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<https://doi.org/10.1057/s41599-025-06022-0>

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# Knowledge management and sustainable innovation for green finance: evidence from Asia

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This study investigates the relationship among digital sustainability, knowledge management capacity, and green finance in Asian countries during the period spanning 2007 to 2023. Previous research has explored the role of digital transformation in promoting sustainability; these studies are predominantly firm-level and lack insight into how macro-level knowledge infrastructure enables or constrains digital technologies in advancing green finance. Recently, the emphasis on digital sustainability and green finance has increased in the Asian continent, primarily because many economies in this region are developing or emerging. These economies largely rely on existing resources and carbon-intensive technologies. Utilizing quantile regression to assess distributional effects and the system generalized method of moments to address potential endogeneity and dynamic panel bias, the study aims to shed light on how knowledge management capacity contributes to the advancement of green finance through digital sustainability. The findings reveal that digital sustainability has a limited or statistically weak direct effect on green finance in the absence of sufficient national-level knowledge management capacity. However, Knowledge Management Capacity significantly affects this relationship, enabling digital technologies to translate into financial sustainability gains more effectively. Countries with stronger research systems, Information and Communication Technology infrastructure, and innovation capabilities exhibit a more robust digital-to-green finance linkage. This study also offers policy insights for Asian economies aiming to strengthen their green finance ecosystems through digital and knowledge-based transformation.

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## Introduction

Digital sustainability is the transformation of advanced technologies into business practices to promote ecological, social, and economic sustainability, aiming to minimize environmental impact and maximize efficiency (Merrill et al., 2019; George et al., 2021). Few studies have shown the importance of environmental business practices and their digital transformations (Lokuge et al., 2021). Empirical evidence is still scarce from this perspective (George et al., 2021; Gregori and Holzmann, 2020). Recent literature increasingly recognizes the significance of knowledge management as a vehicle to drive novel innovations to foster digital sustainability (Di Vaio et al., 2021). A Country's innovative capacity and adequate knowledge-sharing infrastructure play an important role in taking full advantage of digital sustainability (Jinqiao et al., 2022), as they enable economies to effectively leverage advanced technologies for sustainable development. Conversely, inadequate knowledge management resources could hamper innovation and sustainable development efforts. Therefore, it is crucial to understand the role of knowledge management capacity (Chen and Huang, 2009) in the relationship between green finance and digital sustainability.

Prior studies have explored the role of knowledge management in enhancing organizational innovation, environmental performance, and, more recently, sustainable business models (Mardani et al., 2018; Aksu and Akman, 2024; Galunic and Rodan, 1998). For example, research has demonstrated that effective Knowledge Management practices facilitate green innovation at the firm level and support environmental risk management (Sahoo et al., 2023). However, much of this work remains rooted in micro-level analyses, often focusing on individual firms or industry-specific case studies within developed economies (Xu et al., 2023). In contrast, limited attention has been given to how knowledge management capabilities operate at a macroeconomic level across national economies or institutional frameworks to enable digital sustainability and promote green finance. This study addresses this research gap by applying a knowledge management lens to analyse the macro-level dynamics that underpin sustainable financial innovation in Asian economies (Chen and Huang, 2009). Asia's rapidly evolving digital infrastructure, pressing environmental challenges, and emerging commitments to sustainable development goals (SDGs) (Qamruzzaman, Jianguo (2020); Kaygusuz, 2012), this inquiry is both timely and essential.

The United Nations' Sustainable Development Goals (SDGs) for 2030 emphasize the critical need for sustainable practices, including the interaction of eco-innovation and finance, known as green finance. This reflects the environmental aspects of digital transformation in finance. The UN estimates that approximately \$7 trillion will be required to meet the SDGs, and financial institutions are being urged to adopt policies that support green finance (Puplampu et al., 2023); Rizzello and Kabli, 2020). Nevertheless, relationship between digital sustainability and green finance is complex and little is known about the relationship in the extant literature, especially in Asian economies that largely face unique challenges such as reliance on carbon-intensive technologies and under developed financial markets and weak institutional frameworks except few economies like Japan, South Korea, Singapore and Hong Kong (Qamruzzaman, Jianguo (2020)). In this context, the scope for knowledge creation and knowledge-sharing infrastructure are both basic components to enhance the knowledge management capacity of the economy. This is essential for developing innovative solutions that ensure sustainable practices and their effective dissemination among relevant stakeholders within the economy. Knowledge management capacity emerges as a crucial element in facilitating the adoption and implementation of

digital sustainability to promote green finance in Asian economies (Lu et al., 2008; Lock and Seele 2017).

This study contributes to the literature in the following ways: firstly, prior literature has focused on the relationship between digital sustainability and green outcomes at the firm level (Aksu and Akman, 2024). This study extends the inquiry to the national level by integrating knowledge management theory into a macroeconomic framework. It offers novel insights into how country-level knowledge capacity conditions the effectiveness of digital transformation in promoting green finance across Asian economies. Secondly, global discourse on green finance has gained momentum; limited empirical research has examined the relationship between digital sustainability and knowledge management as enablers of green finance (Rasheed et al., 2024). Moreover, extant studies focus on developed nations (Montani and Staglianò, 2022) overlooking the unique institutional, technological, and regulatory environments in Asia. This study addresses this critical gap by exploring how knowledge management capabilities contribute to digital sustainability and, in turn, support green finance across Asian economies. Lastly, this study uses the quantile regression technique, which deals with the heterogeneity that exists in Asian economies, an important aspect, often ignored in extant research on green finance. This approach is useful in such situations because it does not rely on the assumption of constant variance or homoscedasticity. Thus, quantile regression is particularly effective in datasets with heteroscedasticity, where traditional methods may fail or give inefficient estimates. Quantile regression technique is used to examine the impact of digital sustainability on green finance. In doing so, the interaction of knowledge management capacity and digital sustainability could provide novel insights into how this relationship changes at different quantiles. This approach is particularly important for policymakers in the Asian context, as it underscores the need to align strategies to the varying phases of financial and economic development.

Overall, this study contributes to the emerging literature by extending knowledge management theory to the macroeconomic level, examining how knowledge management capacity affects the relationship between digital sustainability and green finance. By focusing on Asian economies and applying both quantile regression and GMM, the study provides empirical insights into how institutional knowledge infrastructure enhances the effectiveness of digital tools in advancing green finance. The conceptual model of this study is based on the premise that digital sustainability has a limited direct effect on green finance, but this relationship is affected by national-level knowledge management capacity. The model draws on knowledge management theory and incorporates macro-level indicators to capture this interaction. The remainder of the paper is organized as follows: Section "Asian context" provides the context of the study, and section "Theoretical framework" provides the reviews of the relevant literature and develops the theoretical framework. Section "Data and methodology" presents the methodology, including variable definitions, data sources, and model specifications. Section "Results" and "Robustness analysis" reports the empirical results, followed by section "Discussion", which discusses the findings considering the literature. Section "Conclusion" concludes with key policy implications, theoretical contributions, and suggestions for future research.

## Asian context

This study uses the sample of Asian countries for several compelling reasons. The focus on Asian economies is both timely and strategically important. Asia is home to over 60% of the world's population and contributes nearly half of global carbon

emissions, making it central to the success of international climate goals and the UN's sustainable development goals (SDGs) (United Nations, Department of Economic and Social Affairs, Population Division (2023)). The region exhibits a diverse economic landscape from highly developed digital economies like South Korea and Singapore to rapidly industrializing nations such as India, Vietnam, and Indonesia, creating a rich context. Asian economies are also undergoing accelerated digital transformation, with investments in AI, fintech, and digital infrastructure growing steadily across the region (Ordóñez de Pablos, 2024). According to the Asian Development Bank (2023), Asia's green finance market exceeded USD 500 billion in issuances, yet remains constrained by gaps in institutional capacity and knowledge-sharing mechanisms. At the same time, environmental challenges such as urban pollution, resource depletion, and climate vulnerability have intensified the urgency of sustainable innovation. These dynamics make the region a compelling case for examining how knowledge management and digital sustainability intersect to drive green finance at a macroeconomic level (Fang and Chang 2016).

The Asian countries provide an appropriate context because they comprise nations with varying levels of dimensions for knowledge creation and sharing. These dimensions are influenced by factors such as education, technological advancements, and cultural attitudes, which are major attributes of the knowledge economy Index as suggested by the World Bank (Andres et al., 2021). Effective utilization of knowledge management assets at the country level is important to understand these differences. Exploring how knowledge management capacity could support the innovation process to enhance the green finance practices offers valuable insights to the UN Sustainable Development Goals. Asia is crucial in achieving the United Nations SDGs, particularly those related to sustainable cities and climate action. Developing knowledge management capacity is crucial for effective green finance strategies (Ding et al., 2022). Analysis of prevailing capacities and highlighting gaps can guide the relevant stakeholders to design the targeted training programs. Understanding how knowledge management supports these goals can enhance regional and global efforts. The integration of digital technologies with knowledge management practices can optimize information flow and decision-making (Dikau and Volz, 2021). Analyzing this interplay in the Asian context can uncover strategies for improving green finance outcomes.

### Theoretical framework

The theory of knowledge management integrates several existing theories into an integrated framework, establishing it as a unique and innovative discipline (Baskerville and Dulipovici, 2006; Scarbrough, 2003). The relationship between knowledge management and its theoretical foundations illustrates how the field has evolved into a distinct, impactful, and practical area within management theory (Lee et al., 2021). Developments in knowledge management have drawn important factors that increase performance in terms of organizational creativity, operational effectiveness, and the quality of products and services (Wiig, 1994). The fast expansion of knowledge management in global business has encouraged research scholars to make sense of the extensive and diverse body of contemporary research. Knowledge management theory can be scaled from the micro (organizational) level to the macro (national) level (Tahir et al., 2023; Asongu and Tchamyu, 2020). While most knowledge management frameworks focus on organizational settings, countries can also apply these concepts to manage their assets, such as innovation, human capital, and expertise, to achieve sustainable economic growth (Shahzad et al., 2021; Omri and Mabrouk, 2020).

At the macroeconomic level, factors like overall knowledge creation capability, a nationwide knowledge-sharing infrastructure (e.g., investment in education and institutional quality), and the strength of research institutions should be considered when evaluating knowledge management capacity. Prior studies have established links between digital transformation and sustainability (Xu et al., 2023). This study complements and extends such work by theorizing a macro-level mechanism through which national knowledge systems influence the effectiveness of digital sustainability in fostering green finance.

To apply Knowledge Management Theory at the macroeconomic level, where the unit of analysis is the country rather than the firm, this study draws on concepts from the knowledge economy literature (Shahzad et al., 2021; Raspe and Van Oort, 2006; Omri and Mabrouk, 2020). The knowledge economy emphasizes the role of innovation, R&D, human capital, and ICT infrastructure in national development elements that are closely aligned with the core constructs of knowledge management, such as knowledge creation, sharing, and application. Integrating these perspectives allows us to conceptualize Knowledge Management Capacity (KMC) as a national-level capability that supports the transformation of digital sustainability efforts into green finance outcomes. Economies that effectively manage their knowledge through robust sharing infrastructure, human capital development, and innovative capabilities build knowledge management capacity, which is likely to positively impact sustainable development. This aligns with endogenous growth theory, which posits that human capital, central to knowledge management theory, is a key driver of economic growth. The endogenous growth theory, reinforced by human capital theory (Becker, 1975), asserts that intrinsic factors, such as human capital and knowledge management, play a more significant role in economic development than physical capital alone (Kruse-Andersen, 2023). Digital sustainability, as a form of physical capital, cannot independently influence green finance within the economy. It requires the effective application of management of the knowledge assets (digitally novel solutions) through enhancing robust knowledge management capacity (Gao et al., 2018). This approach helps economies to harness the full potential of financial technologies, improving human productivity and positively influencing green finance outcomes (Mota Veiga et al., 2023). A comparative analysis of important studies presented in Table 1 reveals that while most research has explored the relationship between digital transformation, knowledge management, and sustainability at the firm level, little attention has been given to how these dynamics operate at the macroeconomic level. This study addresses this gap by applying knowledge management theory to investigate how national-level digital sustainability and knowledge capacities shape green finance outcomes in Asian economies.

**Hypothesis.** In recent years, the use of digital technologies to attain environmental goals has been recognized as a potentially transformative tool in the transition to green finance (Safi et al., 2024). Technologies such as artificial intelligence, blockchain, big data analytics, and digital finance platforms have been shown to increase transparency, efficiency, and access in green financial markets (Dell'Erba, 2024). However, much of this evidence is drawn from firm-level or sector-specific studies conducted in developed economies, where institutional and knowledge infrastructures are relatively advanced (Mota Veiga et al., 2023; Donate and Guadamillas, 2011; Sarkar et al., 2024).

From the perspective of the knowledge-based view (KBV) and knowledge management theory (Grant, 1996), knowledge is a

**Table 1 Review of comparative literature.**

Author	Focus area	Level of analysis	Methodology
Lundvall and Nielsen (2007)	Learning organizations, knowledge management, and innovation in firms	Firm level (Danish private sector)	Survey; evolutionary analysis
Tamazian et al. (2009)	Institutional quality, economic development, and environmental performance	BRICs/National level	GMM
Chen and Huang (2009)	Strategic HR practices, knowledge management capacity, and innovation performance	Firm level (Taiwan)	Survey; regression analysis
Donate and Guadamillas (2011)	Organizational enablers (culture, leadership, HR) for KM and innovation	Firm level (Spain, innovative industries)	Survey ( $n = 111$ ); SEM
Stuermer et al. (2017)	Conceptualizing digital artifacts as sustainable resources in knowledge societies	Conceptual/multi-level (ecosystem perspective)	Theoretical analysis; conceptual framework
Gao, et al. (2018)	Theoretical conceptions and design approaches of knowledge management	Conceptual/Theoretical	Theoretical review and synthesis
Di Vaio et al.(2021)	Digital innovation in knowledge management systems and business governance	Literature-based (Global/business level)	Bibliometric review of 46 articles (1990–2020)
Aksu and Akman (2024)	Eco-determinants, eco-innovation strategies, and SME sustainability performance	Firm level (Turkey)	Survey; PLS-SEM (Smart-PLS)
Ding et al. (2022)	Innovation climate, knowledge sharing, and RandD team effectiveness in green finance	Team level (green finance R&D teams, China)	Survey; SEM
Lee et al. (2023)	Knowledge sharing, organizational culture, structural capital, and innovation performance	Firm level (Taiwan real estate sector)	Survey; Hierarchical Linear Modeling (HLM)
Chung and Huang (2021)	Cultural embeddedness, happiness, and knowledge-sharing in virtual inter-organizational teams	Team/organizational level (Taiwan, Farmers' Associations)	Qualitative case study; interviews and observations
Mardani et al., 2018	KM activities (creation, integration, application) and their impact on innovation and firm performance	Firm level (Iranian Power Syndicate firms)	Survey ( $n = 120$ ); SEM using PLS
Mota Veiga et al. (2023)	Knowledge spillovers, KM capabilities, and innovation in hospitality	Firm level (Portugal)	Survey; multiple regression
Xu et al. (2023)	Digital transformation, eco-innovation, sustainable performance	Firm level (China)	PLS-SEM

critical strategic resource, and its effective use depends on systems that facilitate acquisition, sharing, and application (Birasnav and Rangnekar, 2010). Digital sustainability, defined as the environmentally conscious application of digital technologies, has gained attention for enabling green financial solutions (e.g., green fintech, carbon-tracking platforms, sustainable investment analytics), its impact is not guaranteed in the absence of institutional knowledge capabilities.

In many Asian economies, fragmented knowledge infrastructures, uneven ICT adoption, and limited absorptive capacity hinder the translation of digital tools into effective green financial practices (Taghizadeh-Hesary and Hyun, 2022; Hehua et al., 2024). Therefore, digital sustainability may not have a strong, significant direct effect on green finance, unless it is complemented by national-level systems that manage and mobilize knowledge for sustainable development. This expectation aligns with prior research suggesting that digital solutions require enabling ecosystems to be impactful (Chen and Huang, 2009; Gao et al., 2018). Therefore, based on the above, the first hypothesis is as follows: -

**Hypothesis 1:** *Digital sustainability has a limited direct impact on green finance in Asia.*

Sustainable financial development hinges on the integration of modern technology into the financial sector, emphasizing the importance of digital sustainability (Mridha, Sarkar, 2025; Sarker et al., 2024). This concept contributes to green finance by fostering financial innovation and optimizing economic resources through new financial instruments. In a rapidly changing world, innovative and sustainable solutions play a key role in the development of green economies. However, the impact of these solutions depends on the infrastructure for knowledge creation and sharing, which enhances knowledge management capacity and the ability to effectively absorb these technologies. (Chen and Huang, 2009; Youndt et al., 1996). Knowledge management

capacity, comprising collective skills, innovative abilities, and advanced knowledge of individuals, is becoming increasingly critical with the rise of digital technologies (Ugal and Betiang, 2009; Haini, 2019). Knowledge management is not only about leveraging technology but also about fostering human capital to support green finance and thereby sustainable economic development (Levine, Robert (1998); Ćadil et al., 2014; Bukhari and Nadeem, 2024).

Digital sustainability facilitates financial intermediation, enhances financial transparency, and strengthens financial integrity, leading to the development of efficient and sustainable financial systems (Richardson, 2016). However, financial innovation is beneficial but also introduces risk, as demonstrated by the 2007 financial crisis (Allen et al., 2012). This underscores the need for balanced innovation, supported by appropriate knowledge management practices, to ensure the stability and sustainability of financial systems. The integration of digital transformations into knowledge management helps to implement financial technologies effectively to promote green finance while mitigating potential risks associated with advanced technologies (Banerjee and Roy, 2014). Digital technologies cannot operate in isolation, as they require supportive factors for successful implementation. Knowledge creation capacity plays a vital role in Asian economies, where initiatives are underway to promote green finance through digitally sustainable solutions. It facilitates the development of innovative solutions that can be effectively shared with stakeholders, reinforcing the connection between digital sustainability and green finance. Digital sustainability provides a number of benefits, including increased financial transparency, integrity, and efficiency. However, the effects of knowledge management capacity in many Asian countries are limited, mainly due to the lack of knowledge creation resources and knowledge-sharing infrastructure. Lack of intensity of these

indicators restrict the direct impact of digital sustainability on green finance. Enhancing knowledge management capacity can significantly improve the positive impact of digital sustainability on green finance. A strong infrastructure for knowledge creation and sharing promotes innovation and collaboration among stakeholders, enhancing the impact of digital sustainability initiatives. Therefore, countries investing in enhancing their knowledge management capacity are paving the way to fully utilize the benefits of digital sustainability for promoting green finance and achieving sustainable development across Asian economies. According to Knowledge Management theory, effective knowledge management facilitates knowledge creation, transfer, and application, which are critical processes in supporting green innovation and investment. This reflects the enabling role of knowledge management in translating digital systems into strategic environmental initiatives. Prior literature suggests that economies or institutions with stronger knowledge management systems are better positioned to harness digital transformation for sustainability objectives (Mota Veiga et al., 2023). Based on the above arguments, the second hypothesis is as follows: -

**Hypothesis 2:** *Knowledge management capacity strengthens the positive impact of digital sustainability on green finance in Asia.*

### Data and methodology

This study has nine economies from Asia based on data availability on Green Finance and Green Patents. Data comprises an annual time series of nine Asian economies. These countries include China, India, Indonesia, Malaysia, Japan, South Korea, Singapore, Thailand, and the Philippines. Data sources include Refinitiv (IMF staff calculations), Official websites of the respective countries and World Intellectual Property Organization (WIPO) have also been explored to extract the country-specific data on green patents (Feenstra et al., 2015; Alharbi et al., 2023). All sources are publicly available and widely used in the literature. This study is restricted to nine Asian economies and the period from 2007 to 2023 due to limited data availability on Green Finance.

The study period from 2007 to 2023 is chosen to cover the post-global financial crisis era, a time marked by increasing attention to digital governance, sustainability initiatives, and the integration of environmental concerns into financial decision-making across Asia. This range also enables the capture of structural changes in digital sustainability and green finance policies, including the impact of the 2015 Paris Agreement and the UN SDG framework.

**Empirical model.** The concept of the study is grounded in Knowledge Management Theory and informed by the knowledge-based view of the firm (Grant, 1996), extended to the macroeconomic context. The hypothesized relationships, specifically the limited direct impact of digital sustainability on green finance and the role of knowledge management capacity between them, are developed from a combination of theoretical reasoning and empirical gaps identified in the literature (e.g., Montani and Staglianò, 2022; Donate and Guadamillas, 2011). To ensure statistical authenticity, in this study, a series of robustness checks are conducted, including, use of quantile regression to examine heterogeneity across the green finance distribution, Implementation of GMM estimation to address potential endogeneity and autocorrelation, Multicollinearity testing using variance inflation factor (VIF). To examine the impact of digital sustainability and knowledge management on green finance, we augment Eq. (1) with digital sustainability and knowledge management as additional regressors, as well as

control variables as given in Eq. 1.

$$GF_{it} = \alpha + \beta_1 DS_{it} + \beta_2 KMC - RQ_{it} * DS_{it} + \beta_3 KMC - EX_{it} * DS_{it} + \beta_4 KMC - ICT_{it} * DS_{it} + \beta_5 KMC - PAT_{it} * DS_{it} + \beta_6 GDP_{it} + \beta_7 EC_{it} + \beta_8 TO_{it} + \beta_9 POP_{it} + e_{it} \quad (1)$$

Where,  $\alpha$ , is constant,  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$ ,  $\beta_4$ ,  $\beta_5$ ,  $\beta_6$ ,  $\beta_7$ ,  $\beta_8$ ,  $\beta_9$  are coefficients of variables,  $e_{it}$  is error term. GF green finance, DS digital sustainability, KMC knowledge management capacity, RQ regulatory quality estimates, EX education expenditure, ICT information and communication technology infrastructure, PAT patents, GDP gross domestic product, EC energy consumption, TO trade openness, POP population

**Green finance.** The definition of green finance (GF) has multiple dimensions. One of the better-known definitions considers green finance as a growing process that incorporates environmental, social, and governance issues when making financing and investment decisions (Busch et al., 2021). To limit the negative impact of carbon emissions on the environment, financial institutions must implement environmental and climate change policies, especially after the Paris Climate Agreement was signed in 2015 (Geng et al., 2018). Due to international and regional pressures, institutions are compelled to launch financial products aimed at reducing carbon emissions from industrial waste, pollutants, and fossil fuels, thereby reducing greenhouse gases. Many financial institutions in coal-exporting countries are also providing more carbon finance compared to conventional loans on fossil fuels to mitigate the negative effects of greenhouse gases on the environment (Ganda and Milondzo, 2018; Glomsrød and Wei, 2018). A green bond is a debt instrument that is used to raise capital for environmental investment activities (Freeburn and Ramsay, 2020). Therefore, green finance is measured as total proceeds from the issue of the green bond by various government, non-government, and corporate bodies in a country (Alharbi et al., 2023; Al Mamun et al., 2022).

**Digital sustainability.** In the literature, there is no consensus on defining digital sustainability (DS), with different studies presenting diverse perspectives on the subject (Dapp et al., 2014; George et al., 2021). Digital sustainability can be defined in various contexts, such as the collection of environmental data, the use of sustainable technology, and the digitization of markets and many more. Nevertheless, the essence of all these definitions revolves around the creative deployment of advanced technologies to pursue sustainable development, aiming to provide maximum utility with minimal restrictions without causing environmental deterioration, thereby fulfilling the needs of both current and future generations. In the present context, this study aims to investigate the impact of digital sustainability on green finance. Thus, digital Sustainability can be treated as a form of Green Technology. Digital sustainability refers to the responsible and ethical use of digital technologies in ways that promote environmental sustainability, social equity, and economic development without depleting natural resources. Digital sustainability extends the scope by integrating digital tools that enhance environmental sustainability across sectors. Both need to be viewed as interrelated in today's digital and eco-conscious world, where sustainability in the digital age must include both physical green technologies and digital innovations that drive eco-friendly change. Accordingly, based on previous studies, green patents are used as a proxy to measure green technology. Following the existing literature, a patent is classified as a green patent if it demonstrates the potential to contribute to environmental solutions. The classification of green patents is conducted based on

**Table 2 Definition of variables.**

Symbol	Variable	Definition	Source
GF	Green Finance	Natural logarithm of total proceeds from the issue of the green bond by various government, non-government, and corporate bodies in a country.	Refinitiv (IMF staff calculations)
DS	Digital sustainability DS	Natural logarithm of green patents	Country IPO websites and WIPO
KMC-RQ	Knowledge management capacity- (Regulatory Quality)	Regulatory quality estimates	WDI
KMC-EX	Knowledge management capacity (education expenditure)	Government education expenditure as % of GDP	WDI
KMC-ICT	Knowledge management capacity- (ICT Infrastructure)	Sum of mobile and fixed subscription data per 100 people	WDI
KMC-PAT	Knowledge management capacity- (Patents)	Natural logarithm total no. patents	WDI
EC	Energy consumption	Natural logarithm of energy use (kg of oil equivalent per capita)	WDI
GDP	Economic growth	GDP growth rate	WDI
TO	Trade openness	Import + export (% of GDP)	WDI
POP	Population	Population density per 1000 square meter	WDI

the Organization for Economic Co-operation and Development (OECD)-Environmental Technology (ENV-TECH) guidelines, which were specifically developed for this purpose (Cvijanović et al., 2021; Favot et al., 2023). Following this classification, we identify and quantify the green patent output for each Asian country included in the analysis.

**Knowledge management capacity.** Chen and Huang (2009) define knowledge management capacity at the organizational level, having two basic components that operationalize it. The first component is the organization's ability to create knowledge, and the second is the organization's capacity to ensure the effective utilization of that knowledge creation or innovations. On this backdrop, this study scaled up the application of knowledge management capacity from the organizational level to the country level. Leveraging insights from the study of (Chen and Huang, 2009), this study also relies on the knowledge creation and knowledge-sharing infrastructure to ensure the effective diffusion of knowledge creations among all the stakeholders within the economy (Lu et al., 2008).

Knowledge management capacity comprises two main dimensions, knowledge creation and knowledge-sharing infrastructure. To measure knowledge management capacity, this study used indicators of the knowledge economy index (KEI), which is based on the World Bank's Knowledge Assessment Methodology (KAM) (Chen & Gawande, 2007). The KAM methodology identifies four key indicators that reflect a country's ability to create and diffuse knowledge. These indicators include a combination of institutional frameworks, human capital development, structural factors, and R&D expenditures that enable innovation within the economy. In low-income countries, these elements play a critical role in facilitating knowledge creation and diffusion (Andres et al., 2021). The Knowledge Economy Index is widely considered a composite measure of a country's knowledge economy. It employs the KAM methodology, which organizes proxy variables into four main pillars to provide a comprehensive description of a nation's knowledge economy (Cohen et al., 2020).

Firstly, an economic and Institutional regime, which help to flourish the novel knowledge and can be measured through regulatory quality. To capture institutional quality, this study have used indicator of governance, regulatory quality estimates (RQ).

Secondly, an educated and skilled population, we measure investment in education through government expenditure on education as a percentage of GDP (EX). Educational attainment equips individuals with the specialized knowledge and skills

necessary for a knowledge-based economy. Investing in education creates diverse opportunities, enabling individuals to navigate complex and dynamic environments through experiential learning, thereby enhancing productivity and competitiveness across various industries (Mardani et al., 2018).

Thirdly, an information and communication infrastructure is needed to effectively disseminate the creation of knowledge. This dimension is proxied by the sum of mobile and fixed subscription data per 100 people to measure the ICT access, which is a common proxy used to measure ICT in Asian countries (Amri, 2018; Amri et al., 2019).

Fourthly, an efficient innovation system, strong research institutions, and public bodies to promote knowledge creation and knowledge diffusion. This study measures this dimension through the total number of patent applications produced by the country in a specific year, reflecting the country's innovative capacity (PAT) (Ponta et al., 2020).

**Control variable.** Following prior studies (Khan et al., 2022), control variables are also employed, such as GDP growth rate (GDP), energy consumption (EC), trade openness (TO), and population density per 1000 square meters (POP). Definitions of all variables are presented in Table 2. The GDP growth rate is included as a proxy for economic development and national capacity. Economies with higher growth rates typically have greater financial and institutional resources, which enhance their ability to invest in sustainable initiatives and adopt green technologies (Tamazian et al., 2009). Trade openness is controlled for because international trade can influence environmental practices and financial integration, especially in export-driven Asian economies (Afesorghor and Demena, 2022). Energy consumption per capita is included as a measure of industrial and environmental intensity. High consumption often correlates with environmental degradation, thus affecting green policy outcomes (Radmehr et al., 2021). Population density serves as a demographic control, reflecting urbanization, resource pressure, and sustainability challenges (Khan and Cui, 2022). These control variables help isolate the specific effects of digital sustainability and knowledge management capacity on green finance, ensuring the robustness of the empirical model.

## Results

**Descriptive statistics.** Table 3 presents the descriptive statistics of the study variables for the sample of nine Asian economies over

**Table 3 Descriptive statistics.**

Variable	Mean	SD	Min.	Max
GF	5.393	1.1870	0.594	7.271
DS	2.11	2.35	-0.2308	11.04
KMC-RQ	-0.432	0.274	-0.833	-0.050
KMC-EX	1.894	0.448	1.193	3.078
KMC-ICT	0.5310	0.5031	0.0098	1.552
KMC-PAT	11.71021	10.15831	1.309	15.147
EC	6.938	4.630	6.06	7.708
GDP	2.250	4.209562	-24.461	18.260
TO	54.370	42.2441	9.135	220.406
POP	784.18	1,985.39	22.71	7,714.70

N = 135, observations from nine Asian economies from 2007 to 2023. WDI refers to World Development Indicators and Refinitiv (IMF staff calculations)

**Table 4 Variance inflation factor (VIF).**

Variable	VIF	Tolerance (1/VIF)
DS	2.30	0.435
KMC-RQ	3.10	0.322
KMC-EX	4.50	0.222
KMC-ICT	2.80	0.357
KMC-PAT	3.90	0.256
EC	2.10	0.476
GDP	1.90	0.526
TO	2.40	0.417
POP	3.20	0.312
Mean VIF	2.91	—

the period 2007–2023. The average value of green finance (GF) is 5.39, with a standard deviation of 1.18, indicating moderate variability across countries and time. Digital sustainability (DS) exhibits a mean of 2.11 with a relatively high standard deviation (2.35), reflecting significant heterogeneity in digital sustainability efforts across the region. Notably, the minimum value of DS is negative, possibly reflecting underperformance or transitional phases in some economies.

Among the knowledge management capacity indicators, KMC-RQ (research quality) has a negative mean (-0.432), suggesting lower relative research performance for most countries in the sample, while KMC-EX (research expenditures) and KMC-ICT (ICT infrastructure) show moderate variability, indicating different levels of institutional investment in knowledge infrastructure. KMC-PAT (patents per capita) has a high standard deviation (10.15), implying substantial cross-country differences in innovation output.

The control variables also reveal important trends. GDP growth shows high variability (SD = 4.21), with some countries experiencing negative growth during certain periods (min = -24.46%), likely reflecting global or regional economic shocks. Trade openness (TO) varies widely (mean = 54.37, SD = 42.24), capturing the diversity in economic integration, while population density (POP) ranges from sparsely to densely populated economies (from 22.71 to over 7700 per km<sup>2</sup>). These statistics underline the heterogeneous nature of the sample, which enhances the robustness and generalizability of the results.

**Variance inflation factor (VIF) test.** To assess multicollinearity among explanatory variables, variance inflation factor (VIF) analysis is conducted, which is presented in Table 4. All VIF values were found to be below the conventional threshold of 10, with most values falling below 5, indicating that multicollinearity is not a concern in our model (Gujarati, 2004). This diagnostic

**Table 5 Pesaran’s second-generation panel unit-root test results.**

Variable	PCIPS test (at level)
DS	-5.65228***
GF	-3.34929***
RQ	-3.37327***
EX	-4.92003
ICT	-5.37190***
PAT	-3.56228***
GDP	-8.58428***
EC	-1.62296*
TO	-1.54700*
POP	3.466**

\*, \*\*, and \*\*\* denote statistical significance at the 10%, 5%, and 1% levels, respectively.

supports the reliability of coefficient estimates and ensures the model’s internal validity.

**Pesaran’s second-generation panel unit-root test results.** A test for stationarity is conducted before proceeding to regression analysis (Ozkan et al., 2024). To test stationarity of panel data, Pesaran’s second-generation panel unit-root test is used. This test is designed to deal with the unit roots in the panel data, which accounts for cross-sectional dependence. This property does not exist in the first-generation unit-root tests like the Levin–Lin–Chu test (Jin et al., 2022). The results of Pesaran’s second-generation panel unit-root test are reported in Table 5.

**Quantile regression estimates.** Equation (i) is estimated by employing quantile regression, and the results are presented in Table 6. Quantile regression extends the classical linear regression model. The primary objective of this technique is to estimate the conditional mean, providing comprehensive information on the relationship. Unlike classical linear regression, which aims to estimate the average effect of regressors on regressand and provides limited information (Coad and Rao, 2008; Buhai, 2005). Moreover, this technique does not necessitate the assumption of normality of the residuals, a condition often violated in many regression models with tailed distributions. Quantile regression estimates parameters at different quantiles, thus relaxing the normality assumptions (Cucculelli, 2013). Utilizing quantile regression addresses the issue of heterogeneity in the selected countries for analysis. There is a likelihood that the development of sustainable finance depends on the intensity of digital sustainability and knowledge management within the respective economies. Previous studies have indicated a significant relationship between innovative technologies and financial development, particularly with higher growth of human capital (Haini, 2019). Therefore, it is crucial to employ a technique that accounts for differences in digital sustainability and knowledge management. Quantile regression emerges as an appropriate and superior technique for addressing issues related to heteroscedasticity and skewed distributions

The estimates from the quantile regression are presented in Table 6. The result reveals that the effects of digital sustainability on green finance are small and not statistically significant for the first four quantiles, coefficients for the interaction term are also not found significance. Results of the study reveal that coefficient for digital sustainability along with the coefficient of interaction term are not found significant at the low level of green finance. On the other side, at the median level of green finance that is 50th percentile, results for both the coefficients, digital sustainability, and the interaction term are significant and positive. This

**Table 6** Quantile Regression Analysis.

Quantile (Q)	Q 10	Q 20	Q 30	Q 40	Q 50	Q 60	Q 70	Q 80	Q 90
DS	0.013 (0.03)	0.035 (0.067)	0.052 (0.098)	0.0613 (0.051)	0.063* (0.031)	0.065* (0.33)	0.067* (0.31)	0.0711* (0.031)	0.931** (0.033)
KMC-RQ*DS	0.081 (0.05)	0.087 (0.051)	0.089 (0.047)	0.095 (0.045)	0.132** (0.043)	0.211** (0.062)	0.853** (0.223)	2.253*** (0.123)	2.292*** (0.001)
KMC-EX*DS	0.053 (0.08)	0.059 (0.062)	0.074 (0.057)	0.0918 (0.053)	0.150** (0.033)	0.183** (0.073)	0.992** (0.380)	2.474*** (0.00)	2.690*** (0.00)
KMC-ICT*DS	0.01 (0.37)	0.017 (0.263)	0.036 (0.213)	0.046 (0.137)	0.127** (0.047)	0.191** (0.065)	0.231** (0.112)	1.956*** (0.017)	1.973*** (0.00)
KMC-PAT*DS	0.102 (0.19)	0.144 (0.184)	0.215 (0.18)	0.286 (0.177)	0.360** (0.245)	0.556** (0.237)	0.605*** (0.132)	1.227*** (0.287)	1.610*** (0.346)
GDP	0.67 (0.71)	0.646 (0.702)	0.791* (0.372)	0.839* (0.417)	0.931*** (0.315)	0.165*** (0.018)	0.243*** (0.027)	1.012*** (0.03)	1.021*** (0.315)
EC	0.35 (0.51)	0.372 (0.21)	0.392 (0.745)	0.427 (0.589)	-0.594 (0.435)	-0.552* (0.24)	-0.613*** (0.115)	-0.578*** (0.02)	-0.624*** (0.097)
TO	0.02 (0.19)	0.03 (0.182)	0.035* (0.016)	0.038* (0.019)	0.049*** (0.003)	0.057*** (0.003)	0.081*** (0.00)	1.051*** (0.00)	1.451*** (0.091)
POP	-0.134 (0.55)	-0.15 (0.454)	-0.185* (0.071)	-0.297* (0.147)	-0.708* (0.307)	-0.827** (0.333)	-0.862** (0.170)	-1.490*** (0.092)	-1.796*** (0.334)

Notes: Standard errors are reported in parentheses. \*, \*\*, and \*\*\* denote statistical significance at the 10%, 5%, and 1% levels, respectively.

suggests that in Asian economies with an average level of green finance, increasing knowledge management capacity enhances the positive impact of digital sustainability on green finance. At the 80th quantile, which represents higher levels of green finance, the impact of digital sustainability becomes more robust, with the interaction term exceeding the median value. This indicates that in countries with high levels of green finance, the relevance of knowledge management capacity becomes more prominent, as the results show it plays a crucial role in maximizing the benefits of digital sustainability.

These results could be interpreted as digital sustainability has a modest but statistically significant effect on green finance ( $p < 0.10$ ), suggesting that while digital infrastructure plays a role, its impact is limited in scale without complementary institutional factors like knowledge diffusion and absorptive capacity. The limited direct effect of digital sustainability on green finance aligns with prior research emphasizing that digitalization, in isolation, does not automatically translate into sustainable financial outcomes (Hossain et al., 2024). Studies such as (Mardania (2018)), have argued that without appropriate institutional and knowledge management frameworks, digital tools may remain underutilized or misaligned with green objectives.

Conversely, some literature suggests a more substantial digital impact on green finance (e.g., through green fintech, blockchain applications in ESG reporting, etc.) (Hidayat-ur-Rehman and Hossain, 2024). The divergence in findings may reflect differences in regional institutional maturity, data availability, or measurement approaches. In the context of Asian economies, where digital capabilities are uneven and often disconnected from environmental finance strategies, our finding offers a region-specific insight that supports calls for more integrated policy frameworks. These findings corroborate the hypothesis of the study that economies exhibit their ability to effectively manage knowledge, which allows them to channel innovation efficiently in the right direction. Based on the data analysis using quantile regression in Asian countries, the results reveal that the application of digital sustainability relies on the knowledge creation and Knowledge sharing infrastructure for the development of Green Finance. Previous studies and the endogenous growth theory also highlight the role of human capital development as an imperative variable that aids in effectively managing innovation, leading to rapid economic growth (Qamruzzaman, Jianguo, 2020).

Findings of the study support the concepts of endogenous growth theory, which suggests that effective knowledge management, through enhanced human capacity, leads to improved innovation and productivity, thereby laying the foundation for sustainable development (Lucas, 1988; Becker, 1975; Romer, 1990; Laeven et al., 2015). This suggests that knowledge management plays an important role in the development of green finance through digital sustainability. Without appropriate knowledge management alongside digital sustainability, green finance could not be achieved. The results of the study also

**Table 7** Estimated model coefficients.

Variable	OLS	First difference GMM	System GMM
C	-0.62227 (0.36407)	-14.017 (12.53)	-3.148 (0.861)
DS	0.071 (0.055)	0.042* (0.021)	0.081* (0.0039)
KMC-RQ*DS	0.252*** (0.042)	0.269*** (0.063)	0.273*** (0.054)
KMC-EX*DS	0.617** (0.301)	7.914*** (0.001)	9.732*** (0.023)
KMC-ICT*DS	0.117*** (0.038)	0.180* (0.083)	0.235*** (0.017)
KMC-PAT*DS	0.317*** (0.038)	0.539*** (0.018)	0.752*** (0.005)
GDP	0.047*** (0.016)	0.210 (0.132)	0.078** (0.029)
EC	0.0238* (0.012)	0.092 (0.064)	0.036 (0.031)
TO	0.07** (0.003)	0.043* (0.0361)	0.002* (0.001)
POP	-0.0042 (0.0038)	-0.020 (0.056)	-0.07* (0.02)
DS-1		2.144** (0.818)	2.277** (1.079)
Time Dummies		Yes	Yes
Country Dummies		Yes	Yes
N	135	135	135
R <sup>2</sup>	0.945		
Wald-Chi <sup>2</sup>		1349.735	1471.523
p-Value of Sargantest		0.989	1.000
p-Value of AR(1) test		0.457	0.390
p-Value of AR(2) test		0.252	0.145

\*, \*\* \*\*\* denote statistical significance at the 10%, 5% and 1% levels, respectively. Standard errors are in parenthesis.

further strengthen the prior studies (Di Vaio et al., 2021; Oliinyk, 2021; Oliinyk et al., 2021) that appropriate management of the knowledge plays an imperative role in the development of sustainable growth. Our results are also in line with studies that countries' expenditure in knowledge creation and institutional strengthening enables them to fully reap the benefits of sustainable finance (Sulaiman et al., 2015).

**Robustness analysis**

Table 7 presents a robustness analysis conducted using various multiple regression techniques. The equation is estimated using a panel dataset of (09) Asian countries over the period of 2007–2023, employing pooled ordinary least squares (OLS)

regression, first difference GMM have been applied and system generalized method of moments (GMM). System GMM, and first difference GMM, are utilized to control endogeneity across the data, providing superior and reliable estimations (Saeed and Mukarram, 2022). Dynamic models are deemed appropriate in this situation, given that the development of digital sustainability and green finance are relatively new, resulting in inadequate data. Dynamic models offer numerous advantages over static models in such circumstances (Nickell, 1981).

System GMM estimator developed by Arellano and Bover (1995) and Blundell and Bond (1998). This is particularly suitable for this study given the characteristics of our dataset, a short time dimension and a larger cross-section, potential endogeneity among regressors, and the inclusion of a lagged dependent variable (i.e., green finance) to account for its dynamic nature. Endogeneity may arise due to reverse causality between green finance and its determinants (e.g., digital sustainability or GDP), or from omitted variable bias and measurement errors. GMM addresses these issues by using internal instruments, typically lags of the regressors—which enhance identification without relying on external instruments

Arellano–Bond and Hansen–Sargan tests were conducted for the reliability of GMM estimators. Arellano–Bond test for autocorrelation shows an insignificant AR (1) statistic, which is somewhat atypical, as first-order serial correlation is usually expected in the differenced residuals. A possible explanation for this result could be the short time, combined with the relatively small number of observations per country, which may reduce the power of the AR(1) test. Additionally, the inclusion of higher-order lags and the use of forward orthogonal deviations may have dampened serial dependence in the error structure. Importantly, the AR (2) test remains insignificant, which supports the validity of the GMM assumptions regarding the absence of second-order autocorrelation. Insignificant coefficients for the Hansen–Sargan test for overidentifying restrictions suggested that instruments are valid, which shows that there is no relationship between instruments and the error term. Coefficients for the Arellano–Bond test of second-order serial correlations is also found statistically insignificant, which shows the absence of serial correlation in the analysis. Finally, the Wald test suggests that all regressors are jointly significant. All model specifications include the time dummies.

Overall, estimated coefficients reveal expected outcomes. Particularly, the coefficient for the relationship between digital sustainability and green finance is relatively small and marginally significant. As per our assumption coefficient for interaction term of digital sustainability and variables of the knowledge management capacity are large and found positive and strongly significant. Results are not the same for pooled OLS and dynamic models. However, dynamic models provide similar results, but the magnitude of the system GMM estimates is more robust and stronger. This confirms the efficiency of system GMM over first difference estimates, as first difference suffers from small number of observations bias (Blundell and Bond 1998). Results of the study agree with prior research that postulates that knowledge management of the assets is a key force to effective and efficient allocation of resources that leads to sustainable development (Haini, 2019). More, importantly coefficient of the interaction term is positive and significant that suggests that alone digital sustainability is not enough for green finance, it is the knowledge management within the economy that paves the way for digital sustainability to play its effective role in the development of green finance.

## Discussion

Existing studies on digital sustainability have largely focused on organizational practices, technological innovations, and

policy instruments that promote environmentally responsible digitalization (e.g., Aksu and Akman, 2024). These works offer valuable insights into how digital tools contribute to sustainable outcomes, they often treat digital sustainability as a standalone driver and pay limited attention to the institutional or knowledge-based capacities that enable its effectiveness particularly at the macroeconomic level. This study extends the digital sustainability literature by proposing a model, in which the impact of digital sustainability on green finance is contingent on knowledge management capacity. In doing so, it integrates concepts from the knowledge economy, knowledge management theory, and green finance, providing a novel perspective on how institutional knowledge infrastructure amplifies digital sustainability's contribution to national financial sustainability goals. This macro-level integration fills an important gap in existing research, which has rarely examined these linkages in the context of emerging and diverse Asian economies. Specifically, this study investigates the integration of knowledge management within digital sustainability to enhance green finance, aligning with the central objectives of the UN SDGs Millennium Goal 2030. Without tangible progress in green finance, the completion of the UN SDGs agenda would be unattainable (Puplampu et al., (2023); Rizzello and Kabli, 2020).

Findings of the study revealed that digital sustainability is crucial for fostering green finance, the direct impact of digital sustainability on financial sustainability in Asian economies remain weak, consistent with Hypothesis 1. This weak relationship reflects that digital sustainability alone is insufficient to drive green finance without complementary factors, especially without knowledge management capacity. As highlighted in previous studies (Richardson, 2016), digital technologies, such as blockchain, digital banking, and fintech, enhance financial inclusion, transparency, and efficiency. However, their isolated impact is often limited in economies that face infrastructural, regulatory, or skill-based challenges.

In the context of Asian economies, largely uneven adoption rates of digital financial tools and varying levels of technological development present significant barriers. Prior research by Karkezi et al. (2012) and Qamruzzaman, Jianguo (2020) highlights that while digitalization reduces transaction costs and enhances market access, its effectiveness is dependent on how well financial systems are equipped to integrate these innovations. This study identified the weak direct link between digital sustainability and green finance. This suggests that there are other important factors that may drive the relationship and are important to be identified to fully leverage the potential of digital sustainability.

An important contribution of the study is that indicators of the knowledge economy index, which are measured through regulatory quality, education expenditure, ICT infrastructure and innovation capability significantly moderates the relationship between digital sustainability and green finance, providing strong support for Hypothesis 2. Further results of the study reveal that countries that have robust institutions, infrastructure and innovative capacity amplify the positive impact of digital sustainability on green finance. These findings are corroborated by the findings of Abubakar et al., (2015) and Haini (2019), which suggest that managing knowledge assets through the collective skills and expertise of the workforce is crucial for realizing the full potential of digital technologies within the financial system.

The findings further support the notion that Asian economies that invest in human education, research productivity, and strong institutional quality, cultivate the knowledge management capacity, are better positioned to adapt to and leverage digital sustainability for financial development. This study furthermore supports the view of Mardania (2018), who argues that strong

knowledge management practices help economies effectively use digital tools and technologies, leading to better financial performance and long-term sustainability. The positive impact of knowledge management capacity suggests that economies should focus on improving human skills and expertise to complement technology (Chung and Huang, 2021; Macchiavello and Siri, 2022). This approach ensures that digital sustainability efforts result in the benefits of green finance.

### Conclusion

This study examined the relationship between digital sustainability, knowledge management capacity (KMC), and green finance in nine Asian economies over the period 2007–2023. Grounded in knowledge management theory, the findings reveal that digital sustainability alone has a limited direct impact on green finance. However, when supported by strong knowledge management systems, particularly those related to research quality, ICT infrastructure, and innovation, the influence of digital sustainability becomes significantly more pronounced. These results confirm the theoretical expectation that knowledge capacity acts as an enabling mechanism, translating digital tools and data infrastructures into effective, sustainable financial outcomes. This study contributes to the literature by showing that in Asian economies, digital sustainability alone does not guarantee green financial outcomes, underscoring the need for supportive knowledge systems and institutional readiness to realize the potential of digital infrastructure in promoting sustainability. More importantly, positive coefficients of the interaction term in the additional analysis reveal that the development of green finance depends on the way digital sustainability is deployed through effective knowledge management. This underscores the significance of knowledge creation and knowledge-sharing infrastructure to diffuse the knowledge within the economy to foster sustainable development, which in turn relies on green finance.

**Implications.** The study's findings suggest several policy implications. Asian economies should consistently invest in humans to enhance knowledge management skills within their respective economies. This investment will facilitate the effective and efficient use of innovation, promoting green finance. Given the substantial number of developing nations globally, it is imperative for them to adopt improved knowledge management methods to enhance the utilization of digital sustainability. This is crucial for implementing the United Nations Agenda 2030, which is unattainable without significant development in sustainability, particularly in developing nations.

Moreover, this study offers important implications for business managers of financial institutions and policymakers. It suggests that knowledge management skills can be used to handle, gather, and classify information about sustainable finance in a single, transparent location, thereby aiding the development of digital sustainable finance. The findings of the study

*Theoretical implications.* Theoretically, the study advances the application of knowledge management theory at a macro-economic level, demonstrating its explanatory power in sustainability finance research. Empirically, it offers new insights into the role of knowledge infrastructure in bridging the gap between digital transformation and environmental finance in Asia. In doing so, this study extends knowledge management theory by exploring that in developing economies, the ability of the economy to adequately adapt and manage aggregate skills of the workforce is essential for the effective influence of digital innovations on green finance. This study provides an integrated framework to review the impact of digital transformations on green finance for a sustainable future. This study also emphasizes the

centrality of human capital in driving sustainable development, aligning with endogenous growth theory, which highlights that economic growth is primarily driven by knowledge, skills, and innovation rather than just physical capital. Our findings also add to the literature on endogenous growth theory by showing that digital sustainability alone is insufficient to fully realize the benefits of green finance; it must be considered alongside knowledge management capacity. Further, our findings also contribute to the literature of knowledge management theory. Prior literature on knowledge management mostly contributed at the organizational level. The existing study extends this lens from the organizational level to the country level.

*Managerial and policy implications.* Managers of Financial institutions should actively integrate digital tools and technologies that enhance transparency, efficiency, and innovation in their operations. However, they must ensure that these innovations are supported by strong knowledge management practices, which will enable them to adapt effectively to rapid technological changes. Financial institutions should be aware of the double-edged nature of innovation. These technological advancements bring new opportunities; they also introduce risks, such as increased complexity and information asymmetries. Managers must develop robust frameworks for risk assessment and management to ensure the sustainable adoption of digital financial innovations.

For policymakers in Asia, the findings emphasize that investments in digital technology must be matched by strategic enhancement of knowledge ecosystems. Governments should strengthen research institutions and their linkages with industry and finance, improve ICT access and interoperability to enable data-driven sustainable finance, and foster a culture of institutional learning and knowledge sharing through cross-border collaboration and regional platforms. Policymakers in Asian economies should prioritize investments in education and training programs that focus on knowledge management and digital literacy. Empowering the workforce with the necessary skills to manage and implement digital sustainability initiatives is crucial for achieving green finance. Furthermore, human capital development—through digital and environmental education, training, and reskilling—can ensure that emerging technologies are leveraged toward sustainable finance objectives. International donors and multilateral development banks can also play a role in financing knowledge-intensive infrastructure as part of broader digital sustainability initiatives. Governments in Asian economies should facilitate collaboration between the public and private sectors to promote the adoption of digital financial technologies. This involves creating supportive regulations and policies that encourage digital transformation while also investing in knowledge infrastructure to improve the capabilities of financial institutions. In sum, this study underscores that digital transformation must be accompanied by institutional capacity and knowledge systems to generate sustainable financial outcomes. Without such alignment, even the most advanced digital solutions may fall short of supporting Asia's green finance goals and broader SDG commitments.

**Limitations and future research directions.** The study focuses specifically on Asian economies, which limits the generalizability of the findings to other regions or countries. Asian economies are a unique subset of developing countries, and their challenges may differ from those of other regions. The level of technological development and digital infrastructure varies across Asian economies. These variations may influence the strength of the relationship between digital sustainability and green finance, making it difficult to present a uniform conclusion applicable to all Asian countries. The use of cross-sectional data might limit the ability to capture the dynamic nature of the relationship between

digital sustainability, knowledge management, and green finance. Longitudinal studies could provide deeper insights into how this relationship evolves over time.

Future studies could concentrate across different regions to examine how knowledge management at the country level affects the relationship between digital novel solutions and green finance. This will help to understand how region-specific factors (cultural, geographic, and regulatory) influence this relationship. Further studies should use the longitudinal dataset to encapsulate the developing nature of innovative digital solutions and green finance in the context of knowledge management practices over time. This would shed light on how countries adapt to technological changes and whether these adaptations affect the sustainability of green finance. Moreover, specifically, research could examine how this relationship varies across industries within the financial sector, for example, banking, insurance, and microfinance. This would help us to grasp a more targeted understanding of where such dynamics are more significant.

Future research agenda could also incorporate that which specific emerging digital technology for instance, artificial intelligence, and blockchain interact with knowledge management practices to affect the green finance. This will help to understand the impact of these technologies on financial innovations in Asian countries and provide guidance to them on strategic investment and policy decisions. Another realm of investigation could focus on country-specific regulatory environments in Asian countries to provide actionable insights for policymakers to promote and encourage environment for green finance.

### Data availability

All data used in this study is collected from publicly available databases, World Development Indicators (WDI) and Refinitive (IMF staff calculations), IPO websites of the respective countries, and where websites does not exist, we search the WIPO for the country's green patents. The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Received: 17 February 2025; Accepted: 23 September 2025;

Published online: 17 November 2025

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## Acknowledgements

This work was supported by the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia [KFU253478].

## Author contributions

Dr. Syed Shafqat Mukarram and Dr. Faiza Saleem jointly conceived, designed, and coordinated the execution of the study. Dr. Syed Shafqat Mukarram led the development of the theoretical framework and conducted the data analysis. Dr. Faiza Saleem was primarily responsible for synthesizing the literature review and drafting the initial manuscript. Dr. Abdulrahman Alomair contributed to refining the research methodology

and improving the discussion on empirical results. Dr. Abdulaziz S. Al Naim assisted in reviewing the model specification and enhancing the policy implications and discussion section. All authors reviewed and approved the final manuscript.

## Competing interests

The authors declare no competing interests.

## Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

## Informed consent

Informed consent is not applicable. The study used secondary data from publicly available databases. The authors did not directly engage any participants.

## Additional information

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