.313, t = 11.737, p < 0.001) and GPRI (β = 0.314, t = 11.706, p < 0.001), thereby supporting H8a and H8b. These findings suggest that employees' green knowledge and skills contribute to innovation outcomes primarily through knowledge sharing mechanisms. Similarly, GKS mediates the relationship between GSC and GPDI (β = 0.395, t = 13.587, p < 0.001) and GPRI (β = 0.396, t = 13.631, p < 0.001), supporting H9a and H9b. This indicates that green organizational infrastructure and processes facilitate innovation via the dissemination of green knowledge within the firm. Furthermore, the mediating role of GKS is also confirmed in the relationship between GRC and GPDI (β = 0.337, t = 12.294, p < 0.001) and GPRI (β = 0.338, t = 12.199, p < 0.001), supporting H10a and H10b. These results highlight the importance of leveraging external stakeholder

relationships in promoting internal knowledge sharing which in turn drives GRI. Overall, these findings affirm that GKS is a critical mechanism through which GIC translates into GRI outcomes.

Table 6: ***Mediating and moderating effect***

Hypothesis	Relationships	Beta	Standard Deviation	*T* statistics	*P* values
H8a	GHC→GKS→GPDI	0.313	0.027	11.737	0.000
H8b	GHC→GKS→GPRI	0.314	0.027	11.706	0.000
H9a	GSC→GKS→GPDI	0.395	0.029	13.587	0.000
H9b	GSC→GKS→GPRI	0.396	0.029	13.631	0.000
H10a	GRC→GKS→GPDI	0.337	0.027	12.294	0.000
H10b	GRC→GKS→GPRI	0.338	0.028	12.199	0.000

Note: *GHC* Green Human Capital, *GSC* Green Structural Capital, *GRC* Green Relational Capital, *GKS* Green Knowledge Sharing, *GPDI* Green Product Innovation, *GPRI* Green Process Innovation

Discussion and Conclusions

Key Findings

This study advances the understanding of how GIC contributes to GRI through GKS manufacturing SMEs at Pakistan. Drawing on the NRBV (Hart, 1995) and the KBV of the firm (Grant, 1996), the results illustrate how firms can achieve GRI by strategically leveraging their intangible green resources and capabilities. All three dimensions of GIC exhibited significant direct effects on both GPDI and GPRI. These findings align with the NRBV, which posits that a firm's ability to develop and deploy unique environmental capabilities is critical to achieving sustainable competitiveness (Hart, 1995). GHC represents the eco-conscious knowledge and skills of employees, which are critical for initiating green innovation. GSC provides the systems, routines, and infrastructure necessary to support green initiatives, while GRC enables access to external knowledge and collaboration with environmentally engaged stakeholders (Chen, 2008; Yusliza et al., 2020). Notably, GSC had the strongest direct effect on both types of innovation (GPDI: $\beta = 0.395$; GPRI: $\beta = 0.396$), indicating that organizational systems and institutionalized green practices are foundational enablers of eco-innovation. This reflects the KBV, which holds that knowledge embedded in organizational processes and culture is a key source of innovation (Nonaka et al., 1996; Grant, 1996). Similarly, the contributions of GHC and GRC reinforce the idea that both internal human expertise and external social capital are integral to the firm's innovation capacity.

The mediation analysis confirms that GKS significantly channels the effects of all three GIC dimensions into green innovation outcomes. The strength of the GKS–GPDI ($\beta = 0.883$) and GKS–GPRI ($\beta = 0.884$) pathways highlights the centrality of knowledge dissemination and integration in driving environmentally sustainable innovation. This result is firmly grounded in the KBV, which views organizations as knowledge-repositories where innovation arises from the creation, sharing, and application of knowledge (Grant, 1996). Through GKS, firms can recombine existing green knowledge, facilitate learning processes, and foster a collective orientation toward sustainability. Prior studies have similarly emphasized the importance of knowledge sharing in enhancing innovation performance, particularly in dynamic and environmentally sensitive contexts (Sahoo et al., 2023; Song et al., 2020; Lin & Chen, 2017; Inkinen, 2015). In line with the NRBV, GIC comprises valuable, rare, inimitable, and non-substitutable resources that contribute to

sustainable competitive advantage (Hart, 1995). Grounded in the KBV, GKS is essential for the effective integration, coordination, and utilization of this intellectual capital within the organizations. Through efficient GKS, firms can transform GIC into actionable knowledge, thereby fostering GPRI, such as sustainable production methods and waste reduction techniques, as well as GPDI, including eco-friendly product design and development (Grant, 1996).

Theoretical Implications

This study offers critical theoretical contributions to the fields of GRI, GIC, and GKS, particularly within the context of Pakistani manufacturing SMEs. The findings extend existing theories and provide new insights into the dynamic relationships between GIC, GKS, and GRI. The NRBV (Hart, 1995) posits that firms can leverage their environmental capabilities for a competitive advantage by embracing sustainable practices and green innovation. This study expands the NRBV by demonstrating that GHC, GSC, and GRC are essential resources for promoting green innovation. It reinforces the idea that well managed intellectual resources offer firms a sustainable competitive advantage, particularly in environmentally conscious markets (Hart, 1995; Wei et al., 2023). This study proposes the adoption of GIC, alongside sustainable measures, to help overcome resource constraints for Pakistani SMEs, thereby enabling them to compete on both domestic and international fronts. This further develops NRBV by underscoring the role of intangible assets, particularly knowledge and human capital, in enhancing environmental sustainability and competitive advantage (Hart, 1995; Barney, 1991).

Secondly, this study offers a new insight distinct from other studies by explaining GKS as a mediating variable between GIC and GRI under the KBV of the firm (Grant, 1996), thus showing more clearly how components of GIC influence GPDI and GPRI. The KBV identifies knowledge as one of the most critical resources for firms (Grant, 1996). This study aims to advance the KBV by focusing on GKS's role as a mediator through which GIC is converted into actionable innovations, thereby demonstrating the outcome of green innovation resulting from the interaction between GIC and GKS. This aligns with the findings of other scholars who have emphasized the essential role of knowledge management in sustainable innovation (Abbas & Khan, 2023; Sahoo et al., 2023; Stewart, 2001). Third, this research introduces a new framework for GRI, specifically tailored for SMEs, particularly those based in developing countries such as Pakistan. Despite facing challenges, including limited resources, restricted access to advanced technologies, and stringent regulatory environments, Pakistani SMEs have the potential to achieve considerable outcomes in green innovation by effectively managing GIC and promoting knowledge sharing. This aims to advance the literature on sustainable innovation within SMEs, emphasizing the essential contribution of SMEs to the shift towards sustainable development (Qamar et al., 2024).

Managerial Implications

This study presents numerous managerial implications regarding green strategy in response to the growing environmental pressures from important stakeholders in Pakistan. The findings recommend that managers incorporate GIC to develop a strategy for enhancing GPDI and GPRI. Managers are encouraged to actively engage with key stakeholders to promote the dissemination of environmental knowledge and foster GRI within their organizations. The results indicate that GHC, GRC, and GSC have a positive influence on GPDI and GPRI, which suggest that GIC plays a crucial role in the sustainable development of manufacturing firms. Businesses can enhance GRI and improve performance by prioritizing ecological considerations. Organizations must engage GIC and invest in the development of existing employees' green knowledge to ensure GRI (Asiaei et al., 2023). It is essential for both managers and employees to cultivate a strong foundation of green knowledge to foster a culture of environmental sustainability within organizations. The

implications enable management to consider and apply sustainability knowledge via GIC within their organizations. Employees possessing a greater understanding of responsible business practices are more adept at recognizing environmental challenges from numerous perspectives and suggesting alternate ways to mitigate them. Additionally, it is recommended that policy institutes should arrange environmental awareness programs. Government authorities must engage in dialogue with all stakeholders, including educational institutions, to attain sustainability objectives by integrating green knowledge through GHC, GSC and GRC.

Limitations and Future Research Directions

This study has made several important contributions, but it also has some limitations that should be considered when planning similar studies in the future. First, this study investigated the relationship between GIC, GKS, and GRI using cross-sectional data. Future research employing longitudinal designs would be better positioned to understand the causal relationships among these constructs. Second, the study is undertaken by collecting data from manufacturing SMEs in Pakistan, which limits the generalizability of the findings. Expanding the research to include SMEs from other countries and industries could provide valuable insights into how institutional frameworks, regulatory environments, cultural values, and other societal norms influence the interaction between these factors. Third, future studies should also explore moderating effect of contextual and organizational factors like green corporate culture, digital transformation, corporate social responsibility, stakeholder pressure and leadership styles on the effectiveness of GIC and GKS. Investigating these elements may further clarify the mechanisms that promote green innovation (Chen, 2008a). Fourth, the reliance on self-reported data may introduce common method bias. Although anonymity and validated measurement instruments were used to deal with the CMB concerns, future research could enhance robustness by incorporating multi-source data or objective performance indicators (Podsakoff et al., 2003). Fifth, this study was grounded in the NRBV and KBV theories. Future researchers may consider incorporating further theoretical perspectives, such as the Dynamic Capabilities framework or Institutional Theory, to gain a deeper understanding of how firms adapt, integrate, and reconfigure intellectual resources in response to environmental degradation (Teece, 2007; Scott, 2008). Finally, we anticipate that the findings of the study will assist the managers, practitioners, policymakers, and legislators to formulate green business practices to address global environmental concerns. The study provides a novel framework and serves as a reference for further studies in the context of ecological innovation.

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