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Exploring the linkage between digital transformation, green innovation, and carbon neutrality: Implications for business sustainability

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Abstract
Achieving business sustainability progressively depends on alignment of digital transformation, green innovation and carbon neutrality initiatives. This study aims to identify and prioritize the key factors to achieve green innovation and carbon neutrality. Based on the Technology–Organization–Environment (TOE) framework, the Grey Ordinal Priority Approach (G-OPA) is applied to evaluate the relative importance of factors under uncertainty using insights from 14 industry experts. The results highlight 16 critical factors, with "Digital orientation", "Innovation capability" and "Optimizing energy consumption structure" as three most influential factors that businesses must address to effectively integrate digital transformation strategies with sustainability initiatives. The study contributes a structured understanding of how digital transformation drives sustainability and provides practical guidance for managers and policymakers pursuing carbon-neutral strategies.

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1. Introduction

In recent years, the twin imperatives of green innovation and carbon neutrality have gained significant traction as global priorities. Nations and industries worldwide are dealing with the need to mitigate climate change while sustaining economic growth. For instance, the European Union's Green Deal and China's ambitious carbon neutrality targets exemplify large-scale initiatives aimed at fostering sustainability (EU 2024; Zheng and Dutton 2024). These initiatives underscore the urgency for businesses to adopt sustainable practices. Companies such as Tesla and Unilever have demonstrated that integrating green innovation into business strategies not only addresses environmental concerns but also drives competitive advantage and economic viability (Combs 2024). Despite these promising examples, many organizations struggle to balance sustainability goals with digital transformation efforts, revealing a complex and multifaceted challenge. The convergence of digital transformations with sustainability efforts introduces new dynamics and opportunities. Digital technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain, offer unprecedented capabilities to enhance operational efficiency, reduce waste, and optimize resource utilization (Gill et al., 2019; Bothra et al., 2023). For instance, AI-driven predictive maintenance can significantly cut down energy consumption in manufacturing processes, while blockchain can ensure transparent and sustainable supply chains (Khalid 2024). However, the integration of such technologies into traditional business models poses significant challenges, particularly in identifying and prioritizing the factors that drive both digital and green innovations (Song et al., 2019; Ancillai et al., 2023). The current literature often addresses digital transformation and

sustainability in isolation, leaving a gap in understanding how these paradigms can synergistically advance business sustainability.

This paper aims to bridge this gap by explaining the relationship between digital transformations, green innovation, and carbon neutrality within the context of business sustainability. Utilizing the Technology-Organization-Environment (TOE) framework, this study systematically identifies the key factors influencing green innovation and carbon neutrality. The TOE framework is particularly suited for this analysis as it provides a holistic view encompassing technological, organizational, and environmental dimensions. Moreover, to address the complexity and uncertainty in prioritizing these factors, we employ the grey ordinal priority approach (G-OPA). This method enables a nuanced analysis of the relative importance on various determinants, thereby offering clear guidance for businesses embarking on sustainable digital transformation journeys.

The research objectives of this study are threefold: first, to identify the critical factors within the TOE framework that influence green innovation and carbon neutrality; second, to prioritize these factors based on its importance; and third, to provide actionable insights and strategic recommendations for businesses aiming to integrate digital transformation with sustainability efforts. By achieving these objectives, this study makes several novel contributions to the existing body of knowledge. It offers a unique integrative perspective that combines digital transformation and sustainability frameworks, provides a robust prioritization methodology adaptable to varying business contexts, and delivers practical guidance for industry practitioners and policymakers. In conclusion, this study addresses significant research gaps by linking digital transformations with green innovation and carbon neutrality through a structured and comprehensive framework. The insights derived from this study are expected to assist businesses in navigating the complexities of sustainable digital transformation, thereby contributing to broader efforts in achieving global sustainability goals. Through rigorous analysis and practical recommendations, this study aspires to advance both academic discourse and real-world application in the realm of business sustainability.

2. Literature review

This section is divided into two subsections. We reviewed the literature on green innovation and carbon neutrality in the first subsection. In the second subsection, we extend this discussion and focus on digital transformation for business sustainability. The second subsection also highlights the need for the present research work.

2.1. Green Innovation and Carbon Neutrality

The initial debate on green technology and innovation highlights the need for enhanced focus on ecological treatment, pollution reduction and recycling (Braun and Wield 1994). Literature reports that green technology innovation is pivotal in reducing carbon emissions and is imperative for sustainable development (Zhang et al., 2023a). Green innovation can be considered as the development of new hardware or software that aims to create environmentally sensitive products or processes. This includes technological innovations contributing to energy conservation, pollution reduction, waste recycling, green product designs, and corporate environmental management (Chen et al., 2006). Xu et al. (2023) refer to green innovation as the development of commercially viable, ecologically sustainable, and socially responsible goods and processes. Organizations moved towards green innovation in response to increased calls for environmental protection and business sustainability. Literature on green innovation has seen rapid growth in the past two decades (Schiederig et al., 2012). A recent review reports a positive outlook on the research related to carbon neutrality and economic growth (Zhang et al., 2023b). The authors revealed that energy research innovation could substantially improve environmental quality.

Zhang, Zhang and Xie (2023) extend this debate with consideration of technology diffusion and tax revenue along with green innovation and carbon neutrality. They show a positive correlation between technology diffusion, green innovation and carbon emission reduction. The authors also highlighted the need for policy intervention, more focus on technology diffusion, and more on technology inclusivity during the development phase. Qin et al. (2021) included a risk index in their research and suggested modification of environmental policies and political stability to achieve carbon neutrality. Analyzing the green technology innovation in China, Zeng et al. (2022) reports that innovation rate is slow and its impact on carbon emission reduction is more in underdeveloped regions of the country. Xu et al. (2023) developed an index to measure green innovation and environmental regulation. The results from study indicate that green innovation and environmental regulation moderate the expansion of fossil fuels energy, GDP and consumption of renewable energy. They suggest various measures to achieve carbon neutrality while keeping G20 countries in consideration. Brahmi et al. (2023) explored the intersection of green technology and financial inclusion. They report that green technology innovation generates new funding opportunities and contributes to sustainable development.

Few researchers focused on the tax and considered it as a determinant of green innovation (Vandyck and Van Regemorter 2014). Ren and Chen (2023) studied the correlation between environment regulation and green innovation. They confirmed that command-control environmental regulation and tax-based environmental regulation significantly influence enterprise green product and process innovation, and green R&D investment. Several authors discussed the implication of carbon-saving technologies for sustainable development. Silva, Soares and Pinho (2020) highlighted the urgency of decarbonizing economy and how carbon capture and storage technologies can help achieve carbon neutrality. They also advocated the use of green and pollution taxes to fund the technological advancement and promotion of renewable energy resources. Rodríguez-Serrano and Martín-Armario (2019) examined the interrelation between environmental taxes and the environmental economy in the context of

Portugal. They found out that taxes have helped significantly improve the environmental quality. Hong et al. (2024) present a contrary picture and report that green innovation can have a rebound effect. The results indicate an inverted U-shaped relationship of green innovation with carbon emission and GDP per capita. Another researcher correlated with these findings and reported that new technology innovation can open new markets and may lead to more carbon emissions (Ouyang et al., 2020).

The above discussion asserts that green technology and innovation are critical for reducing environmental pollution and decreasing carbon emissions. Additionally, several measures are necessary to push the culture of green innovation, such as tax, policy interventions, and regulatory compliance. These measures offer a lucrative revenue stream for the government and contribute to ecological sustainability.

2.2. Digital Transformation for Business Sustainability

Digital transformation (DT) can be referred to as the process of reinventing an organization by digitising its processes and establishing expanded links across the supply chain (Bowersox et al., 2005). DT involves the radical adoption of information technology to enhance corporate performance. Mazzone (2014) incorporated strategic and tactical aspects in this definition and described DT as a deliberate and ongoing process of technology advancement inside a firm, business model, or technique, encompassing both. Recent literature refers to DT as a disruptive process that profoundly impacts on societies, organizations and value chain networks (Vial 2019). They found 23 unique definitions of DT in the extant literature. These multiple definitions and ever-growing interest in DT from industries and academics established the strategic and operational significance of DT (Guandalini 2022). DT encompasses multiple structural, tactical, and cultural shifts in the working environment and organization to yield beneficial results. DT is associated with multiple benefits, including improved productivity, decision-making, resource allocation and utilization (Du and Li 2024).

Since the 1990s, a substantial amount of scholarly literature has studied the consequences of DT on the economy, society, and the environment (Kunkel and Matthess 2020). Kunkel and Matthess (2020) examined digital and industrial strategies of African and East Asian countries to assess their anticipated effects of Information and Communication Technologies (ICTs) on industry's environmental sustainability. They reported the abundance of vague expectations from ICTs and asked to explore the focussed measures that deal with environmental sustainability while adopting ICTs. George and Schillebeeckx (2022) studied DT in a complex business environment scarred by crisis and geopolitical tensions. They suggest the need for empirical research on the drivers, contingencies, and contexts where DT can be fruitful and comply with Sustainable Development Goals (SDGs). Hilali, El Manouar and Janati Idrissi (2020) empirically examined the impact of DT on business sustainability. They concluded that customers, data and innovation are the key drivers of DT-driven sustainability. Yüksel and Dinçer (2023) modelled the fundamental criteria required for cycle manufacturing and DT. Their results highlight the role of green innovation and new-generation energy technologies in achieving carbon neutrality. Chatzistamoulou (2023) examined digital transformation in the context of European MSMEs and how it can help achieve sustainability. They empirically confirmed that DT fosters sustainability. Robertsone and Lapiņa (2023) studied the role of DT in fostering open innovation and sustainability. They raised concerns related to the potential negative impact of DT on environmental sustainability. Ptashchenko et al. (2025) investigates digital entrepreneurship and its implications for marketing strategies in a rapidly transforming global landscape. They show that digital technologies drive competitiveness, but also introduce regulatory, cybersecurity, and innovation-related challenges. Their findings reveal the need to explore how organizations can design adaptive and sustainable digital strategies that balance opportunity with risk. The authors call for further work on identifying the enablers that integrate digital transformation with long-term business sustainability across diverse markets. Kamari et al. (2025) examines digital supplier selection as a core component of economic decision-making within digital transformation. Their results emphasize that uncertainty-aware evaluation methods are necessary for SMEs, as traditional deterministic approaches overlook incomplete information and financial constraints. They highlight the need for more research on how advanced MCDM models can strengthen economically sustainable digital ecosystems and support cost-efficient transformation. Specifically, they point to the importance of frameworks that reduce financial risks and improve transparency in digital procurement. Another study by Alam et al. (2025) investigates the barriers that hinder digital transformation in courier supply chains, identifying technological, organizational, and strategic challenges. Their results show that unclear goals, limited workforce readiness, and difficulties integrating new systems are among the most influential obstacles. They highlight the need for more research on how organizations can overcome these persistent barriers, particularly in developing economies where digital readiness varies widely. The authors also point to the importance of prioritizing DT enablers and understanding how managerial decisions, investment constraints, and capability gaps shape the success of digital transformation efforts.

Lu, Li and Yuen (2023) developed a framework to evaluate the impact of DT on sustainability innovation ambidexterity and sustainable performance. Payer, Quelhas and Bergiante (2024) provided circularity indicators and technological resources considering DT for sustainable production. Huang and Huang (2024) proposed the concept of green digital transformation capability and studied its interplay with ambidextrous green learning and sustainable performance. They asked future researchers to study the role of green innovation in achieving sustainable performance in this context. A recent review by Guandalini (2022) analyses literature that caters to the DT, sustainability challenges and sustainable innovation. They called for more research on innovation processes, digital sustainability, sustainable transformation and its challenges. Specifically, that sought more research on the mechanisms of

DT that promote sustainable development goals and what factors influence sustainability and DT. Another review reports DT as a predecessor of sustainability (Gomez-Trujillo and Gonzalez-Perez 2022). They reported the need to study enablers driving green jobs and DT considering SDGs. Vial (2019) highlights the lack of understanding of DT and sustainability. They also underscored the complexity of DT and how it should not be only associated with technology adoptions. Wang and Zhao (2025) analyzes how the digital economy reshapes income disparities in smart tourism cities. Their results indicate that digital development can reduce the urban-rural income gap, particularly in lower-tier cities, with tourism acting as a critical mediating mechanism. They highlight the need for deeper examination of how digital infrastructure affects regional equity and what policies can strengthen inclusive digital transformation.

Considering these recent research directions highlighted by previous literature, understanding the interplay between digital transformations and sustainability goals can be considered a research gap.

3. Research Methodology

The main purpose of this research is to identify the factors that drive green innovation and carbon neutrality. To attain this aim, the present study adopted an integrated methodology that combined the TOE framework with G-OPA. Initially, a list of factors was derived from existing research focusing on "green innovation", "carbon neutrality", "digital transformation" and "sustainable change". The list was then shared with a panel of experts to assist in refining the identified list of factors. The panel of experts is constituted using the purposive sampling method, with the experts chosen based on their knowledge in the research context. A total of 20 professionals in the domain of technology, digital transformation, innovation and strategy, change management, and sustainability were asked to attend. Out of these, 14 experts accepted the invitation to participate in the study. Table 1 provides basic information about the experts who participated in this study. Furthermore, the updated list of factors is categorized using the TOE framework. The experts were then invited to evaluate the categorization and prioritize the factors and their categories according to their importance. To prioritize this, the study used G-OPA as a multi-criteria decision-making (MCDM) technique. The methodological flow used in this study is shown in Figure 1. The combined use of the TOE framework and G-OPA ensures both theoretical depth and decision-making relevance, enabling actionable insights for practitioners and policymakers. The following sections explain the methodology used in this study.

3.1. TOE Framework

The current digitalization era is perfect to attain green innovation and carbon neutrality with the help of digital transformation. However, transforming current way of doing businesses is not an easy task which has to go through friction within an organization. In such a case, adopting frameworks or models would pave a way in smooth transformation. There are different frameworks, theories and models available in the literature including, technology adoption model (TAM), diffusion of innovation (DOI), unified theory of acceptance and use of technology (UTAUT), to name a few. But such a transformation in organization is being affected by both internal and external factors. Thus, TOE framework is best suited in this context which covers both internal and external factors influencing the transformation. Tornatzky and Fleischer (1990) developed TOE framework to understand the factors that impact the adoption of technological innovation in an organization. The technological context involves the technological characteristics in terms of capability, functionality, current practices or external technologies available (Abed 2020; Ullah et al., 2021; Sarkar et al., 2024). Organizational context covers the firm's characteristics including, its size, resources, structure, culture or readiness, to name a few (Awa and Ojiabo 2016; Chittipaka et al., 2023; Das and Bala 2023). Whereas, the environmental context involves the external factors such as, industry structure, competitive pressure, regulations, suppliers, etc. (Cho et al., 2022; wael AL-khatib 2023). It is considered as an effective framework to study adoption of innovations which provides holistic view of inner and outer dynamics of an organization (Cruz-Jesus et al., 2019; Abed 2020). Hence, this study expands its application in classifying the factors that influence green innovation and carbon neutrality through digital transformation.

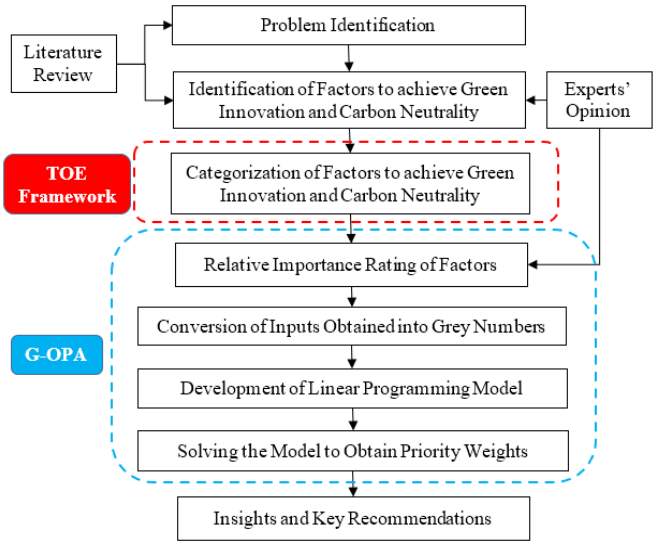

Fig. 1. Research Methodology Flowchart

3.2. Expert Panel Selection

A purposive sampling strategy was adopted to ensure that expert judgments were informed, relevant, and credible. Fourteen experts were selected based on three criteria: (i) a minimum of ten years of professional experience, (ii) direct involvement in digital transformation, sustainability, or carbon management initiatives, and (iii) decision-making or advisory roles within manufacturing, energy-intensive, or technology-enabled service organizations. The panel included senior

managers, sustainability officers, digital transformation leads, and academic experts with industry engagement, ensuring cross-sectoral representation.

To mitigate individual and group bias, expert responses were collected independently and anonymously. Experts were not informed of other participants' evaluations, thereby reducing conformity and dominance bias. The G-OPA method further minimizes subjectivity by relying on ordinal preferences rather than exact numerical judgments, making it particularly suitable under conditions of uncertainty.

Table 1. Details of experts participated in the study.

Expert No.	Designation	Educational Qualification	Domain of Expertise	Total Experience (in years)
Expert 1	Lead - Technology	Graduate	Information Technology	10
Expert 2	Sr. Officer	Post-graduate	Innovation	13
Expert 3	Manager – Strategic Innovation	Post-graduate	Innovation	11
Expert 4	Technology Officer	Graduate	Technology Transformation	13
Expert 5	Director	Ph. D.	Sustainable Development	21
Expert 6	Sr. Engineer	Graduate	Information Technology	11
Expert 7	Centre Head	Ph. D.	Climate Change	16
Expert 8	People and Change Consultant	Post-graduate	Change Management	12
Expert 9	Professor	Ph. D.	Sustainability	17
Expert 10	Professor	Ph. D.	Green Operations, Supply Chain	21
Expert 11	Manager	Post-graduate	Sustainability	13
Expert 12	Sr. Consultant	Post-graduate	Green Innovation Strategy	14
Expert 13	Associate Professor	Ph. D.	Strategy & Innovation	12
Expert 14	Executive Director	Post-graduate	Environmental NGO	20

3.3. Grey Ordinal Priority Approach

Prioritizing factors based on its importance is a difficult task and the complexity increases when it is categorized into categories of diverse groups. Such problem is characterized as MCDM problems. There are several MCDM techniques available in the literature including, Analytic Hierarchy Process (AHP), Best-Worst Method (BWM), Decision-Making Trial and Evaluation Laboratory (DEMATEL), Complex Proportional Assessment (COPRAS), Full Consistency Method (FUCOM), to name a few. Ordinal Priority Approach (OPA) is a recent advancement in MCDM techniques which was developed by (Ataei et al., 2020). It possesses several advantages over other similar MCDM techniques. Some of these advantages includes, elimination of pairwise comparisons and thus there is no requirement of normalization, ability to handle incomplete data which provides flexibility to decision-makers and, supports group as well as individual decision-making (Mahmoudi et al., 2022). However, like other techniques it has major limitation that is, its inability to capture ambiguity and imprecisions involved in human judgement. To cater this, Mahmoudi et al., (2021) integrated OPA with grey numbers. This study also employed grey-OPA (G-OPA) to prioritize the factors. It is worth noting that the steps followed to apply G-OPA is adapted from the study of Mahmoudi et al. (2021) which are as follows:

Step 1: Identifying the problem. The first step begins with the identification of the problem. The problem defined in our case is to prioritize the factors affecting green innovation and carbon neutrality.

Step 2: Finalizing the decision-makers. The constitution of decision-makers to be involved in the study is an important step. To do this, panel of experts with expertise in research domain is formed. The brief details of the experts participated is shown in Table 1.

Step 3: Identify the criteria and alternatives. The next step is to identify the set of criteria and alternatives which are to be examined. In our study, the list of factors and its categories are considered as criteria which are to be investigated.

Step 3: Collecting the input data. Once the criteria are defined, then next step is to collect the data. The experts are asked to rate the importance of criteria based on its importance. The experts are required to rate the importance using the linguistic scale as presented in Table 2.

Step 4: Transforming the input data into grey numbers. This step involves conversion of linguistics scale into grey numbers.

Step 5: Developing the model. The input data in terms of grey numbers are used to develop the linear programming model. The model can be formulated as per equation 1 which is as follows:

$$Max \ \otimes Z$$

s.t.

$$\begin{aligned} \otimes Z \leq \otimes i \Big(\otimes j \Big(\otimes r \big(\otimes D_{ij}^{r} \\ - \otimes D_{ij}^{r+1} \big) \Big) \Big) \quad \forall i, j \ and \ r \\ \otimes Z \leq \otimes i \otimes j \otimes n \otimes D_{ij}^{n} \quad \forall i \ and \ j \\ \sum_{i=1}^{e} \sum_{j=1}^{n} \otimes D_{ij} = [0.8, 1.2] \\ \otimes D_{ij} \geq 0 \quad \forall i \ and \ j \end{aligned} \tag{1}$$

Step 6: Obtaining grey weights. Once the G-OPA model is developed as per equation 1, then it is solved to obtain grey weights of criteria.

Step 7: Converting grey weights into crisp weights. The results obtained in terms of grey weights are required to be converted into crisp weights for prioritization of criteria. The conversion can be done using the equation 2 which is as follows (Huang 2011):

$$\otimes \hat{A} = \frac{1}{2}(\underline{A} + \overline{A}) \quad (2)$$

where, $\underline{A}$ *and* $\overline{A}$ are lower and upper weights of grey number $\otimes A$

Table 2. Grey linguistics scale.

Source: (Mahmoudi et al., 2021)

Linguistic Variables	Grey Numbers	Rank
Very Low Importance (VLI)	(6.5, 7.5)	7
Low Importance (LI)	(5.5, 6.5)	6
Medium Low Importance (MLI)	(4.5, 5.5)	5
Medium Importance (MI)	(3.5, 4.5)	4
Medium High Importance (MHI)	(2.5, 3.5)	3
High Importance (HI)	(1.5, 2.5)	2
Very High Importance (VHI)	(0.5, 1.5)	1

4. Results

This section presents the results obtained from different analyses. The first sub-section represents the factors that influence green innovation and carbon neutrality identified from the literature survey. Further, results obtained from G-OPA to prioritize the factors are presented and discussed in subsequent sub-section.

4.1. Identification and Categorization of Factors

This study investigates the factors influencing green innovation and carbon neutrality through digital transformation. Initially, relevant literature of green innovation, carbon neutrality, sustainable change and digital transformation have been reviewed. This resulted into preliminary list of factors influencing green innovation and carbon neutrality, which was further refined by panel of experts, as presented in Table 1. Further, the authors categorized the factors based on TOE framework which is also supported by the literature. The factors along with categories were further validated by the pane of experts and final list is presented in Table A1. Now, the list of factors and its categories undergoes G-OPA analysis which is discussed in following sub-section.

4.2. Prioritization of Factors

As previously stated, the second major objective of this study is to prioritize the factors driving green innovation and carbon neutrality. To achieve this objective, G-OPA is used in the present study. Following the G-OPA steps outlined in sub-section 3.3, the problem must first be defined, which is to prioritize the factors driving green innovation and carbon neutrality in our situation. The next step is to identify the decision-makers, briefly described in Table 1. The panel of experts is made up of professionals with at least ten years of expertise in the field of this study. Following this step, the list of factors to be investigated is finalized which is discussed in previous sub-section and presented in Table A1. Then, an online questionnaire on Google Forms is formed as per requirement of G-OPA. The questionnaire was shared with the panel of experts and were requested to rate the factors and their categories based on their importance using grey linguistic scale as presented in Table 2. The input data filled by experts regarding importance of categories is presented in Table 3, for reference. After several reminders, the data was collected and fed into Microsoft Excel for further processing. The data was cleaned, and linguistic data was converted into corresponding grey numbers. This step led to development of the linear programming model as presented in equation 1. The developed model was then solved on Python software using *gekko* package. This step resulted in grey weights of factors along with its categories. Afterwards, the grey weights were then converted into crisp weights using equation 2. Following this step, local weights of factors and categories are obtained. Then, the global weights of factors are calculated by multiplying local weights of factors and its corresponding categories' weights, is presented in Table 4.

Table 3. Experts' opinion regarding importance of categories.

	Expert(s)										
Categories	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
Technology	VHI	HI	VHI	MI	MHI	HI	MHI	HI	MHI	HI	VHI
Organization	HI	MI	HI	HI	MHI	HI	MHI	MI	MHI	HI	MHI
Environment	MHI	VHI	HI	MHI	HI	VHI	HI	VHI	HI	MHI	HI

Table 4. Factors to achieve green innovation and carbon neutrality with its local and global weights.

Dimension	Factors	Local Weights	Global Weights	Rank
Technology (0.388)	Innovation capability	0.326	0.126	2
	Adaptive capacity	0.118	0.046	9
	Digital orientation	0.557	0.216	1
Organization (0.239)	Social inclusiveness	0.089	0.021	15
	Absorptive capacity	0.142	0.034	11
	Employees commitment and support	0.196	0.047	8
	Reducing resource redundancy	0.103	0.025	14
	CSR mechanism fulfilment	0.033	0.008	16

Environment (0.373)	Investment in research and innovation	0.436	0.104	4
	Green dynamic capability	0.083	0.031	13
	Environmental awareness	0.130	0.048	7
	Government subsidies	0.130	0.049	6
	Stakeholder acceptance	0.102	0.038	10
	Optimizing energy consumption structure	0.309	0.115	3
	Environmentally regulatory policies	0.161	0.060	5
	Competitive advantage	0.086	0.032	12

The top three ranked factors influencing green innovation and carbon neutrality are "Digital orientation", "Innovation capability" and, "Optimizing energy consumption structure" with global weights of 0.216, 0.126 and, 0.115, respectively. It is worth noting that "Investment in research and innovation" ranked at 4th position despite having 2nd highest local weights of 0.436. This is due to "Environment" aspect is rated higher than "Organization" perspective. Relatively, the experts opined "Reducing resource redundancy", "Social inclusiveness" and, "CSR mechanism fulfillment" as lowest three ranked factors. The insights drawn from the findings and key implications are discussed in the subsequent sections.

5. Discussions

Businesses globally are under pressure to innovate and overhaul their operating models due to the enhanced compliance towards sustainability goals. Previous literature has indicated that green innovation can be a potential pathway to achieve SDG (Zhou et al., 2020). A recent analysis by Arman, Kundakcı, and Katrancı (2025) evaluates digital innovation performance across EU member and candidate countries using an integrated MCDM framework. Their findings reveal substantial disparities in digital innovation capacity, highlighting the need for deeper research into the structural, institutional and technological factors that shape cross-country digital competitiveness. They emphasize that objective weighting and transparent evaluation models are essential for understanding how digital innovation contributes to broader transformation agendas. In this context, the current study aims to extend this debate and develop an understanding of how digital transformation is an integral component of green innovation. Thus, the study examines the key factors that impact green innovation and carbon neutrality via. digital transformations, with a specific focus on technology, organization, and environment as the fundamental dimensions. We identified 16 factors and prioritized them in order of their effectiveness using the grey-OPA method. This section discusses the results and provides key insights.

Results indicate that digital orientation from the technology dimension is the most influential factor. Digital orientation refers to the strategic integration and utilization of digital technologies within an organization to drive innovation. In the context of green innovation, digital orientation can be considered a dynamic capability that plays a crucial role in enabling businesses to optimize their operations, reduce carbon emissions, and contribute to a sustainable future. Previous research has also linked digital orientation with innovation performance, environmental performance and radical green innovation (Khin and Ho 2019). On the contrary, the study by Wang et al. (2024) also presented the negative effect of digital capability which may result into inefficient. One of the experts recommended that organizations strategically invest in digital transformation and earmark the fund for green innovation. This will help push environmentally sensitive innovations within the supply chain. Several formal and informal fund mechanisms, such as green bonds, are available to support such initiatives. Green bonds are reported to have a significant impact and are instrumental in achieving SDGs (Liu and Zhu 2024). Another expert expressed concerns regarding potential failures and suggested that organizations must be prepared for early failures and setbacks. Provisions to compensate for these failures will also help propel the innovation culture.

The second most important factor is Innovation capability, also from technology dimension. This capability enables firms to create sustainable solutions that address environmental challenges. Innovation capability underscores the organizational readiness for digital transformation and culture of innovating. Findings indicate that innovation capabilities are essential for the culture of continuous improvement and creativity; businesses can innovate processes and products that are both economically viable and environmentally friendly. This finding stands out in the study by Olaleye et al. (2024) which presents innovation capability has indirect effects on organizational sustainability, moderated by environmental turbulence. One of the experts foresee the greater role of emerging technologies in managing and disseminating knowledge which will drive innovation. In line with these insight, (Sofiyabadi et al., 2022) underscored the importance on knowledge management for generating innovation capabilities. During the interview, one expert highlight that the innovations capabilities are instrumental in balancing the duality of economic viability and sustainability. These results signal that companies with strong innovation capability can align their strategic directions with environmental goals, ensuring that their innovation efforts contribute to sustainability. Nascimento et al. (2024) also confirmed this and conceptualized Sustainable Technology Development Capability, Sustainable Operations Capability, Sustainable Management Capability, and Sustainable Transaction Capability.

The third most influential factor belongs to environment dimension and explores the approaches to optimize energy consumption. Digital transformation is crucial for adopting and promoting energy saving initiatives. Digital transformation enhances international carbon competitiveness by facilitating improvement in energy structure, scaling and advancing global value chains position. Jin et al. (2024) empirically

validated this statement and suggested integrating digital with manufacturing sector for coordinated green development. Additionally, DT enhances the monitoring and tracking capabilities that improves the carbon consumption in the logistics sector. Logistics has been one of the leading contributors of carbon emissions (Liu et al., 2018). With DT and stakeholders' integration, firms can optimize the distribution, share resources, minimizes transport disruption and maximizes the fleet utilization. Many organizations have improved their energy consumption by adopting intelligent building energy system (Huang et al., 2023). Similarly, DT is essential for automation which can improve resource allocation, can reduces waste and improves decision making (Feng et al., 2023; Long et al., 2024). While our study discusses the potential of DT in optimizing energy consumption, previous literature presents a rather contrary perspective. In the seminal article, (Lange et al., 2020) concluded that digitalization increases energy consumption. They also suggest that the most effective approaches could be to increase energy efficiency by innovation and research. In extensions with these suggestions, we recommend future researchers to investigate the direct relationship between digital transformation and the support capacity of carbon saving technologies.

The fourth highest-rated factor is investment in research and innovation (R&I). This factor belongs to the organization dimension and is the only factor that comes in the top 5 factors from this dimension. This signifies that stakeholders may prioritize factors from technology and environment dimension to achieve business sustainability. Rationale investment in developing, deploying and improving new tools, technologies, processes or systems is necessary for sustainable growth and to remain competitive in the market. Previous literature has confirmed that increased R&I funds pushes the competitiveness in carbon technologies and improves the sustainable performance (Fragkiadakis et al., 2020). In this context, few key insights emerged during the interview process. Many developed countries have provisioned dedicated funds for research and innovation to achieve the carbon neutrality goals (Jesic et al., 2021). Business also needs to adopt these models and earmarked the research and innovation funds to target carbon neutral goals. A culture of R&I also helps disseminate the low-carbon solutions by reducing the cost so that emerging and under development economies can afford these solutions (Warren 2020). Glachant and Dechezleprêtre (2017) also confirmed these findings and highlighted the contribution of climate negotiations to international technology diffusion specifically focusing on least developed economy. Similarly, (Wood et al., 2022) highlighted the importance of incremental innovation for firms performance and signifies this as a solution for firms struggling with working capital. It is evident from our findings and previous literature that earmarked investment in R&I is essential for sustainable growth and competitiveness in the market.

The fifth factor concerns regulatory policies and belongs to environmental dimensions. Environmentally supportive regulatory policies compel firms to become proactive and adopt environmentally friendly practices. Cautioning about misuse or misrepresentation in regulatory compliances, one of the experts advised using change management approaches and monitoring the cost-benefit analysis of non-compliance. Policies can be a motivating factor if disciplinary and supportive tactics are deployed to direct managers to promote low-carbon solutions (Dhanorkar et al., 2018). Regulatory policies also help develop best practices and benchmark firms against each other. Fu et al. (2020) also confirmed that environmental policies stimulate innovations and help organizations become competitive. Regulations have been a win-win game for both organizations and the environment (Wagner 2017). Prior research indicates that environmental regulatory policies should embody characteristics such as participatory decision-making, decentralized governance, flexibility, simplicity, clarity, prevention-oriented approach and promotion of innovation (Ribeiro and Kruglianskas 2015). One insight emerged regarding the reduction of compliance costs. Experts recommend making the compliance cost a part of the carbon trading component so that the compliance burden can complement the environmental goals. It is noteworthy that reducing resource redundancy has been ranked at 14th position relatively. This finding is different from studies reported in the context of digitalization and sustainability (Li and Long 2024; Wu et al., 2025). The reason behind this lower ranking might be because innovation, technology adoption, or green process redesign, which yield more visible sustainability benefits. Also, reducing resource redundancy is moreover operational measures and may less impact on strategic sustainability relatively.

The rest of the factors that have been considered also need reasonable consideration from policymakers and practitioners. Government subsidies are a necessary catalyst to promote holistic growth among multiple industrial sectors. Previous literature has confirmed that subsided and support drive green innovations, supporting infrastructure and capacity building (Chen et al., 2024a; Liu et al., 2024a). Environmental awareness is another important factor that aims to generate sensitivity towards environmental goals. Awareness helps attract R&I funding, talent, and positive customer perception and is also instrumental in guiding policy development (Huang et al., 2019; Mandaroux et al., 2023). The employee's commitment and support also ranked eighth in the analysis, which underscores the importance of hiring skilled employees. The findings of the study help develop an actionable plan that prioritizes the most effective actions towards business sustainability.

6. Implications

The insights derived from this study have several implications for managers seeking to combine digital transformation with green innovation in order to attain carbon neutrality and improve corporate sustainability. The study provides robust theoretical underpinning from the technology, organization and environmental dimensions. Stakeholders can use these findings to make future operations efficient in the complex business environment that faces rapidly changing technologies, dynamic demand, competition, and increased environmental protection concerns. Several insights on factors promoting green innovations have been extracted to complement

the technological transition. These comprehensive range of factors can help managers decide the suitable mix of strategies based on the unique requirements of the operations. Specifically, the following managerial implications can be derived from the study findings.

6.1. Collaboration and Trust among Stakeholders

To develop trust and make long-term mutually beneficial collaborative agreements, managers must adopt emerging technologies that can streamline the information flow. The study's findings pave the path for adopting the emerging technologies that can help generate these capabilities. Specifically, information sharing capabilities, information security, copyrights, innovation practices, recognition, and reward systems can be effectively utilized by adopting emerging technologies. The study findings prioritize factors such as innovation capabilities and energy optimization, focusing on the technology transition and adaptation. Results indicate the greater role of orientations that can be generated by collaborative programs. Further, the social inclusiveness discussed in the study highlights the importance of integrating various internal and external stakeholders for R&I innovations. Thus, the managers are recommended to foster a culture of mutual trust, collaboration and information sharing to drive sustainable growth.

6.2. Strategic Investment for Technology Maturity

Investing strategically in R&I is crucial for technology maturity and for achieving carbon neutrality. The strategic investment in technology maturity will help prioritizing high impact and low carbon technologies, developing innovation culture and capabilities. The study pointed out the importance of technology standardization so that suppliers and distributors working across the globe can be integrated into the system. Discussion also shed light on the early failures and importance of pilot programs. Separate provisions for failures are recommended to overcome these early failures. In order for technology to reach a state of maturity and make a meaningful impact on sustainability objectives, managers need to derive investment approaches insuring that resources are deployed in a proficient and productive manner.

6.3. Innovation Capabilities Generations

Innovative capabilities enable organizations to develop and implement new ideas, products, and processes contributing to their sustainability goals. Extending innovation capabilities relies on internal and external factors such as information retention, information dissemination, stakeholder integration and recognition. The study discusses and underscores the importance of emerging technology in generating and amplifying different types of capabilities, such as green dynamic capabilities, adaptive capacity, innovation capabilities, and absorptive capacity. These capabilities enable the organization to perform at a higher efficiency level and achieve sustainable growth.

6.4. Leveraging Government Support and Regulatory Compliance

Active endorsement of regulatory compliance and taking advantage of government incentives is an essential step towards achieving carbon neutrality. Regulatory compliance activities promote a culture of monitoring, documentation and policy advocacy. These steps help reiterate the strategies and standards across the industries, thereby facilitating a growth momentum. Regular audits and training programs facilitate cross-firm learning. Previous literature has highlighted increased pressure from regulators, customers and society to make economic activities sustainable and carbon neutral (Dubey et al., 2019; Patil et al., 2024). Leveraging government support is essential to push the R&I across the supporting and primary industries. Government plays a critical role in the development of technologies and their widespread use. The stakeholder integration also opens the windows for active stakeholders to participate in the policy formulation. Government bodies are recommended to work on green innovation clusters so that technologies are considerate to carbon-neutral objectives. Utilizing technology for compliance and reporting activities eases the process, and managers can effectively utilize the available resources.

6.5. Energy Saving and Process Optimization

The study discusses the development of low-energy solutions and process modification approaches that result in optimum resource utilization. Since organizations actively explore approaches to maximize value generation and minimize cost, businesses must innovate or redesign their current operating processes. Thus, process redesign becomes one of the critical aspects of achieving carbon neutrality. Further, adopting emerging technology disrupts the current business process (Bressanelli et al., 2019). The alignment between what can be achieved from the emerging technologies and what is needed to achieve carbon neutrality is necessary. Managers need to clearly delineate the goals and reiterate the benefits of emerging technology adoption they want to achieve. This is necessary to avoid early disappointments and evolve the business process with technological change.

7. Conclusion

This paper offers an integrative understanding of the relationship between digital transformations, green innovation, and carbon neutrality, framed within the context of business sustainability. By employing the TOE framework, we identified the key factors influencing these areas and prioritized them using the G-OPA. This dual-theoretical and methodological integration represents a novel contribution to the sustainability literature.

Our findings highlight the importance of integrating technological advancements, organizational readiness, and environmental pressures to drive sustainable business practices. The

insights provided can guide industry leaders and policymakers in making informed decisions that align with global sustainability goals. From a theoretical standpoint, the research extends the TOE framework by embedding it within the context of digital sustainability, highlighting its applicability beyond traditional technology adoption studies. Methodologically, it demonstrates the practical utility of G-OPA in addressing uncertainty and weighting complex interdependent factors an advancement over conventional multi-criteria approaches.

However, this study has several limitations that need to be acknowledged. Firstly, the reliance on the TOE framework, while comprehensive, may not capture all the nuanced factors relevant to specific industries or regional contexts. Future research could explore additional or alternative frameworks that might better address the unique challenges faced by different sectors. Secondly, the G-OPA, although robust in handling uncertainty, relies heavily on the quality and reliability of input data. Variations in data accuracy and availability could impact the prioritization results. Further studies could investigate the sensitivity of the results or use of other multi-criteria decision-making methods to validate and enhance our findings.

Another limitation pertains to the scope of our empirical analysis. While our study provides a broad overview, it does not delve deeply into the sector-specific applications of digital technologies for green innovation and carbon neutrality. Future research could conduct case studies or sector-specific analyses to provide more detailed insights into how these factors play out in various industries. Additionally, longitudinal studies could track the evolution of digital transformation and sustainability efforts over time, offering a dynamic perspective on their interplay and impact on business sustainability. Future research directions should also consider the role of emerging technologies and their potential to further drive green innovation and carbon neutrality. Technologies such as quantum computing, advanced materials, and biotechnology could revolutionize sustainability practices in ways that are not yet fully understood. Investigating the impact of these cutting-edge technologies on sustainable business practices would provide valuable foresight into future trends. Furthermore, the role of policy and regulatory frameworks in shaping the adoption of digital and green innovations warrants deeper exploration, particularly in different geopolitical contexts.

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Appendix

Appendix A

Table A1. Factors to achieve green innovation and carbon neutrality.

Dimension	Factors	Description	References
Technology	Digital orientation (T1)	Technological advancements can be leveraged by the businesses to achieve carbon neutrality via Green Innovation.	(Chotia et al. 2024; Liu et al. 2024b)
	Innovation capability (T2)	Ability to combine strategic innovation directions with innovation behaviors to develop new product.	(Liu et al. 2022; Yang et al. 2023)
	Adaptive capacity (T3)	Ability to align the organization with the external environment by flexibly adjusting strategies and allocating resources.	(Yang et al. 2023)
Organization	Absorptive capacity (O1)	Ability to identify and assimilate valuable external knowledge and integrate with internal knowledge.	(Yang et al. 2023; Haller et al. 2024)
	Social inclusiveness (O2)	Inclusive society promotes environment consciousness and lead to carbon emission reduction.	(Shobande et al. 2023; Song et al. 2023)
	Reducing Resource redundancy (O3)	Redundant resources impact the focus of enterprises from lower energy consumption to managing resources.	(Chen et al. 2024a; Zhou et al. 2024)
	Employees commitment and support (O4)	Committed employees or their support eases out the digital transformation process result in heavier impact of green innovation on carbon emission reduction.	(Xu et al. 2023; Bhatia et al. 2024)
	CSR mechanism fulfillment (O5)	Digital technologies strengthen the enterprises' ability to fulfill CSR in turn helps in carbon emission reduction.	(Chen et al. 2024a)
	Investment in research and innovation (O6)	Increased investment in research and innovation results in emerging technologies and its spread to other nations for combating climate issues.	(Qin et al. 2021; Wang et al. 2022; Haller et al. 2024; Zhou et al. 2024)
Environment	Government subsidies (E1)	Government support to enterprises impacts heavily on carbon emission reduction through digital transformation.	(Shao et al. 2021; Wang et al. 2023; Xu et al. 2023; Zhou et al. 2024)
	Stakeholder acceptance (E2)	Enterprises' focus on carbon emission reduction heavily depends on stakeholders' acceptance.	(Bhatia et al. 2024)
	Optimizing energy consumption structure (E3)	Conventional energy sources are carbon intensive and advanced technologies regarding carbon capture broaden the support capacity of digital transformation.	(Shan et al. 2021; Shao et al. 2021; Shobande et al. 2023; Zhou et al. 2023)
	Environmentally regulatory policies (E4)	Regulatory policies related to environment in terms of taxes discourage the enterprises to use carbon intense fuels ultimately helps in decrease carbon emission with a higher magnitude.	(Shao et al. 2021; Zameer et al. 2021; Zheng et al. 2021; Zhou et al. 2023)
	Competitive advantage (E5)	Now a days, competitive advantage incorporates green concepts which enterprises aspire for. As a result, enterprises adopt green innovation for carbon neutrality.	(Zameer et al. 2021; Chen et al. 2024b)
	Green dynamic capability (E6)	Capacity to utilize resources to promote sustainability and a green environment.	(Long et al. 2020; Chotia et al. 2024)
	Environmental awareness (E7)	Increasing awareness enforces firms to quickly adapt to new changes related to sustainable solutions.	(Sun et al. 2021; Chotia et al. 2024; Patil et al. 2024)