

Kim, Chang Hyun; Lee, Kyung Yul; Kwon, Youngsun

Conference Paper

Towards a Sustainable Digital Economy: The Role of Knowledge Search in Green Innovation

ITS 33rd European Conference 2025: "Digital innovation and transformation in uncertain times", Edinburgh, UK, 29th June – 1st July 2025

Provided in Cooperation with:

International Telecommunications Society (ITS)

Suggested Citation: Kim, Chang Hyun; Lee, Kyung Yul; Kwon, Youngsun (2025) : Towards a Sustainable Digital Economy: The Role of Knowledge Search in Green Innovation, ITS 33rd European Conference 2025: "Digital innovation and transformation in uncertain times", Edinburgh, UK, 29th June – 1st July 2025, International Telecommunications Society (ITS), Calgary

This Version is available at:

<https://hdl.handle.net/10419/331286>

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Towards a Sustainable Digital Economy: The Role of Knowledge Search in Green Innovation

Chang Hyun Kim¹, Kyung Yul Lee², Youngsun Kwon¹

¹School of Business and Technology Management, Korea Advanced Institute of Science and Technology (KAIST)

²College of Economics and Business, Hankuk University of Foreign Studies

Abstract

This study explores how knowledge search depth and breadth in green patenting influence environmental innovation in the mobile industry, a sector facing increasing scrutiny for its environmental impact. Using a panel of 42 mobile firms from 2001 to 2023, we find that search depth exhibits an inverted U-shaped relationship with green innovation, suggesting that while leveraging internal knowledge initially boosts environmental innovation, excessive reliance can hinder progress due to organizational rigidity. Conversely, search breadth demonstrates a consistently positive effect, indicating that expanding external knowledge sources enhances a firm's capacity for sustainable innovation. These findings underscore the strategic importance of balancing internal and external knowledge strategies to foster green innovation in the mobile sector.

<Keywords: Green Innovation, Knowledge Search, Mobile Industry, Sustainability>

1. INTRODUCTION

The urgency of combating climate change and the growing importance of sustainable business practices have placed Environmental, Social, and Governance (ESG) considerations at the heart of corporate strategy (Bagh et al., 2024; de Souza Barbosa et al., 2023). This trend is also emphasized in the telecommunications and mobile industries, which are significant contributors to global energy consumption, carbon emissions, and generation of electronic waste, making their environmental impact a focal point for regulators, investors, and consumers alike (Kahila, 2024; GSMA, 2022; Kuehr, 2012). In an increasingly digital world where approximately 70 percent of the global population uses Information and Communications Technology (ICT) services, the telecommunications and mobile industry is a significant contributor to environmental harm, accounting for 2-4% of global CO₂ emissions and producing vast amounts of e-waste and energy consumption that continue to

rise with expanding data traffic and network infrastructure (GSMA, 2022; 5G Americas, 2023). In alignment with the global efforts toward sustainability and climate risk mitigation, technological innovation in environmental dimensions has become an essential mechanism for companies striving to enhance sustainability, comply with regulatory requirements, and maintain competitive advantage (Chen et al., 2022; Wu et al., 2024).

Green patents, defined as environmental-related patents for inventions and innovations that provide environmental benefits such as improved energy efficiency, reduced emissions, or the use of renewable resources, serve as both a strategic asset and a signal of a firm's commitment to sustainability (Haščić & Migotto, 2015). A growing body of empirical research demonstrates that green patents play a pivotal role in advancing both firm-level innovation and broader environmental objectives, suggesting these green patenting activities are closely linked to improvements in environmental performance, such as pollution control and resource efficiency (Ma et al., 2021; Xu et al., 2024). However, the effectiveness of green innovation strategies through patenting activities depends not only on the quantity of green patents. Recent studies highlight that the impact of green patenting on both environmental outcomes and firm value is shaped by the quality, novelty, and strategic context of these innovations. For instance, recent evidence shows that firms with an increasing share of green patents, rather than simply a large number, achieve greater reductions in emissions and innovation impact, and that many foundational green technologies originate from traditionally excluded sectors, revealing a disconnect between ESG ratings and actual environmental innovation (Schlosser et al., 2024; Cohen et al., 2024).

The concepts of search breadth, which describes how deeply a firm reuses its existing knowledge, and search scope, which describes how widely a firm explores new knowledge, have been shown to influence the quality and impact of innovations outcomes (Katila & Ahuja, 2002; Laursen & Salter, 2006; Wu et al., 2014). While these concepts have been extensively studied in the broader innovation literature, particularly in manufacturing and high-tech sectors, their application to green innovations remains limited. In this study, we aim to examine how the search breadth and search depth of green patents influence both ESG innovation and environmental innovation, with a particular focus on the mobile industry. Specifically, we find that search depth exhibits an inverted U-shaped relationship with green innovation capacity, indicating that while reusing internal knowledge initially fosters innovation, excessive reliance leads to diminishing returns. In contrast, search breadth has a

consistently positive effect, suggesting that expanding external knowledge sources enhances a firm's environmental innovation capacity. The remainder of this paper is structured as follows. Section 2 reviews the relevant literature on sustainability, green innovation, and knowledge search strategies. Section 3 describes the data, variables, and empirical methodology. Section 4 presents the main empirical results, followed by a discussion of their implications in Section 5.

2. LITERATURE REVIEW

2.1. Sustainability and Green Innovation in the Mobile Industry

In recent decades, embedding Environmental, Social, and Governance (ESG) principles into corporate strategies has emerged as a central pillar of sustainable business performance. Such initiatives may encompass sustainable supply chain management, transparent environmental disclosures, and active community engagement efforts. A growing body of research shows that incorporating ESG criteria into business operations enhances corporate reputation and encourages innovation that supports long-term value creation (Aydoğmuş et al., 2022; de Souza Barbosa et al., 2023; Junius et al., 2020). Among various ESG initiatives, green innovation represents a critical pathway for enhancing environmental performance while preserving firm competitiveness.

Green innovation broadly refers to technological or organizational advancements that mitigate the environmental impacts associated with production and consumption. Haščič and Migotto (2015) describe green innovation as the development of environment-related technologies aimed at lowering environmental harm while creating new market opportunities. In academic literature, green innovation is often used synonymously with eco-innovation and environmental innovation (Schiederig et al., 2012). Similarly, Chen et al. (2006) define green innovation as “hardware or software innovation related to green products or processes, including technologies in energy-saving, pollution prevention, waste recycling, green product design, or corporate environmental management”. Green innovation also involves new or improved products and processes that reduce environmental impacts across their life cycle (Kemp & Pearson, 2007). Taken together, these definitions suggest that green innovation encompasses any new idea or practice intended to mitigate environmental damage (Takalo & Tooranloo, 2021).

The literature commonly highlights green innovation as a means to achieve both environmental sustainability and improved competitive performance. By design, green innovations aim to cut pollution, energy use, and waste, thereby reducing firms' ecological footprints. At the same time, these innovations can improve operational efficiency and open new market opportunities, bolstering business performance and sustainable competitive advantage (Batoool et al., 2025; Hur et al., 2013). Extensive empirical research has shown that green innovation not only contributes to improved quality of life and reduced environmental harm but also facilitates cost reduction, R&D investment, productivity gains, and technological advancements, especially when firms adopt proactive environmental strategies (Aguilera-Caracuel & Ortiz-de-Mandojana, 2013; Castellacci & Lie, 2017; Chen et al., 2018; Du et al., 2018; Tseng et al., 2013; Yan, 2015). Ultimately, green innovation represents a strategic approach that enables firms to pursue environmental goals while simultaneously achieving economic returns.

Green innovation is particularly crucial in energy- and resource-intensive sectors, such as telecommunications and the mobile industry, characterized by high energy consumption. For instance, telecommunications networks, while enabling digital connectivity, consume significant energy and contribute to carbon emissions. Studies note that energy use in telecommunications operations has become a growing source of greenhouse gases as network traffic expands (Lee et al., 2020). With the growing importance of going net zero in this industry, telecom firms worldwide have adopted green initiatives, including more energy-efficient equipment, renewable energy for base stations, and improved cooling and power management systems (Chatley, 2015). Such innovations help reduce the carbon footprint of network infrastructure while simultaneously lowering energy costs, exemplifying the dual benefits of green innovation. The dual benefits of green innovation have also been empirically observed in the telecommunications and mobile industry, with previous studies observing its positive effects, including reduced environmental impact, cost savings, and enhanced stakeholder trust (Charley, 2015; Lee et al., 2020; Tătaru et al., 2020). Firms with active ESG strategies in this industry also tend to enjoy stronger reputational outcomes, greater customer and employee engagement, and improved financial and non-financial performance (Grishunin et al., 2021; Kwilinski et al., 2023; Jasni et al., 2020; Vetrova et al., 2022).

Despite the growing significance of green innovation, the mechanisms that support effective environmental innovation remain insufficiently explored. The mobile telecommunications industry offers a relevant setting to examine how firms respond to these demands. As mobile service providers around the world commit to ambitious sustainability targets, their ability to deliver on these goals depends heavily on environmental innovation. Ongoing efforts such as the development of energy-efficient 5G infrastructure, the adoption of renewable energy at network sites, and device recycling initiatives exemplify this transformation. Yet, academic research on how firms in this sector generate green innovation remains limited. Against this backdrop, it becomes important to consider how firms organize their search for knowledge to support environmental innovation. Understanding the patterns and outcomes of innovation search activities, particularly in the context of green technological development, provides a foundation for evaluating the strategic levers firms can use to enhance their sustainability performance.

2.2. Knowledge Search Strategies: Search Depth and Breadth

Scholars of innovation management have shown that the ways firms search for new knowledge profoundly influence their innovation outcomes. A significant contribution by Katila and Ahuja (2002) conceptualized firms' search behavior as a two-dimensional construct comprising "search depth" and "search scope". Search depth refers to how intensively a firm reuses and builds upon its existing knowledge base, and search scope describes how widely the firm explores new and diverse knowledge beyond its current experience (Katila & Ahuja, 2002). Using patent-citation measures in the robotics industry, Katila and Ahuja observed that both an overly narrow search focus and an overly broad exploration can hinder effective innovation, implying that firms must balance depth and breadth in their search strategies to optimize innovative performance.

Search depth entails an exploitative learning strategy, which includes leveraging the firm's accumulated knowledge and expertise. By searching deeply, firms refine and extend existing technologies, which can enhance innovation efficiency through reduced trial-and-error and effective routinization (Katila & Ahuja, 2002). Indeed, moderate reuse of prior knowledge allows firms to recombine proven components in novel ways, yielding green innovations that are both innovative and feasible given the firm's competencies. Such incremental depth-based innovations can be less risky and faster to develop since the firm builds on what it already knows (March, 1991; Katila & Ahuja, 2002). This local search can

also create an entry barrier for competitors and a cost advantage, as the firm exploits economies of scope and a reputation in its niche (Christensen, 2000; Katila & Ahuja, 2002).

However, overly high search depth can become counterproductive (Shi et al., 2019). As a firm continually reuses the same knowledge, it risks diminishing returns in idea generation and “competency traps” (Leonard-Barton, 1992). Katila and Ahuja (2002) argue that when the limits of a firm’s existing knowledge base are reached, solving problems with the same knowledge becomes increasingly costly and complicated. Excessive focus on internal knowledge tends to petrify a firm’s problem-solving approach, leading to organizational rigidity and a decline in innovative output. In other words, beyond some point, additional search depth yields smaller and less novel improvements, which can stall innovation when breakthrough solutions require new knowledge. This is supported by numerous studies that have examined the curvilinear, or inverted U-shaped, relationship between search depth and innovative outputs. In other words, firms with moderate depth introduced most new products, whereas those searching too narrowly experienced reduced innovation. Based upon previous studies that largely demonstrate an inverted U-shaped relationship between search depth and innovation outcomes, we propose the following hypothesis:

Hypothesis 1 (H1): Search depth has an inverted U-shaped relationship with green innovation capacity

Search breadth represents another dimension of searching strategy, along with search depth. It refers to the extent to which firms reach beyond organizational boundaries to tap into diverse knowledge domains, reflecting an exploratory approach to search. A broad search exposes the firm to diverse ideas, technologies, and perspectives, which can spark novel combinations conducive to innovation breakthroughs (Katila & Ahuja, 2002). By tapping into external knowledge sources, firms can increase the likelihood of radical innovations by recombining distant knowledge with existing capabilities (Rosenkopf & Nerkar, 2002; Laursen & Salter, 2006). For instance, Rosenkopf and Nerkar (2001) find that firms that span technological boundaries produce more influential inventions. Such external breadth increases the pool of knowledge variants available, thereby expanding opportunities for recombinant innovation (Ahuja & Lampert, 2001). And improving the odds of novel green solutions. Moderate levels of search breadth can thus help firms generate creative, sustainable

technologies by integrating ideas from diverse domains while still relating them to the firm's core knowledge (Cohen & Levinthal, 1990).

Nevertheless, extensive search breadth also entails substantial challenges and costs. Integrating too many new knowledge elements from disparate sources can strain a firm's capacity to absorb and utilize information (Laursen & Salter, 2006). Katila and Ahuja (2002) caution that sourcing knowledge from a wide array of unfamiliar domains without adequate expertise and resources presents significant difficulties, such as technical incompatibilities, coordination problems, and heightened investment costs. Laursen and Salter (2006) similarly highlight that an excessively wide search can create an attention allocation problem, timing mismatches, and absorptive capacity overload for the firm. This implies that the effort of knowledge search becomes greater than the benefit of obtaining new knowledge (Dosi, 1988). Numerous empirical studies further confirm the non-linear relationship between search breadth and innovation. For instance, Dahlander et al. (2016) find that individuals' external search breadth has a curvilinear (inverted U-shaped) relationship with idea generation, suggesting that while accessing diverse external knowledge initially enhances creativity, excessive breadth can hinder idea development due to increased complexity. Ardito and Petrzelli (2017) also empirically demonstrate that external knowledge search breadth exhibits an inverted U-shaped relationship with product innovation. In accordance with previous literature documenting a curvilinear relationship between search breadth and innovative capacities, we propose our second hypothesis as follows.

Hypothesis 2 (H2): Search breadth has an inverted U-shaped relationship with green innovation capacity

Across the literature, the recurring theme is that breadth and depth in searching strategies are complementary dimensions. High search depth can amplify the benefits of search breadth by providing the absorptive capacity to make sense of varied new knowledge. At the same time, some breadth is necessary to avoid the competency traps of too much depth. In other words, applying both depth and breadth strategies offers robust methodologies for understanding the intricate relationship between a firm's internal and external knowledge, as well as its capacity for innovation.

3. DATA & METHODOLOGY

3.1. Data and Sample

This study obtains data for the dependent variables from Refinitiv ESG, one of the leading corporate social responsibility (CSR) and ESG databases widely used by researchers and practitioners (de Villiers et al., 2022). Refinitiv ESG provides standardized and comprehensive firm-level data on environmental, social, and governance performance across a broad set of globally listed companies. These data points cover a wide range of topics such as carbon emissions, resource use, human rights, community engagement, board structure, and ESG-related scores. From the dataset, we use metrics on ESG innovation score to measure a firm's commitment to environmental innovation, specifically its efforts to develop environmentally sustainable products, technologies, and practices.

Green patent data are collected from the United States Patent and Trademark Office (USPTO), which provides detailed information on firms' technological innovations, including patent application year, assignee, technology classification, and citation linkages. Whether a patent is green or not is classified based on the OECD ENVTECH classification, a widely used taxonomy for identifying environmental-related technologies using International Patent Classification (IPC) (Haščič & Migotto, 2015). These include, but are not limited to, patents related to environmental management, water-related adaptation technologies, biodiversity protection and ecosystem health, as well as climate change mitigation technologies. Our final panel dataset consists of 42 mobile industry firms covering the period from 2001 to 2023.

3.2. Dependent Variable

Our dependent variable is *Green Innovation*, which indicates the extent of a firm's commitment to environmental innovation, as captured by the Green Innovation Score from the Refinitiv ESG database. This variable reflects a firm's efforts to develop environmentally sustainable products, technologies, and practices. In this study, we use *Green Innovation* as a proxy for a firm's green innovation capacity, as it encompasses both the strategic talent and operational implementation of environmentally oriented innovation activities.

3.3. Independent Variables

To examine how search depth and search breadth influence the extent of green innovation among telecommunications firms, we use *Search Depth* and *Search Breadth* as our key independent variables. Following the study of Katila and Ahuja (2002), we define search depth as how often a firm reuses knowledge it has previously cited, and search breadth as the degree to which a firm uses external knowledge for product innovations.

Search Depth for firm i in year t is calculated as the proportion of the firm's patent citations in year t that reference its own patents filed within the previous five years. The value of *Search Depth* thus ranges from 0 to 1. *Search Breadth* for firm i in year t is defined as the number of new citations made by firm i in year t , divided by the total number of patent citations made by firm i in year t , and its value also ranges from 0 to 1. The equations below formalize the computation of these two dimensions of search behavior.

$$Search\ Depth_{i,t} = \frac{\sum_{y=t-5}^{t-1} self\ citation_{i,t}}{total\ citations_{i,t}} \quad (1)$$

$$Search\ Breadth_{i,t} = \frac{new\ citations_{i,t}}{total\ citations_{i,t}} \quad (2)$$

These methodologies have been widely used in previous literature for calculating the degree of search depth and search breadth at a firm-level (Caner & Tyler, 2015; Katila & Ahuja, 2002; Yu et al., 2019; Zhong et al., 2021)

3.4. Control Variables

To account for potential confounding factors that may influence firms' innovation search behavior, we include the following control variables in the analysis. First, *Firm Age* is measured as the number of years a firm has operated in the mobile industry since its founding and is log-transformed for use in the analysis. This variable captures firm longevity, acknowledging that while some firms sustain long-term market presence, others may exit the industry more quickly due to competitive pressures (Lee et al., 2024; Giachetti & Dagnino, 2014). Second, *Innovative Firms* is a dummy variable equal to 1 for firms that fall within the top 5% in the mobile industry in terms of most applied patents in the previous year ($t-1$), and 0 otherwise. This variable is included to capture the effect of high innovation intensity, as firms operating in technologically dynamic sectors such as the mobile industry tend to engage in frequent patenting activity (Lee et al., 2024). Third, *Product Diversity* is a dummy variable indicating whether a firm engages in product diversification. Firms producing only a single product category are coded as 0, whereas those producing two or more categories within a given year are coded as 1. This variable accounts for heterogeneity in firm strategies within the mobile industry, where some firms diversify by offering multiple types of smartphones annually. Fourth, *Smartphone Number* is the number of smartphones that the firm released in a given year. Fifth, *Market Share* is calculated as the proportion of a firm's shipments relative

to total industry shipments in a given year. This metric is commonly used in the mobile industry to approximate market dominance, as shipment volume serves as a key indicator of competitive position. Sixth, *New Entrants* indicates the number of new firms that entered the mobile industry in a given year. Seventh, *HHI* is the measure of market concentration calculated by the Herfindahl-Hirschman index for the market share only for the five top firms. Market concentration is widely used by strategic management scholars to capture the environmental effect of the smartphone industry (Mani & Nandkumar, 2015). Seventh, Average Smartphone Number captures the average number of smartphones released annually by all firms in the industry, excluding the focal firm. This variable serves as a proxy for industry-wide product release intensity and competitive pressure in a given year. Lastly, *Industry Growth* indicates the annual growth rate of the mobile industry (See Table 1 for details).

(Insert Table 1 about here)

3.5. Methodology

The study utilizes ordinary least squares (OLS) regression models to estimate the relationship between knowledge search strategies and green innovation performance. Both linear and quadratic terms for search depth and breadth are included to test for potential non-linear (e.g., inverted U-shaped) effects. Year and firm-level fixed effects are added to control for time-specific trends and unobserved firm heterogeneity that may influence green innovation outcomes.

4. MAIN RESULTS

Table 2 presents the descriptive statistics and correlation matrix for all variables used in the analysis. All pairwise correlations are below 0.7, suggesting no serious multicollinearity concerns among the explanatory variables. The dependent variable, *Green Innovation*, has a mean value of 0.673 and a standard deviation of 0.181, with values ranging from 0.088 to 0.933. This indicates moderate variation in mobile firms' environmental innovation across the sample. Among the main explanatory variables, *Search Depth* and *Search Breadth* exhibit mean values of 0.357 and 0.111, respectively, suggesting that firms rely more heavily on internal knowledge reuse than on external knowledge exploration in terms of green innovations in our sample.

(Insert Table 2 about here)

Table 3 reports the results of OLS regressions examining the relationship between firms' knowledge search strategies and their environmental innovation. Across all model specifications, we find robust evidence that both *Search Depth* and *Search Breadth* are significantly associated with green innovation performance, albeit in distinct ways. The coefficient on *Search Depth* across columns (2), (3), (6), and (7) is consistently positive and statistically significant at the 5% level, suggesting that firms that intensively reuse and build upon their own prior knowledge are more likely to engage in environmental innovation, and tend to exhibit higher green innovative capacity. In columns (3) and (7), negative and statistically significant coefficients on the squared term of *Search Depth* reveal a curvilinear, or inverse U-shaped relationship with green innovation capacity. This may imply that while internal knowledge recombination initially enhances green innovation, excessive reliance on existing knowledge may lead to diminishing returns or cognitive rigidity, aligning with Hypothesis 1. This is also consistent with prior literature suggesting that overexploitation of internal knowledge can hinder breakthrough innovation (Katila & Ahuja, 2002).

Search Breadth also shows a consistently positive and statistically significant effect on *Green Innovation* across specifications (columns 4-7), with coefficients ranging from 0.032 to 0.038. These results support the idea that engaging with a broader array of external knowledge sources enables firms to access diverse environmental technologies and practices, fostering innovation in sustainability. However, the inclusion of the squared term *Search Breadth*² in columns (5) and (7) does not yield a significant coefficient, indicating a linear positive relationship rather than a curvilinear relationship. Unlike search depth, the effect of breadth does not appear to taper off within the observed range, only partially supporting Hypothesis, which posited an inverted U-shaped relationship between search breadth and green innovation.

Several control variables further yield notable insights into the determinants of green innovation. First, firms identified as highly innovative – those in the top 5% in terms of patent applications – consistently exhibit a positive and statistically significant relationship with the green innovation score. This finding suggests that firms with strong baseline innovative capacity are more likely to engage in environmental innovation efforts. Second, the coefficient on *New Entrants* is negative and significant across all model specifications, indicating that a greater number of firms entering the industry in a given year is associated with lower levels of green innovation among incumbents. This may reflect the heightened

competitive pressure that arises from increased market entry, which can shift firms' strategic focus away from long-term environmental innovation toward short-term profitability goals. Third, *HHI*, a proxy for market concentration, shows a robust negative association with *Green Innovation*, implying that the more concentrated the market, the lower the incentive for firms to invest in environmental innovation.

(Insert Table 3 about here)

5. DISCUSSION & CONCLUSION

5.1. Discussion

This study provides several important implications for both research and practice, particularly within the mobile industry. First, the findings demonstrate that both search depth and search breadth in green patenting are significant drivers of environmental innovation among mobile firms. The observed inverted U-shaped relationship between search depth and green innovation suggests that while leveraging internal knowledge is initially beneficial, excessive reliance can lead to diminishing returns and organizational rigidity. Thus, mobile firms should strive for a balanced approach—intensively exploiting their core competencies without becoming trapped by them. In contrast, the positive linear relationship between search breadth and green innovation indicates that expanding the scope of external knowledge sources consistently enhances firms' capacity for sustainable innovation. For the mobile industry, which faces mounting regulatory and stakeholder pressure to address environmental issues such as energy consumption, carbon emissions, and e-waste, this underscores the value of open innovation and collaboration with diverse partners, including suppliers, research institutions, and even competitors. By broadening their search for green technologies, mobile firms can accelerate the development and adoption of energy-efficient infrastructure, renewable energy solutions, and circular economy practices, thereby strengthening their contributions to global sustainability goals. From a policy perspective, these results highlight the importance of fostering environments that encourage both internal R&D investment and external knowledge exchange. Policymakers and industry associations may consider supporting platforms for knowledge sharing, patent pools, and collaborative innovation networks to facilitate the diffusion of green technologies within the mobile sector.

Despite its contributions, this study has several limitations. Despite its contributions, this study is subject to several limitations that suggest avenues for future research. First,

while the ESG Innovation Score captures a broad measure of environmental innovation, it remains a composite indicator based on third-party evaluations and public disclosures. Future studies may enhance validity by incorporating direct measures of environmental performance, such as carbon intensity, energy consumption reductions, or data on environmentally oriented products. Second, the patent-based measures of search depth and breadth are constructed using USPTO data, which may underrepresent non-U.S. patenting activities of globally operating firms. Future research could incorporate international patent databases such as EPO or PATSTAT to ensure a more comprehensive picture of innovation search behavior.

This research still successfully makes several noteworthy contributions to the literature on innovation management and sustainability. First, it extends the understanding of how knowledge search strategies, such as search depth and search breadth, affect innovation output, with a particular emphasis on environmental innovation. By focusing on the mobile industry, a sector characterized by both significant environmental externalities and increasing sustainability pressures, the study provides context-specific insights into how firms organize their innovation processes to address ESG-related challenges. Second, by empirically demonstrating the distinct effects of search depth (inverted U-shaped) and search breadth (positive linear) on green innovation, the study refines theoretical models of innovation search and highlights the need for nuanced, context-specific strategies. Third, the findings offer actionable insights for managers and policymakers in the mobile industry, emphasizing the importance of balancing internal knowledge exploitation with external exploration to maximize environmental innovation outcomes. Lastly, this work contributes to ongoing discussions about the role of ESG integration and green patenting as strategic levers for advancing sustainability in technology-intensive industries.

5.2. Concluding Remarks

In summary, this study sheds light on the nuanced roles of knowledge search depth and breadth in driving green innovation within the mobile industry. Our findings highlight that while a balanced approach to internal knowledge exploitation can foster environmental innovation, excessive focus may hinder progress, whereas expanding external knowledge sources consistently enhances green innovation outcomes. These insights carry significant implications for industry practitioners and policymakers aiming to accelerate sustainable transformation in the mobile sector. Nevertheless, the study is not without limitations,

including potential measurement constraints, sample representativeness, and the influence of unobserved contextual factors. Despite these challenges, this research contributes valuable perspectives to the ongoing discourse on sustainable innovation strategies, offering a foundation for future studies to further explore and refine approaches that can effectively promote environmental responsibility and competitive advantage in technology-driven industries.

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Table 1. Variable Descriptions

Variable	Description
<i>Green Innovation</i>	Green Innovation Score from Refinitiv ESG database, capturing a firm's commitment to environmental innovation and green innovation capacity through green products and practices.
<i>Search Depth</i>	Proportion of citations to the firm's own patents filed in the previous five years, reflecting internal knowledge reuse.
<i>Search Breadth</i>	Proportion of citations to new external patent sources, indicating the firm's level of external knowledge exploration.
<i>Firm Age</i>	Number of years the firm has operated in the mobile industry since founding, log-transformed for analysis.
<i>Innovative Firms</i>	Dummy variable equal to 1 if the firm is in the top 5% of patent applicants in the previous year ($t-1$); 0 otherwise.
<i>Product Diversity</i>	Dummy variable equal to 1 if the firm released two or more smartphone categories in a year; 0 if only one.
<i>Smartphone Number</i>	Total number of smartphone models released by the firm in a given year.
<i>Market Share</i>	Proportion of the firm's smartphone shipments relative to the total industry shipments in a given year.
<i>New Entrants</i>	Number of new firms that entered the mobile industry in a given year.
<i>HHI</i>	Herfindahl-Hirschman Index measuring market concentration among the top five firms, based on market share.
<i>Average Smartphone Number</i>	Average number of smartphones released by all other firms in the industry, excluding the focal firm, in a given year.
<i>Industry Growth</i>	Year-over-year growth rate of the mobile industry, based on total smartphone shipments.

Table 2. Descriptive Statistics

	1	2	3	4	5	6	7	8	9	10	11	12
1 <i>Green Innovation</i>	1.000											
2 <i>Search depth</i>	-0.031	1.000										
3 <i>Search breadth</i>	-0.123	0.680	1.000									
4 <i>Firm age (log-transformed)</i>	0.143	-0.273	-0.120	1.000								
5 <i>Innovative firms</i>	0.247	0.107	0.114	0.016	1.000							
6 <i>Product diversity</i>	0.097	0.184	0.146	-0.063	0.172	1.000						
7 <i>Smartphone number (log-transformed)</i>	0.117	0.535	0.381	-0.252	0.244	0.109	1.000					
8 <i>Market share (log-transformed)</i>	0.028	0.241	0.231	0.016	0.359	0.074	0.337	1.000				
9 <i>New entrants (log-transformed)</i>	-0.082	0.381	0.279	-0.474	0.020	0.104	0.180	0.068	1.000			
10 <i>HHI (log-transformed)</i>	-0.098	0.101	-0.097	-0.623	0.016	-0.046	0.145	0.020	0.104	1.000		
11 <i>Average smartphone number</i>	-0.024	0.107	0.126	0.082	-0.065	0.070	-0.018	0.013	0.259	-0.550	1.000	
12 <i>Industry growth</i>	-0.097	0.311	0.172	-0.455	-0.014	0.103	0.201	0.148	0.491	0.203	0.445	1.000
Mean	0.673	0.357	0.111	7.458	0.147	0.853	10.01	1.760	4.523	1259.5	5.069	0.191
Std. Dev.	0.181	0.388	0.144	4.150	0.355	0.355	17.51	5.567	3.564	433.8	1.318	0.235
Min	0.088	0	0	1	0	0	0	0	0	856.8	2.580	-0.123
Max	0.933	0.986	0.793	15	1	1	127	38.60	12	2580.2	8.210	0.721
Obs.	415	415	415	415	415	415	415	415	415	415	415	415

Note: Logged values used for regression and correlations, and untransformed values for descriptive statistics. All correlations greater than 0.2 are statistically significant at the $p < 0.01$ level (two-tailed).

Table 3. Knowledge Searching Strategies and Green Innovation

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	<i>DV: Green Innovation</i>						
<i>Search depth</i>		0.052** (0.026)	0.136** (0.061)			0.059** (0.026)	0.093** (0.065)
<i>Search depth</i> ²			-0.078* (0.052)				-0.028* (0.058)
<i>Search breadth</i>				0.035** (0.016)	0.034** (0.017)	0.038** (0.016)	0.032* (0.017)
<i>Search breadth</i> ²					0.014 (0.078)		0.055 (0.086)
<i>Firm age</i>	-0.005 (0.019)	-0.010 (0.019)	-0.013 (0.019)	-0.004 (0.019)	-0.004 (0.019)	-0.008 (0.019)	-0.010 (0.019)
<i>Innovative firms</i>	0.037* (0.022)	0.037* (0.021)	0.036* (0.021)	0.043** (0.022)	0.043** (0.022)	0.043** (0.021)	0.041* (0.022)
<i>Product diversity</i>	0.000 (0.026)	0.001 (0.026)	0.005 (0.026)	-0.001 (0.026)	-0.000 (0.026)	0.001 (0.026)	0.003 (0.026)
<i>Smartphone number</i>	0.001 (0.002)	0.001 (0.002)	0.001 (0.002)	0.001 (0.002)	0.001 (0.002)	0.001 (0.002)	0.001 (0.002)
<i>Market share</i>	-0.001 (0.003)	-0.002 (0.002)	-0.002 (0.002)	-0.001 (0.002)	-0.001 (0.002)	-0.001 (0.002)	-0.001 (0.002)
<i>New entrants</i>	-0.012** (0.006)	-0.013** (0.006)	-0.013** (0.006)	-0.012** (0.005)	-0.012** (0.006)	-0.013** (0.005)	-0.013** (0.006)
<i>HHI</i>	-0.280*** (0.092)	-0.289*** (0.092)	-0.304*** (0.092)	-0.267*** (0.092)	-0.267*** (0.092)	-0.277*** (0.092)	-0.285*** (0.093)
<i>Average smartphone number</i>	-0.046 (0.037)	-0.051 (0.037)	-0.051 (0.036)	-0.044 (0.036)	-0.044 (0.037)	-0.050 (0.036)	-0.049 (0.036)
<i>Industry growth</i>	-0.224* (0.121)	-0.233* (0.120)	-0.239** (0.120)	-0.225* (0.120)	-0.224* (0.120)	-0.235* (0.120)	-0.235* (0.120)
Constant	2.896*** (0.802)	2.947*** (0.799)	3.047*** (0.800)	2.790*** (0.799)	2.790*** (0.800)	2.837*** (0.795)	2.884*** (0.801)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	407	407	407	407	407	407	407
R-squared	0.385	0.392	0.396	0.394	0.394	0.402	0.404

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1