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Sustainable development and green innovation: The role of green dynamic capabilities

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Abstract

Green innovation is increasingly regarded as a strategic approach enabling manufacturing firms to achieve environmental sustainability and maintain a competitive advantage. However, limited research has explored how green dynamic capabilities drive green innovation and sustainable development. This study aims to fill this gap by developing a conceptual framework grounded in the natural resource-based view and dynamic capabilities theory to examine the relationships among green dynamic capabilities, green innovation, and sustainable development. A quantitative survey was conducted with 386 manufacturing firms in Thailand, and structural equation modeling was used to analyze the data. The results reveal that green dynamic capabilities have a significant positive effect on both green innovation and sustainable development. Furthermore, green innovation not only directly enhances sustainable development but also plays a crucial mediating role between green dynamic capabilities and sustainability outcomes. These findings indicate that building green dynamic capabilities enables firms to innovate effectively toward sustainability goals. This study contributes to the literature by integrating dynamic capabilities with green innovation and sustainability research. It also provides practical guidance for managers and policymakers to strengthen green dynamic capabilities and promote green innovation initiatives, ultimately supporting long-term sustainable development in the manufacturing sector.

Keywords: Green dynamic capabilities, Green innovation, Sustainable development.

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1. Introduction

As the global population grows, urban areas expand, and economies undergo rapid intensification, a variety of environmental and resource-related challenges have emerged and are intensifying. These challenges encompass climate change, resource depletion, environmental pollution, excessive industrial waste, and elevated carbon emissions resulting from manufacturing processes [1-3]. Manufacturing firms play a crucial role in driving economic and industrial development, particularly in developing and emerging economies. However, the growth and expansion of these manufacturing entities significantly contribute to a range of environmental issues, including ecological disruption, the depletion of natural resources, and the contamination of air and water systems [4]. In response to escalating environmental and resource challenges, and in pursuit of sustainable economic growth and long-term development within the manufacturing sector, numerous nations and businesses are progressively prioritizing and implementing green innovation. This approach aims to address environmental pollution and resource waste at their source, thereby promoting the sustainable advancement of both society and industry [1, 5].

Environmental degradation, stringent regulatory frameworks, and heightened consumer awareness have collectively driven companies to adopt environmentally sustainable practices, thus fostering innovation. Green innovation enables businesses to meet consumer expectations while ensuring compliance with governmental regulations pertaining to environmental protection. This innovation emphasizes energy efficiency, pollution prevention, waste management, and resource conservation, all aimed at mitigating the negative environmental impacts of corporate operations [6-8]. Increasingly, green innovation is recognized by enterprises as a vital strategy for securing competitive advantages [9-11]. As a distinctive form of organizational innovation, green innovation not only contributes to the reduction of environmental costs but also enhances overall environmental quality.

Green innovation necessitates the development of dynamic capabilities and a strong commitment from all stakeholders within an organization to adopt environmentally sustainable practices and integrate green values [12]. It is essential to thoroughly assess and comprehensively cultivate these internal capabilities to ensure the successful implementation of green innovation. Ultimately, organizations that embrace green innovation are positioned to achieve sustainable development [13, 14]. Dynamic capabilities are widely recognized as a fundamental element of green innovation [14]. However, many organizations lack the requisite experience and expertise to effectively shape their business environments. Therefore, a focused effort on the development of these capabilities is crucial for the success of green innovation initiatives. In addition to dynamic capabilities, knowledge, particularly external knowledge, plays a pivotal role and is intricately linked to the success of green innovation. A firm's capacity to absorb and effectively apply external knowledge serves as a key determinant of the success of its green innovation endeavors.

Despite the growing interest in green innovation, the precise impact of green dynamic capability on the concept of green innovation and its relationship with sustainable development remains unclear [15]. Existing literature suggests that a higher degree of green innovation adoption within an organization increases the likelihood of developing sustainable organizational capabilities, such as green products, green consumption, and enhanced performance [16]. While some studies have found a negative correlation between the adoption of green innovation and financial performance, others report a positive correlation [17, 18]. Institutional pressures, government regulations, environmental laws, competition, and market dynamics are examples of exogenous organizational factors that, according to prior research, influence the adoption of green innovations [19]. Furthermore, the literature remains unclear regarding the role of green innovation as a mediator in the relationship between green dynamic capabilities and sustainable development. The primary objectives of green innovation are to reduce pollution, conserve energy, minimize waste, and mitigate a company's negative environmental impact [20, 21]. Sustainable development, as originally defined, refers to "development that meets present needs without compromising the ability of future generations to meet their own needs" [22]. Within the framework of green innovation research, the green dynamic capability is considered a valuable asset for companies seeking to address sustainability challenges, including environmental degradation and the rapid depletion of natural resources. It also has the potential to significantly enhance firm performance, particularly in areas such as reputation, asset growth, and profitability [23-25]. In the pursuit of green innovation within manufacturing companies, the development and enhancement of green dynamic capabilities are essential, as these capabilities enable firms to leverage available resources and knowledge bases to better adapt to dynamic market conditions [26]. Therefore, green dynamic capability plays a critical role in addressing stakeholder demands and establishing a robust foundation for green innovation. Consequently, research focused on green dynamic capabilities offers valuable managerial insights that can facilitate the promotion of corporate green innovation [1].

2. Literature Review

2.1. Theoretical Foundation

This study is grounded in Dynamic Capabilities Theory (DCT) and the Resource-Based View (RBV), which together provide insights into the relationship between green dynamic capability and green innovation in promoting sustainable development. According to DCT, a firm's strategic capabilities are essential for achieving sustainable development through green innovation. In a similar vein, RBV asserts that a firm's dynamic capabilities are critical in explaining how the firm creates new resources or reconfigures existing assets to attain its objectives, rather than focusing solely on the resources the firm currently possesses [27].

2.2. Dynamic Capacity Theory (DCT) and Resource-Based View Theory (RBV)

Dynamic capabilities refer to the consistent patterns through which firms manage their resources to achieve strategic objectives [28, 29]. The Dynamic Capabilities Theory (DCT) explains how firms adapt and reconfigure their resources and capabilities to maintain a competitive advantage in an ever-evolving business environment. According to Wang and Liu [30] dynamic capabilities are defined as the intrinsic ability of a firm to integrate, develop, adapt, and reshape both internal and external resources in response to changes in the business environment. These capabilities are essential for securing a sustained competitive advantage in dynamic and rapidly changing markets. Consequently, dynamic capabilities are embedded throughout the organization, optimizing resource allocation and fostering superior performance.

Furthermore, DCT elucidates the impact of green resources and capabilities on organizational behavior, particularly in mitigating environmental uncertainty. The theory also highlights the interrelation between a firm's competitive advantage and environmental sustainability, emphasizing the importance of green dynamic capabilities. With the increasing recognition of the need for a cleaner and more sustainable business environment, green innovation has emerged as a pivotal strategy for achieving these objectives. As such, the role of green innovation in securing a competitive edge is widely acknowledged. The conceptual framework of this study, which centers on green dynamic capability and green adoption, is theoretically grounded in DCT.

RBV theory posits that a firm's distinctive competencies are essential for gaining a competitive edge in the marketplace. This theory aids firms in systematically integrating internal resources and competitive advantages to address related challenges [10, 27, 31, 32]. Teece's analysis of the RBV model affirms that a firm's resources refer to the tangible assets it currently controls, while dynamic capabilities are more closely associated with the firm's ability to effectively utilize these assets to achieve desired outcomes [33]. Additionally, Xie et al. [34] suggest that the unique resources a firm possesses, along with its ability to leverage them effectively, are critical in establishing a competitive advantage. According to Muangmee et al. [31] the strategies a firm formulates and executes are intricately tied to its capacity to deploy its resources and implement dynamic capabilities.

The implementation of dynamic capabilities is closely linked to a firm's green innovation initiatives. While the RBV is widely regarded as a foundational theory in strategic management, it has faced certain criticisms. According to Kraaijenbrink et al. [35] the RBV theory is limited in its ability to explain how firms utilize resources and capabilities in a dynamic market. While RBV focuses on maintaining competitive advantage through the leverage of existing resources, it overlooks the development and integration of resources in rapidly changing environments [36]. To address these limitations, the Dynamic Capabilities Theory (DCT) was introduced as an extension of the RBV, emphasizing the critical role of innovation in enabling firms to adapt to dynamic and evolving markets [37].

2.3. Green Dynamic Capabilities (GDC) and Green Innovation (GI)

An enterprise's dynamic capabilities refer to its capacity to create, extend, or modify its resource base in response to the evolving demands of dynamic markets [38, 39], thereby facilitating the development of green innovation in both products and processes to maintain competitiveness. Firms' dynamic capabilities are multifaceted, encompassing components such as 'sensing,' 'seizing,' and 'transforming,' which are critical for designing and implementing a business model [40]. Given that dynamic capabilities emerge from a firm's unique managerial characteristics, routines, and organizational culture, they are inherently difficult for competitors to replicate [41]. Dynamic capabilities are defined as a firm's ability to flexibly utilize and reorganize its resources in response to both external and internal changes [42, 43]. This concept underscores an organization's ability to integrate, build, and reconfigure itself in response to continuously changing conditions [44]. These capabilities are embedded within established business processes [45], enabling organizations to effectively manage their resources and make progress toward strategic objectives through predictable and communicative patterns [29]. An organization's dynamic capabilities are embedded throughout its structure, fostering the optimal use of resources and supporting high-quality performance. This forms the foundational premise of Dynamic Capabilities Theory (DCT). Furthermore, DCT highlights the influence of environmentally sustainable resources on organizational behavior and illustrates how environmental uncertainty can be mitigated [46].

The theory also emphasizes the contingency context, suggesting that a company's ability to develop green dynamic capabilities is closely linked to its competitive advantage and environmental sustainability [47]. The term 'green dynamic capability,' as used in this study, is adapted from [48]. In this research, green dynamic capabilities are defined as the ability of firms to leverage existing resources and knowledge to renew and create green organizational capabilities. Through this capacity, firms can modify their products and processes to meet environmental requirements and adapt to dynamic environmental changes.

Dynamic capabilities consist of three key components: sensing capability, seizing capability, and reconfiguring capability. Sensing capability refers to a firm's ability to identify, interpret, and pursue opportunities related to environmental sustainability [49-53]. This capability reflects the extent to which a company engages in scanning, searching, exploring, and observing best practices for sustainability within its industry. Seizing capability pertains to a firm's ability to respond to 'green' opportunities by developing new products, processes, or services [50, 51]. Reconfiguring capability involves a firm's ability to realign its strategies, reorganize, and protect both tangible and intangible assets in response to environmental changes [50, 51].

A firm's dynamic capabilities are defined as its ability to effectively integrate resources to address green environmental concerns and achieve sustainability. Green dynamic capability refers to a firm's ability to sense environmental opportunities, enabling the transition of its business toward sustainability, and to respond efficiently to these environmental needs.

Green innovation involves the transformation of a firm's products or processes to minimize negative environmental impacts through the adoption of environmentally friendly technologies [52]. It focuses on the development of sustainable products and environmentally sound processes.

Green dynamic capability (GDC) refers to a firm's capacity to adapt to necessary changes in environmental management, serving as the foundation for the development of green innovation [53]. Given the increasing urgency of environmental concerns and the growing importance of green innovation, firms are increasingly compelled to strengthen their GDCs [54].

Companies with more robust green dynamic capabilities are better positioned to adopt innovative and sustainable solutions that meet customer needs and drive green innovation [55]. According to Camisón and Monfort-Mir [56] green innovation is facilitated by green dynamic capabilities, which are linked to advancements in technologies related to waste management, recycling, green product and process design, energy efficiency, and pollution control. Green innovation is heavily influenced by a firm's green dynamic capabilities, especially in comparison to its competitors, as it enables the firm to efficiently organize resources to deliver value to consumers [53]. The concept of dynamic capabilities includes resource integration, which involves both internal and external resource integration. Internally, this encompasses the exchange and integration of environmental knowledge and capabilities within the firm, emphasizing the importance of interdepartmental collaboration and the ability to incorporate sustainability knowledge into manufacturing operations [57]. Externally, it underscores the firm's capacity to absorb knowledge from external sources, such as customers, suppliers, shareholders, research institutions, and government agencies. In general, green innovation emphasizes the necessity for manufacturing firms to collaborate more with external partners, such as customers, suppliers, and academic institutions, rather than relying solely on internal resources to develop new green products or technologies. Green innovation requires manufacturing firms to actively create, transfer, and learn new knowledge, and to disseminate this knowledge throughout the organization. This process is essential for transforming the firm's original business model and organizational strategy, overcoming organizational inertia, and enhancing competitiveness. Green innovation progressively strengthens the organizational learning capabilities of manufacturing firms. As a key component of the sustainable development strategy for manufacturing, green innovation compels firms to focus on environmental and social issues, stay informed about policies supporting green development, understand customer demand for green products, and keep up with advancements in green technologies. Manufacturing firms must continuously accumulate experience, adapt to the external environment, and reduce pollution, thereby advancing green development. Therefore, green innovation enhances the environmental insight capabilities of manufacturing firms, helping them establish core competitive advantages. Based on this, the authors propose the following hypothesis:

H_1: Green dynamic capability is positively associated with green innovation.

2.4. Green Dynamic Capabilities (GDC) and Sustainable Development (SD)

Green dynamic capabilities are essential for businesses to effectively identify, allocate, and manage resources within their operational frameworks. These capabilities significantly impact an organization's core activities, contributing to improved operational efficiency [58] and the maintenance of sustainable development goals [59]. Robust operational capabilities are closely linked to enhanced organizational performance and the consistent delivery of efficiency [60]. In particular, such capabilities can lead to higher revenues [61], lower costs in product development [62] and improvements in the quality of both processes and products [63]. In today's rapidly changing business environment, the adoption of innovative operational practices allows firms to remain agile and responsive to shifting market trends and stakeholder expectations. Delivering differentiated value to customers becomes a strategic necessity for achieving sustainability [64]. As consumer needs and preferences evolve, diversifying product offerings becomes increasingly important. In these volatile conditions, inflexible and outdated business strategies may hinder growth. To stay competitive, firms must be willing to adapt, revamp, or even replace their existing business models, drawing on insights from both internal operations and external environments [65].

Consequently, green dynamic capabilities become a vital enabler of sustainable development [50]. Organizations that possess these capabilities are better equipped to synthesize cross-sector knowledge and drive innovation, converting emerging opportunities into sustainable outcomes. By closely monitoring environmental changes, firms can collect and act upon relevant market intelligence, enabling them to quickly detect both opportunities and risks. In the digital age, the speed of decision-making has become a decisive factor in sustainability. Companies that act swiftly are better positioned to seize emerging opportunities and counter potential threats, thereby securing a competitive advantage [66]. A wealth of previous research supports the positive influence of green dynamic capabilities on sustainable development [62, 67, 68]. Therefore, the authors propose the following hypotheses:

H_2: Green dynamic capability is positively associated with sustainable development.

2.5. Green Innovation (GI) and Sustainable Development (SD)

Green innovation refers to the adoption of environmentally friendly technologies in production processes to create goods and services that minimize negative environmental impacts [52, 69, 70]. It contributes to cost reduction and enhances firms' competitiveness in dynamic markets [57]. Firms committed to green innovation often prioritize the use of recycled materials in product development, as these materials are both cost-effective and environmentally sustainable. Additionally, with the increasing environmental awareness among stakeholders, firms can improve their corporate image and strengthen market competitiveness through sustainable development [71] supported by green intellectual capital [72].

Green innovation, also known as "sustainable innovation," "ecological innovation," or "environmental innovation," is closely associated with concepts such as green development, sustainability, and environmental concerns. As a form of innovation applied to both products and processes, it aims to significantly minimize the ecological footprint of business activities while delivering added value to customers and organizations alike. In contrast to conventional innovation, green innovation focuses more heavily on leveraging novel technologies and creative approaches to enhance resource efficiency, curb pollution, and boost economic outcomes. Its primary objective is to produce environmentally beneficial results, rather than merely mitigating environmental damage.

Green innovation plays a vital role in helping enterprises improve their environmental performance, pursue sustainable development goals, lower environmental-related costs, and strengthen their competitive position. It is proposed that the effectiveness of green innovation relies heavily on a firm's green dynamic capabilities, which enable organizations to better respond to environmentally conscious markets by offering differentiated, eco-friendly products [57]. We posit that both green product and process innovation are positively correlated with competitive advantage [73] and significantly predict firm performance [15, 69, 74]. Additionally, firms' environmentally focused actions related to products and processes have a positive influence on their performance [75].

When product development is integrated with environmental sustainability efforts, it can lead to the discovery of new markets, increased sales, higher return on investment, and a stronger competitive advantage [20]. Green innovation can drive both sustainable development and improved market performance [67, 76]. Investments in green innovation are associated with better customer retention, sales growth, improved productivity, higher returns on investment, and enhanced financial performance [77]. Therefore, the authors propose the following hypotheses:

H_3: Green innovation is positively associated with sustainable development.

2.6. The Mediating Role of Green Innovation

The increasing emphasis on innovation within firms is largely driven by its potential to boost productivity and deliver greater value and output from the same set of inputs [78]. This focus permeates all levels of organizational activity, prompting businesses to adopt environmentally sustainable practices. Whether targeting general or eco-specific goals, achieving successful innovation, particularly green innovation, requires organizations to function both efficiently and effectively. This includes facilitating operations throughout the production process to support the development of environmentally friendly products and services. A substantial body of research has highlighted the positive relationship between operational capabilities and innovation performance [79]. In rapidly changing environments, firms must not only be agile but also respond with innovative solutions [50]. This makes green dynamic capabilities-an extension of dynamic capabilities focused on ecological resources-crucial for fostering innovation [80]. Green innovation, which aims to improve products or processes with sustainability in mind, is strongly influenced by a firm's ability to adapt to regulatory shifts and environmental policies [73]. Numerous previous studies further support the view that green dynamic capabilities significantly contribute to the advancement of green innovation within companies [53].

Several prior studies have supported these findings, demonstrating that green dynamic capabilities positively influence green innovation in enterprises [12, 81].

Green innovation includes both environmentally friendly products and process innovations, forming strategic protective barriers through distinctive competencies that help businesses sustain long-term competitive advantages [82-84]. Green product innovation plays a key role in differentiation strategies by enabling firms to gain a market-leading position and a competitive edge [83]. Enhancements in product features and quality not only strengthen a company's public image and credibility but also foster customer trust and loyalty, allowing products to stand out against competitors. In contrast, green process innovation focuses on cost reduction and environmental preservation by cutting down on waste and harmful emissions [85, 86]. It also enhances resource efficiency through strategies like recycling and material conservation [7, 87, 88]. When effectively implemented, green process innovation can generate cost benefits [89], thereby aligning with sustainable development goals [73]. Therefore, the authors propose the following hypotheses:

H_4: Green innovation positively mediates the relationship between green dynamic capability and sustainable development.

Based on the above hypotheses, the conceptual framework proposed in this study is shown in Figure 1.

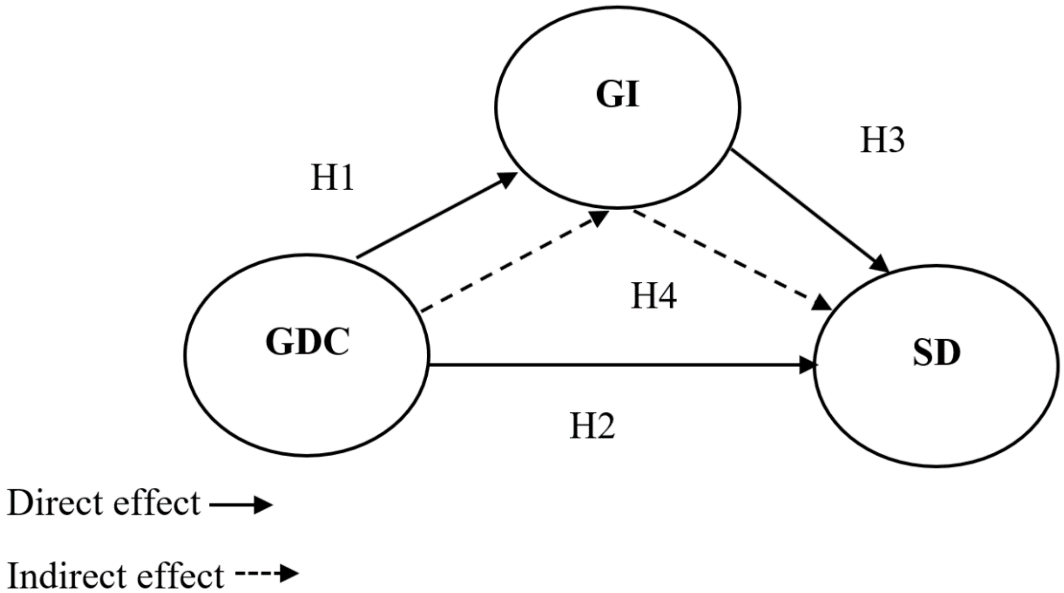

Figure 1.
The conceptual framework.

3. Methodology

3.1. Sampling and Data Collection

This study employed a quantitative research methodology, utilizing a questionnaire distributed via Google Forms from March to April 2025 to collect data from the manufacturing industry in Thailand. The sample population was drawn from the database at [90]. A non-probability sampling method, specifically the stratified sampling technique, was employed. The inclusion criteria for the respondents were executive directors and managers of manufacturing firms, who were considered the key population for the sample selection. These firms were specifically chosen due to their engagement in producing innovative products and processes, along with their commitment to adopting green practices. Although focusing on environmentally friendly products and services may incur higher costs, the shift toward addressing environmental concerns is becoming increasingly evident. For empirical analysis, the study employed the Partial Least Squares Structural Equation Modeling (PLS-SEM) technique. Structural equation modeling has become widely utilized in social science research due to its ability to measure latent variables that are challenging to observe directly, as well as its capacity to account for measurement errors of observed variables [91]. The analysis was conducted from an integrated perspective, considering both internal and external factors influencing the firm. Given its ability to reliably estimate parameters and validate integrated causal relationships, PLS-SEM was deemed the most appropriate analytical method for this study. The unit of analysis for this study was the manufacturing industry. A total of 637 questionnaires were distributed, and 386 respondents participated in the survey, as detailed in Table 1.

Table 1.
Demographics of respondents (N = 386).

Variables	Values	Percentage	Frequency
Gender	Male	53.10 %	205
	Female	46.90 %	181
Age	Less than 30 years old	11.90 %	46
	30-40 years old	25.40 %	98
	41-50 years old	16.30 %	63
	More than 50 years old	46.40 %	179
Marital	Single	24.40 %	94
	Married	74.40 %	287
	Divorce	1.20 %	5
Education level	Bachelor’s degree or lower	43.80 %	169
	Higher than a bachelor’s degree	56.20 %	217
Industry type	Automobile parts manufacturing	3.10 %	8
	Energy production and distribution	11.00 %	85
	Production of consumer goods	59.00 %	189
	Production of chemicals and petrochemicals	26.90 %	104
Firm age	1-5 years	4.10 %	16
	5-10 years	18.90 %	73
	11-15 years	44.60 %	172
	More than 15 years	32.40 %	125
Firm size	Less than 50 employees	4.10 %	16
	51 - 250 employees	32.40 %	121
	251 - 1,000 employees	44.60 %	174
	More than 1,000 employees	18.90 %	75
Working experience	Less than 5 years	3.70 %	12
	5-10 years	18.90 %	80
	11 - 15 years	51.80 %	190
	More than 15 years	25.60 %	104
Current revenue average	Less than 50,000 Baht	1.00 %	4
	50,000-60,000 Baht	6.50 %	25
	60,001-70,000 Baht	38.10 %	147
	More than 70,000 Baht	54.40 %	210
Current position	Executives	44.80 %	173
	Managers	55.20 %	213

Table 1: Demographics of respondents. The majority of respondents were male, accounting for 205 or 53.10%, while the remaining 181 or 46.90% were female. The largest age group was over 50 years old (46.40%), followed by those aged 30-40 years (25.40%) and 41-50 years (16.30%). The smallest age group consisted of individuals under 30 years old (11.90%). Most respondents were married, totaling 287 or 74.40%, single, 94 or 24.40%, and divorced, 5 or 1.20%. Regarding education level, the majority held a degree higher than a bachelor's, with 217 respondents (56.20%), while 169 respondents (43.80%) had a bachelor's degree or lower. In terms of industry type, most organizations were involved in the

production of consumer goods, accounting for 189 or 59.00%, followed by chemicals and petrochemicals at 104 or 26.90%, energy production and distribution at 85 or 11.00%, and automobile parts manufacturing at 8 or 3.10%. Firm age distribution was as follows: 10-15 years for 172 respondents (44.60%), over 15 years for 125 (32.40%), 5-10 years for 73 (18.90%), and 1-5 years for 16 (4.10%). Firm size showed that 174 respondents (44.60%) had 251-1,000 employees, 121 (32.40%) had 51-250 employees, 75 (18.90%) had more than 1,000 employees, and 16 (4.10%) had fewer than 50 employees. Regarding working experience, 11-15 years was reported by 190 respondents (51.80%), over 15 years by 104 (25.60%), 5-10 years by 80 (18.90%), and less than 5 years by 12 (3.70%). The average current monthly revenue was more than 70,000 baht for 210 respondents (54.40%), 60,001-70,000 baht for 146 (38.10%), 50,000-60,000 baht for 25 (6.50%), and less than 50,000 baht for 4 (1.00%). For current positions, 213 respondents (55.10%) were managers, and 173 (44.80%) were executives.

3.2. Measurement

The questionnaire used in this study consisted of 18 items. All constructs were adapted from prior research, and the questions were structured as closed-ended, with responses measured on a 5-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). Green dynamic capabilities were assessed using a 6-item scale adapted from the work of [89]. To measure green innovation, a 6-item scale was utilized, based on the study of González-Benito and González-Benito [92]. Additionally, the measurement of green dynamic capabilities incorporated 6 scale items, adapted from the studies of Chiou et al. [67], Ramanathan [93], and Wang [94].

4. Results

4.1. Validity and Reliability Tests

This study utilized Partial Least Squares Structural Equation Modeling (PLS-SEM) for data analysis. PLS-SEM facilitates regression analysis in evaluating complex relationships among constructs and is particularly advantageous due to its non-parametric nature, which eliminates the need for large sample sizes or normally distributed data [95]. Multivariate analysis was applied to examine both the measurement and structural components of the model, ensuring reduced error. Version 4 of the PLS-SEM software was used to assess the proposed framework and clarify interrelationships among variables. As noted by Hair et al. [95], PLS-SEM is well-suited for validating variable relationships. The structural model was further tested through a bootstrapping technique involving 5,000 resamples. Since reliance on a single data source may introduce common method bias (CMB), measures were taken to mitigate this issue. An anonymous questionnaire was distributed to help minimize bias and encourage honest feedback. To verify the presence of CMB, Harman's single-factor test was conducted, resulting in a value of 43%, which falls below the 50% threshold, suggesting CMB had no significant effect on the results. This approach also helped improve response accuracy and participation rates [96]. As shown in Table 2, the variables exhibit modest but statistically significant bivariate correlations.

Table 2.
Bivariate correlation.

Variables	GDC	GI	SD
GDC	1		
GI	0.418**	1	
SD	0.315**	0.306**	1

Note: ***p < 0.01, **p < 0.05, *p < 0.10.

4.2. Testing and Measurement Model

The validity and reliability of the model were assessed using confirmatory factor analysis (CFA) and Partial Least Squares Structural Equation Modeling (PLS-SEM). These tests focused on evaluating the reliability, convergent validity, and discriminant validity of the constructs [97]. The results indicated that all items had outer loading scores ranging from 0.756 to 0.926, which adhere to the recommendations provided by Hair et al. [98]. These results are presented in Table 3. Furthermore, the R-squared values for sustainable development ($R^2 = 0.132$, $p < .001$) and green innovation ($R^2 = 0.173$, $p < .001$) were above the recommended threshold of 0.10 [99], as shown in Table 4. Reliability was assessed using Cronbach's α, composite reliability, and average variance extracted (AVE), which are summarized in Table 5. The Cronbach's α values for green dynamic capability, green innovation, and sustainable development were 0.928, 0.885, and 0.897, respectively, all of which exceed the recommended threshold of 0.80, indicating good internal consistency. The AVE values for these constructs were 0.739, 0.634, and 0.654, respectively, all of which exceed the critical threshold of 0.50, confirming adequate convergent validity [91]. Additionally, composite reliability (CR) was calculated to assess the internal consistency of the constructs. The rho_a values for green dynamic capability, green innovation, and sustainable development were 0.929, 0.889, and 0.912, respectively. The rho_c values for these constructs were 0.944, 0.912, and 0.919, respectively. Since all CR values exceed the threshold of 0.70, the data can be considered reliable and consistent. To assess discriminant validity, both the Fornell-Larcker criterion and the heterotrait-monotrait (HTMT) ratio were employed. The HTMT test, shown in Table 6, revealed a maximum value of 0.455, which is below the threshold of 0.9 [91], indicating satisfactory discriminant validity. Additionally, the Fornell and Larcker [100] (Presented in Table 7), the square root of the AVE for each construct surpasses the construct's highest correlation with any other construct. Figure 2 shows the path coefficient with outer loadings.

Table 3.
Outer loading.

Variables	Outer loading
GDC1 ◄— GDC	0.926
GDC2 ◄— GDC	0.917
GDC3 ◄— GDC	0.820
GDC4 ◄— GDC	0.756
GDC5 ◄— GDC	0.868
GDC6 ◄— GDC	0.860
GI1 ◄— GI	0.781
GI2 ◄— GI	0.767
GI3 ◄— GI	0.805
GI4 ◄— GI	0.808
GI5 ◄— GI	0.793
GI6 ◄— GI	0.824
SD1 ◄— SD	0.760
SD2 ◄— SD	0.816
SD3 ◄— SD	0.778
SD4 ◄— SD	0.798
SD5 ◄— SD	0.846
SD6 ◄— SD	0.850

Table 4.
R-Square and Adjusted R-Square.

Variables	R-square	R-square adjusted
SD	0.136	0.132
GI	0.175	0.173

Table 5.
Composite reliability, Cronbach's alpha, and Average variance extracted.

Variables	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance (AVE)
GDC	0.928	0.929	0.944	0.739
GI	0.885	0.889	0.912	0.634
SD	0.897	0.912	0.919	0.654

Table 6.
Heterotrait - monotrait ratio (List).

Variables	Heterotrait- monotrait ratio (HTMT)
GI ◄—► GDC	0.455
SD ◄—► GDC	0.326
SD ◄—► GI	0.316

Table 7.
Criterion of fornell and larcker.

Variables	GDC	GI	SD
GDC	0.860		
GI	0.418	0.797	
SD	0.315	0.306	0.809

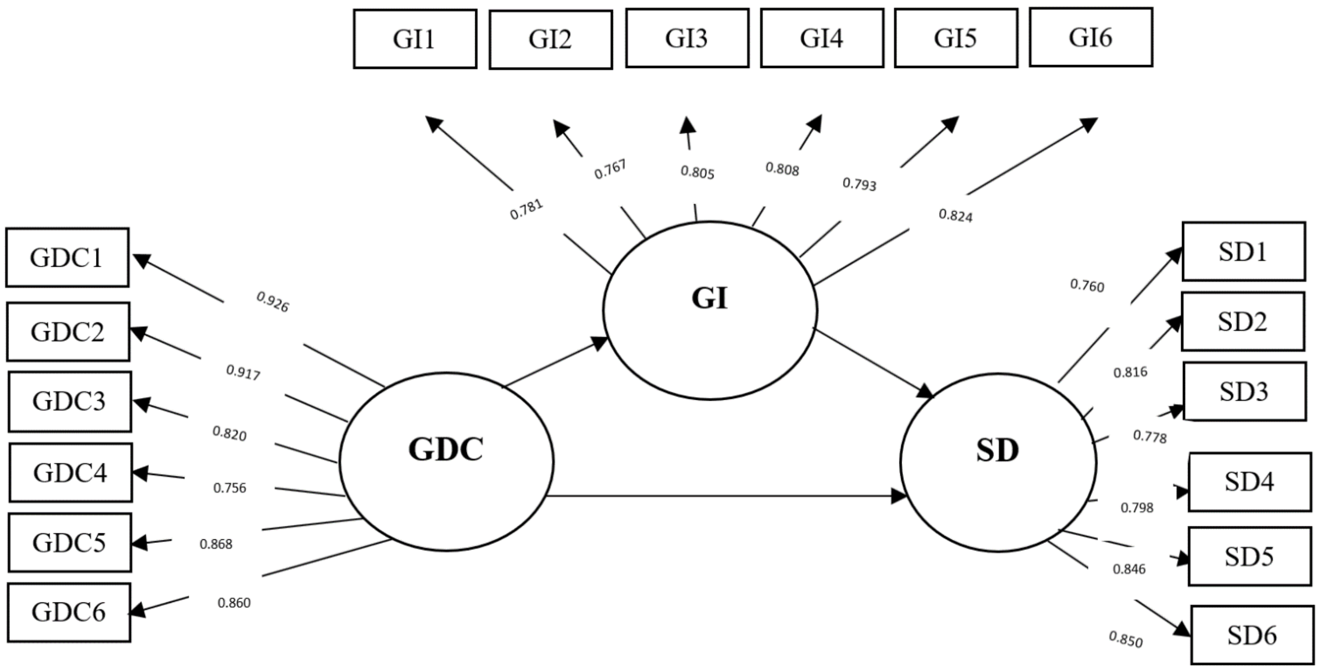

Figure 2.
Path coefficients with outer loadings.

To test the study's hypotheses, the PLS-SEM technique was employed. Model fit was assessed using predictive relevance values, with cross-validated redundancy (Q2) serving as the primary measure of predictive power. According to Hair et al. [95], Q2 values must exceed zero to confirm the model's validity. These values were obtained through the blindfolding procedure, and the model was considered valid only when all Q2 values for the latent constructs were above zero. Hypothesis testing results are summarized in Table 8, using path coefficients, p-values, and t-statistics. The strength of relationships among variables is interpreted through path coefficients. Values closer to 1 indicate strong relationships, while those approaching -1 suggest weaker connections [95]. The significance of each hypothesis was determined by examining both the p-values and the corresponding t-statistics. Table 8 provides an overview of the outcomes for the four hypotheses tested within the conceptual framework.

Table 8.
Total effect.

Variables	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P value
GDC→ GI	0.418	0.422	0.049	8.562	0.000
GDC→SD	0.315	0.317	0.056	5.649	0.000
GI → SD	0.211	0.215	0.056	3.748	0.000

First, green dynamic capability is positively associated with green innovation (β = 0.418, $p < 0.000$, t = 8.562), supporting Hypothesis 1. Moreover, green dynamic capability is positively associated with sustainable development (β = 0.315, $p < 0.000$, t = 5.649), supporting Hypothesis 2. Second, Hypothesis 3 was supported (β = 0.211, $p < 0.000$, t = 3.748), proposing that green innovation is positively associated with sustainable development. Furthermore, Hypothesis 4 was accepted (β = 0.088, p = 0.002, t = 3.144), revealing that green innovation significantly mediates the relationship between green dynamic capability and sustainable development. Supporting results are presented in Table 9 (Total Indirect Effects), Table 10 (Specific Indirect Effects), and Table 11 (Outer Loading). These findings highlight that firms with strong green dynamic capabilities are more likely to achieve sustainable development when they simultaneously enhance their green innovation practices, which is an insight acknowledged by managers, executives, and employees in the manufacturing industry.

Table 9.
Total indirect effect.

Variables	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P value
GDC→SD	0.088	0.091	0.028	3.144	0.002

Table 10.
Specific indirect effect.

Variables	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P value
GDC → GI → SD	0.088	0.091	0.028	3.144	0.002

Table 11.
Outer loading.

Variables	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P value
GDC1 ← GDC	0.926	0.926	0.011	83.581	0.000
GDC2 ← GDC	0.917	0.917	0.011	83.167	0.000
GDC3 ← GDC	0.820	0.821	0.025	32.679	0.000
GDC4 ← GDC	0.756	0.756	0.029	26.218	0.000
GDC5 ← GDC	0.868	0.867	0.021	41.005	0.000
GDC6 ← GDC	0.860	0.860	0.021	40.741	0.000
GI1 ← GI	0.781	0.779	0.035	22.041	0.000
GI2 ← GI	0.767	0.765	0.036	21.041	0.000
GI3 ← GI	0.805	0.805	0.024	33.860	0.000
GI4 ← GI	0.808	0.808	0.023	35.643	0.000
GI5 ← GI	0.793	0.792	0.026	30.665	0.000
GI6 ← GI	0.824	0.824	0.023	35.539	0.000
SD1 ← SD	0.760	0.795	0.032	23.857	0.000
SD2 ← SD	0.816	0.815	0.024	33.465	0.000
SD3 ← SD	0.778	0.776	0.040	19.671	0.000
SD4 ← SD	0.798	0.796	0.037	21.302	0.000
SD5 ← SD	0.846	0.845	0.022	37.672	0.000
SD6 ← SD	0.850	0.849	0.023	37.177	0.000

5. Conclusion and Theoretical Contributions

This study examines the environmental challenges faced by heavy-polluting manufacturing industries, particularly their contribution to environmental degradation. By exploring the relationship between green dynamic capabilities, green innovation, and sustainable development at the micro level, this research significantly enhances our understanding of how manufacturing firms can incorporate environmental responsibility into their business strategies. The findings of this study have important implications for business strategy in the manufacturing sector. Promoting green innovation awareness: manufacturing enterprises with high pollution levels should prioritize increasing awareness of green innovation. Unlike traditional innovation, green innovation extends beyond economic objectives to incorporate ecological and environmental factors. By adopting green innovation, these firms can not only improve their environmental performance but also enhance their overall business performance. Green innovation aids in mitigating environmental harm while contributing to a more sustainable and competitive business model. This study advances the expanding body of literature on sustainable business models by connecting green dynamic capabilities with green innovation and sustainable development. While prior research has examined both internal and external factors affecting green strategies, it has not fully explored the role of an eco-friendly organizational culture in fostering environmentally responsible innovation. This research bridges this gap by demonstrating how green dynamic capabilities serve as a driving force for sustainable development and green innovation.

The findings suggest that an organization's capacity for sustainable innovation is crucial for advancing sustainable business practices, particularly within the manufacturing sector. Additionally, the integration of green dynamic capabilities into the resource-based view (RBV) and dynamic capabilities theory (DCT) offers a novel approach to evaluating business strategies in Thailand's manufacturing industry. This expanded theoretical framework provides a new perspective for assessing the integration of environmental innovation capabilities. Focus on green dynamic capabilities while prior research has examined the relationship between green dynamic capabilities and creative outputs, limited attention has been given to their impact on entrepreneurial success. This study emphasizes the importance of cultivating green dynamic capabilities, which are both dynamic and difficult for competitors to replicate. Strengthening these capabilities can unlock the potential for green innovation within firms, resulting in enhanced business performance. Resource integration and allocation. To develop green dynamic capabilities, firms should focus on enhancing their ability to integrate and allocate green resources effectively. This involves fostering both green product and process innovations, as well as collaborating with key stakeholders such as customers, suppliers, and investors. Through these efforts, businesses can create and acquire green resources, thereby reinforcing their sustainable competitive advantages and improving overall performance. Employee learning and development. Internal learning and knowledge sharing are essential components in the development of green dynamic capabilities. Firms should foster a culture of learning that encourages employees to engage in green innovation. Implementing a performance evaluation system based on internal learning outcomes can further motivate employees to contribute to green initiatives. Market-driven innovation. Firms must proactively understand customer needs and expectations. By aligning research and development with market demands, businesses can design more targeted green products and improve green process innovations, making their offerings more relevant and competitive. This study underscores the importance of green dynamic capabilities in driving sustainable business practices within the manufacturing industry. The findings demonstrate how these capabilities not only facilitate green innovation but also contribute to long-term competitive advantages and improved performance. As environmental concerns continue to intensify globally, businesses that integrate green practices into their core operations will be better positioned for success in an increasingly competitive marketplace.

6. Practical Implications

This study emphasizes the essential role that green dynamic capabilities play in promoting green innovation and advancing sustainable development within manufacturing industries, especially in emerging economies. The findings provide several practical implications for business managers and industry leaders. Investing in green dynamic capabilities is crucial. Managers should recognize that green dynamic capabilities significantly impact green innovation, which, in turn, supports sustainable development. To effectively navigate shifts in the business environment, firms must invest in developing their digitalization capabilities. This includes adopting digital tools and processes that enable organizations to remain agile, monitor environmental trends, and implement innovations that contribute to sustainability. Leveraging digitalization is vital. Given the positive relationship between green dynamic capabilities and green innovation, business managers should embrace digital transformation as a key strategy for fostering green innovation. Digitalization allows firms to manage resources efficiently, optimize supply chains, and innovate processes that reduce environmental impacts. By strengthening their digitalization capabilities, businesses will be better positioned to respond to emerging trends and market demands, which are increasingly focused on environmental sustainability. Encouraging proactive innovation is also important. The study highlights the critical role of green innovation in achieving sustainable development. Managers should actively explore new green technologies and practices, integrating sustainability into all levels of organizational strategy, from product development to supply chain management. Doing so enables firms to position themselves as leaders in the green economy, gaining competitive advantages that promote long-term success. The implications for emerging economies are significant. The empirical findings from Thailand's manufacturing sector offer valuable insights for other emerging economies facing similar challenges. Manufacturing firms in these regions can adopt the strategies discussed in this study to enhance their green dynamic capabilities, drive innovation, and contribute to sustainable development. It is essential for businesses in emerging economies to recognize that investing in sustainability benefits the environment and yields long-term economic advantages, including improved competitiveness and market differentiation. In conclusion, the findings suggest that when effectively nurtured, green dynamic capabilities can drive innovation and substantially contribute to firms' sustainable development. This requires managers to strategically focus on digitalization, innovation, and sustainability in their operations.

7. Limitations and Future Research

Despite the valuable insights offered by this study, certain limitations must be acknowledged, including internal versus external factors driving green dynamic capabilities. While this study primarily focused on external environmental factors influencing the development of green dynamic capabilities, it is essential to recognize that internal factors also play a significant role. Future research could explore the interaction between internal organizational factors (e.g., leadership, culture, and resources) and external influences to offer a more comprehensive understanding of green dynamic capabilities. Subcomponents of green dynamic capabilities remain an emerging concept, and future studies should delve deeper into its components and sub-capacities. A more granular understanding of how different aspects of green dynamic capabilities contribute to innovation and sustainability will provide more precise insights into how firms can enhance their green capabilities. Geographical and sectoral limitations exist, as the data for this study were collected from manufacturing firms in Thailand; therefore, the generalizability of the findings may be limited to this specific context. Future research should investigate how green dynamic capabilities function across various industries and countries, particularly in regions with differing levels of industrialization and environmental regulations. Cross-country comparisons could yield valuable insights into how contextual factors influence the relationship between green dynamic capabilities, green innovation, and sustainable development. In conclusion, while this study provides significant insights into the relationship between green dynamic capabilities and sustainable development, further research is necessary to explore the internal drivers of green dynamic capabilities, refine the concept itself, and expand the scope of the study to diverse geographical and industrial contexts.

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