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Original Research Paper

AI-Driven Digital Transformation for Sustainable Manufacturing: Exploring the Impact of Carbon Intensity and ESG Through Eco-Innovation Theory

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ABSTRACT

This study aims to examine the influence of carbon intensity and ESG performance on the adoption of digital transformation through the perspective of eco-innovation theory in supporting sustainable production and decarbonization goals. Quantitative methods were used by analyzing 91 samples of secondary data from manufacturing firms in Indonesia. The result shows that firms with scope 1 carbon intensity tend to adopt digital transformation because emissions can be clearly seen in direct operational activities and high ESG performance can maximize performance through digital transformation adoption. The significant negative relationship between scope 2 carbon intensity and digital transformation indicates that firms may have alternative non-digital solutions to reduce scope 2 carbon intensity. These results support eco-innovation theory which states that digital and non-digital-based innovations are essential for environmental sustainability and production efficiency, particularly in the manufacturing industry. This study has demonstrated a practical understanding of management and of course, those who formulate policies on how to design digital strategies that go hand in hand with environmental conservation efforts, which can then encourage stronger sustainability in the manufacturing sector.

1. INTRODUCTION

Industry 4.0 focuses on the development of technological advances that support major changes throughout the world. (Shang et al., 2023). The emergence of Artificial Intelligence, Big Data, Blockchain, and the Internet of Things are some examples of how firms are beginning to focus on implementing digital transformation (hereafter – DT) as a strategy to support efficiency and productivity while minimizing operational costs and optimizing resources utilization (Chen et al., 2020; Qian et al., 2023). In recent years, many firms in Indonesia have been encouraged to accelerate the adoption of digital technologies to support operational activities, as presented by the increasing adoption index figures each year.

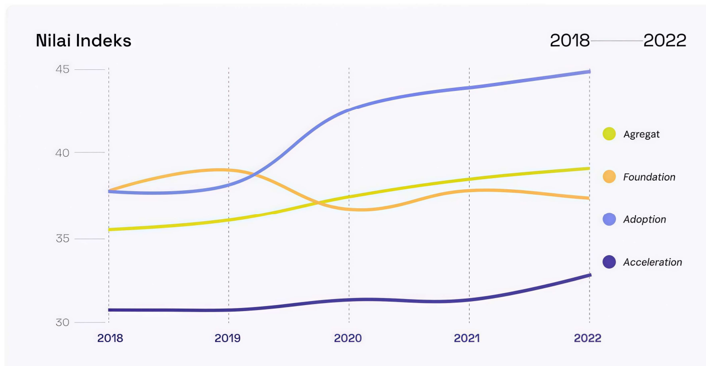

Fig. 1: Digital Transformation Index in the Business Pilar (Kementerian Komunikasi dan Digital RI, 2024)

Indonesia still faces a gap between digital awareness and its implementation. This is evident from the relatively low acceleration index shown in figure 1. This data demonstrates that firms in Indonesia still face various challenges in developing their technological capabilities, so many firms in Indonesia still need strategies to strengthen and accelerate digital implementation (Kementerian Komunikasi dan Digital RI, 2024). In response, Indonesia has initiated 'Making Indonesia 4.0' as a roadmap toward the DT of the manufacturing industry through AI, IoT, robotics, 3D printing, and Augmented Reality, with a focus of five main priority sectors; food and beverage, textiles and clothing, automotive, chemical, and electronics (Ramli, 2023). Kementerian Perindustrian Republik Indonesia (2018) introduced the Indonesia Industry 4.0 Readiness Index (INDI 4.0) as a measurement tool for Industry 4.0 Readiness. This index is expected to strengthen national industrial competitiveness by improving production efficiency, reducing operational costs, and improving product quality. DT is any type of process that utilizes existing digital technology. DT has become a very appropriate step to help a business entity improve efficiency and effectiveness ranging from strengthening its commitment to sustainability to improving the quality of organizational governance (Aldieri & Vinci, 2021). These changes can be helpful for firms in developing better work systems, preparing for changes better, and staying competitive in an evolving market performance monitoring, thereby promoting more efficient, transparent, and accountable corporate operations (Zhang et al., 2025). Moreover, ESG implementation encourage more environmentally friendly practices and accountable governance. This condition is increasingly supported by the availability of data that is now more transparent and easier to access, so that the openness of a business entity can run better and more effectively (Zhang & Huang, 2024). The integration of DT further supports the achievement of Sustainable Development Goals (SDGs) 9, which emphasize sustainable industrialization, increased innovation capacity, and the development of resilient infrastructure (United Nations, 2025). Accordingly, DT serves as a key linkage between national policies, firm performance, and the integrated implementation of ESG practices (da Cunha et al., 2025; Zhang & Huang, 2024).

Manufacturing sector in Indonesia contributes significantly to carbon emissions, which are high due to its production activities, reaching 340.71 million tons of CO_2e in 2022 (Ahdiat, 2024). The increasing carbon emissions have prompted the government to accelerate the development and enforcement of policies aimed at reducing the carbon intensity through the establishment of a national framework for achieving Indonesia's Nationally Determined Contribution (NDC) targets as stipulated in Presidential Regulation No 98 of 2021. This regulation covers emission mitigation efforts, monitoring and evaluation mechanisms, financing schemes, and the management of carbon economic value (Andrian & Sudibyo, 2019). In line with this national policy development, the Financial Services Authority (OJK) regulation No.51/POJK.03/2017 requires financial institutions, issuers, and public firms to prepare and disclose sustainability reports, which aims to improve transparency and accountability concerning ESG performance as these elements are consistently reported (Otoritas Jasa Keuangan, 2017). This reporting obligation is anticipated to enhance business understanding of the environmental consequences of their operations and to reinforce their responsibilities in applying sustainability principles. In addition, the establishment of IDX Carbon in 2023 has provided a transparent and market-based carbon trading mechanism to support Indonesia' decarbonization pathway toward net zero emissions by 2060 (IDX, 2023).

Carbon intensity, measured as carbon emissions relative to a firm's total assets, serves as an indicator of environmental efficiency. Carbon intensity is often used as an indicator to assess the magnitude of transition risk, particularly in carbon-intensive industries (Cheng et al., 2014). Firms with higher levels of emissions tend to face overlapping pressures, including tighter supply chain requirements, shifts in consumer preferences, and rising financing costs. These pressures reflect larger economic dangers connected with unsustainable business practices (McDougall et al., 2025). This tension has been further amplified by the increasing prevalence of greenwashing cases, which expose persistent issues related to ESG credibility and the reliability of sustainability reporting. In response, regulators have become more active in scrutinizing and sanctioning misleading environmental claims (Greenwell et al., 2025). These developments underscore the need to empirically examine the validity and explanatory power of ESG scores, as such ratings often capture corporate reputation rather than measurable environmental performance.

As digital technology advances, its transformation continues to attract public attention due to its potential in improving company operational efficiency. Prior research has been examined in DT in relation to firm performance (Wang & Sun, 2025; Yavuz et al., 2025), energy consumption (Yue et al., 2025), and sustainable development performance (Li, 2024). In parallel, the literature on ESG and carbon emission has grown rapidly, including studies on the relationship between ESG and carbon performance (Yin et al., 2023) and corporate performance (Nareswari et al., 2023). Building on this literature, prior research has adopted different perspectives on the causal relationships among DT, ESG practices, and carbon emissions. Some studies position DT as a driver of ESG practices (Baboe et al., 2025; Liu et al., 2025; Yang et al., 2024) and as a mechanism for carbon emission reduction (Chen et al., 2024; Song et al., 2025). However, previous studies often rely on aggregate carbon emissions without distinguishing between scope 1 and scope 2 emissions (Zhang et al., 2024), which may limit understanding the contribution of each emission scope to DT. In addition, most prior research relies on theoretical framework such as stakeholder theory (Baboe et al., 2025; Chen et al., 2024) and dynamic capability theory (Gao et al., 2024; Yavuz et al., 2025). Nevertheless, the application of eco-innovation theory remains largely unexplored. Eco-innovation theory is important as it explains how firms use innovation, including DT, to improve efficiency while simultaneously reducing environmental impact (Fussler & James, 1996). Many studies primarily focus on countries with relatively high levels of digital infrastructure and institutional support, such as China and European nations (Chen et al., 2024; Li, 2024; Khatib et al., 2023) while evidence from contexts with lower digital readiness and less developed institutional frameworks remains limited.

Based on this background, this study attempt to expand on existing discussions by adopting scope 1 and scope 2 carbon emission intensity and ESG performance as important factors that can encourage firms to adopt DT. Scope 1 and Scope 2 carbon emission intensity can be represent the sources of emissions that are closest to a company's operational activities and can still be controlled directly. In the context of Indonesian manufacturing, this condition makes emission a salient pressure point for cost efficiency, regulatory compliance, and market expectations (Rohayati & Abdillah, 2024). This research focuses on Indonesian manufacturing firms because the sector is both energy-intensive and a major contributor to national Scope 1–2 emissions (Ahdiat, 2024), making it a high-impact setting to examine carbon-driven incentives for DT. Moreover, Indonesia's manufacturing landscape features heterogeneous ESG readiness and uneven digital maturity, allowing the study to capture meaningful variation in how emission intensity translates into DT adoption (CRSM Indonesia, 2024; Kristianto et al., 2025).

The next section provides a literature review on the relationship between carbon emission, institutional ownership, and DT. It is followed by the development of research hypotheses and theoretical justification. Section 2 describes the research methodology; Section 3 presents the results and discussion. The final section concludes the study by outlining its main findings and implications for both theory and practice.

Digital Transformation

According to Matt et al. (2015), DT is defined as the transformation of products, processes, and organizational aspects driven by modern technology. DT uses networks and computing to drive companies towards sustainability (Khan & Singh, 2023; Vial, 2019), enabling them to make informed decisions, conduct evaluations, and develop new business models (Guo & Tang, 2024). DT also encourages the digitization of products and services to improve efficiency and overall company performance (Chen et al., 2024; Vial, 2019).

In digital development, the industry is increasingly proving the potential of AI as a catalyst for energy efficiency, big data analysis, productivity enhancement, and decision-making that support sustainable manufacturing (Plathottam et al., 2023). AI is considered a company-owned resource capable of responding to internal issues such as emission intensity by detecting emissions and monitoring ESG performance. Therefore, the adoption of this technology aligns with sustainable production goals (Chen et al., 2019).

Hypothesis Development

Scope 1 emissions originate from a firm's internal operational activities (Emmanuel et al., 2023). Scope 1 carbon emission intensity represents the level of carbon emissions generated relative to the utilization of a firm's productive assets. A high level of scope 1 carbon emission intensity is often associated with technologically inefficient assets, reflecting aging capital stock with declining operational efficiency (Dan et al., 2023). From an efficiency perspective, higher carbon intensity implies that firms generate greater emissions per unit of assets, indicating lower environmental efficiency. This condition not only signals operational inefficiency but also reflects higher ESG-related risks, thereby creating strong incentives for firms to reduce emissions that are fully under their direct control (Emmanuel et al., 2023). In response, firms are more likely to adopt DT to enhance operational efficiency and optimize asset utilization (Bhatia et al., 2024).

This relationship aligns with the eco-innovation theory proposed by Fussler & James (1996) as an effort to develop business, technology, and operational practices that create economic value while reducing negative impacts on the environment. Xu et al. (2023) state that DT strengthens the implementation of eco-innovation by increasing a company's capability to integrate digital technology into production processes and operational practices, especially in companies with high emission levels. DT such as AI, IoT, and big data analytics have been shown to help optimize energy use and resource efficiency, directly contributing to reducing the carbon footprint of production (Chauhan & Sahoo, 2024; Zhou & Liu, 2024). Given this, the hypothesis is:

H1a: *Scope 1 carbon intensity has a positive effect on digital transformation adoption*

Scope 2 emissions, which are indirect emissions originating from all electricity, steam, heat, or cooling purchased from external parties and used by the company (Emmanuel et al., 2023). In contrast with scope 1 emissions intensity which under firm's direct operational control, Scope 2 emissions intensity are highly dependent on external energy systems, consequently, companies have more limited capacity to directly influence the sources of these emissions, thereby constraining the role of DT as a primary solution for reducing scope 2 intensity.The increase in carbon intensity in scope 2 relates to a company's carbon performance, which depends on the company's energy used to operate each of its assets (Hoffmann & Busch, 2008). High scope 2 emissions do not necessarily indicate a company's wasteful use of electricity but can be influenced by factors such as electricity emissions in specific operational areas (grid mix as direct factor) and electricity tariff structures (as indirect factor), indicating that increases in Scope 2 emissions intensity are also driven by external conditions that are difficult for firms to controlFirms may experience a cost and risk burden (e.g., rising electricity expenditures, margin pressure, and ESG scrutiny) that crowds out investment in digitally enabled process change. As a result, managerial attention and capital may be redirected toward short-term operational stabilization and compliance activities rather than longer-horizon DT initiatives.

To reduce scope 2 emissions intensity, companies need to identify their energy usage and identify which assets consume more energy under certain conditions. This allows them to take appropriate action to reduce energy consumption, such as stopping the use of these assets when not in use (Griffin et al., 2014). Companies choose to focus on routine asset maintenance to maintain stable machine performance and reduce energy consumption, purchase renewable energy, or choose other non-digital strategies to reduce emissions intensity rather than adopting a DT, which also requires significant funding (Baniya & Giurco, 2025). These initiatives are preferable to implement rather than DT initiatives.

Eco-innovation theory posits that environmental challenges and stakeholder/regulatory pressure can stimulate innovation (Fussler & James, 1996). However, this inducement effect depends on firms having sufficient resources, capabilities, and strategic alignment to respond (Song et al., 2018) In the context of Scope 2 emissions, limited managerial control and cost pressures may weaken a firm's ability to effectively respond to such pressures through digital innovation, making DT implementation more complex, costly, and uncertain (Alrawadieh et al., 2020). Under these conditions, firms may adopt a defensive response—prioritizing incremental efficiency measures or reporting improvements—rather than transformative digital investments (Zhai et al., 2022). Moreover, if DT is not explicitly designed as an eco-innovation (i.e., not integrated with energy-management objectives and decarbonization targets), firms may perceive DT as potentially increasing electricity use in the near term (through automation, sensors, computing, and data processing), thereby reinforcing firms' reluctance to deepen digital transformation (DT) and encouraging the postponement of its adoption when Scope 2 emission intensity remains high (Alsanie, 2025). Given this, the hypothesis is:

H1b*: Scope 2 carbon intensity has a negative effect on digital transformation adoption*

ESG performance represents a company's commitment to sustainability, which includes environmental, social, and governance aspects, and responds to pressure from stakeholders such as investors, regulators, and society (Bolognesi et al., 2025). ESG is measured by assessing a company's performance across these three aspects and is used to gauge performance and its impact on the company's reputation, as well as a benchmark for capital allocation, such as investment and credit risk assessment (Miller, 2024). When company achieves high levels of ESG performance, this pressure can drive performance improvement, which can be achieved through DT. This, in turn, is beneficial for maintaining and improving performance (Ren & Cheng, 2024). Implementing digital technologies such as cloud computing, the Internet of Things (IoT), and data-driven management systems can help companies monitor energy consumption, optimize operational efficiency, and control emissions in real time, thus supporting environmental aspects (Chauhan & Sahoo, 2024; Yavari et al., 2023).

To achieve good ESG performance, in addition to focusing on the environment, firms also need to balance their social and governance aspects. Employees of companies actively engaged in social responsibility are believed to be more motivated to improve new production processes and seek innovative solutions in digital technology (Broadstock et al., 2020). In the current era, companies have implemented a Work from Home (WFH) scheme for certain conditions (Wade & Shan, 2020), thus encouraging firms to implement digital-based innovations to connect employees so that operational performance remains stable even though they are not in the same location. For example, through a cloud-based system that can monitor flexible working hours, WFH attendance, and employee satisfaction levels, supporting Work-Life Balance (Li et al., 2025). Companies with a strong commitment and social spirit tend to be more motivated to continue prioritizing the welfare of their employees, one way of doing this is through digital innovation that reflects strong social values.

Furthermore, companies with good governance practices have a strong capital base to drive the adoption of DT, as they can mitigate agency problems and increase corporate capital investment in the digitalization process. This is beneficial for companies reaching their stable period (Hossnofky & Junge, 2019; Zhao et al., 2023). This argument is in line with research by Sun et al. (2025), which shows that ESG has a significant impact on DT during a company's stable period, but is not statistically significant during growth and decline. This suggests that companies in the stable phase are generally considered to have more time and funds for long-term thinking, including regarding ESG and DT. Therefore, ESG scores will increase and accelerate DT adoption. Companies can utilize digital technologies such as AI and IoT to monitor operational performance in real-time and for sustainability innovation and ESG practices, thereby fostering stakeholder trust in the company's sustainability commitments (DesJardine et al., 2025).

At the firm level, DT and ESG are increasingly recognized as strategic components in enhancing competitiveness and supporting the development of sustainable infrastructure, alongside the growing integration of ESG principles into corporate governance and policy framework (Aldieri & Vinci, 2021). From an eco-innovation theory (Fussler & James, 1996), DT adoption can be understood as a mechanism through which firms incorporate sustainability objectives into their operational processes, thereby contributing to the achievement of SDGs 9, which emphasizes sustainable industrialization, innovation, and resilient infrastructure (Aldieri & Vinci, 2021). In this context, ESG performance reflects firms' organizational capabilities and resource capacity that support DT adoption. Given this, the hypothesis is:

H2: *ESG score has a positive effect on digital transformation adoption*

2. MATERIALS AND METHODS

2.1 DATA SOURCE AND SAMPLE

The sample used in this study was taken from manufacturing companies listed on the Indonesia Stock Exchange (IDX) during period 2020 to 2024. Of 228 listed manufacturing companies in Indonesia, only 20 companies met the research criteria and included in the analysis. Some data were excluded from the analysis due to missing data or not available data; such as data scope 1 emissions, scope 2 emissions, and ESG Score. Therefore, the total observations are 91 sample-year.

2.2 VARIABLES

Table 1: Variable definitions and measures

Variable Type	Variable Name	Variable Code	Variable Definition and Measure

Dependent Variable	Digital Transformation	DT	ln(digital transformation); word frequency of DT keywords in annual reports with Python, using Google Colab
Independent Variables	Scope 1 Carbon Intensity	CISc1	Company's direct carbon emission intensity; ln(total Scope 1 emissions in tons CO_2e)/total asset) from the company
	Scope 2 Carbon Intensity	CISc2	Company's indirect carbon emission intensity; ln(total Scope 2 emissions in tons CO2e/total asset) from the company
	ESG Score	ESG	ln(Environment, Social, and Governance (ESG)); obtained from Refinitiv in a numerical score (0-100)
Control Variables	Institutional Ownership	IO	ln(percentage of share ownership by institutions)
	Firm Size by Revenue	FS_Rev	Firm size measured by revenue; ln(company's operating revenue)
	Debt-to-Equity Ratio	DER	Leverage ratio; ln(total liabilities/total equity)
	Listing Age	Listage	Firm's listing duration; ln(research year - IPO year)

Dependent Variable: Digital Transformation. Information on digital transformation keywords ware obtained from the annual reports published by companies. The calculation process was carried out using Google Colab through text analysis and Python-based calculations (Li, 2024; Yang et al., 2024). Text analysis enables hypothesis development by capturing the extent of AI and digital transformation implementation through explicit keywords disclosed in annual reports. First, DT keywords were compiled based on several studies, such as (Gao et al., 2024; Ma & Tao, 2023; Wang et al., 2023). Keywords were entered into a Python script to be extracted from the company's annual report from 2020-2024, and the output will be the frequency of how often these keywords appear in each company's annual report, as shown in Table 2. The keywords used for this study were all keywords related to DT that appeared in the company's annual reports during 2020-2024 period. Second, we counted all keywords that appeared for each company based on the results of the Python analysis to serve as an indicator in measuring the company's level of DT.

Independent Variable: Carbon Emission Intensity Scope 1 & Scope 2, and ESG Score. This study collected carbon emission data from Scope 1 and Scope 2 disclosed in the sustainability reports. Carbon intensity was calculated from Scope 1 emission (measured in tons of CO2e) are divided by the total assets. The carbon intensity for Scope 2 is calculated by dividing carbon emissions (measured in tons of CO2e) from Scope 2 by the total assets. ESG Score data are drawn from the Refinitiv database, that shows how well a company did in terms of Environmental, Social, and Governance (ESG) issues in a given year, using a numerical scale ranging from 0 to 100, where higher values indicate better ESG performance.

Control Variable: These variables are selected from prior research, to improve the precision of the model's estimates, as well as, to account for factors that might influence both independent and dependent variables. Without controlling these confounding factors, the relationship between the main variables might be distorted, leading to biased or inaccurate results. These variables include percentage of share ownership by institution (Institutional Ownership/IO) (Lin et al., 2023), company size based on revenue level (Yang et al., 2024), the ratio of total liabilities to total equity (Debt-to-Equity Ratio/DER) (Grishunin et al., 2022), and the company's length of IPO (Listage) (Guo et al., 2025; Wang et al., 2023). Table 1 provides the definitions and measurements of these variables.

Table 2: Digital Transformation Keywords

Index	Keywords	References
Artificial Intelligence	AI, Artificial Intelligence, Automatic, Automation, biometric, business intelligence, deep learning, face recognition, machine learning,	(Tang et al., 2025)
Blockchain	Blockchain, digital currency	(Ma & Tao, 2023; Tang et al., 2025)
Cloud Computing	Cloud Computing, Internet of Things, IoT	(Baboe et al., 2025; Wang et al., 2023)
Big Data	Augmented Reality, big data, data, data mining, data visualization, virtual reality	(Tang et al., 2025)
Digital Application Technology	B2B, B2C, C2B, C2C, O2O digital, digital marketing, digital technology, e-commerce, fintech, financial technology, industrial internet, internet connection, mobile internet, smart energy, smart home	(Tang et al., 2025; Yang et al., 2024)

This study uses the following regression model in the analysis:

$$DT_{it} = \alpha_0 + \alpha_1 CISc1_{it} + \alpha_2 CISc2_{it} + \alpha_3 ESG_{it} + \alpha_4 IO_{it} + \alpha_5 Fs\_Rev_{it} + \alpha_6 DER_{it} + \alpha_7 Listage_{it} + \varepsilon_{it} \quad \ldots (1)$$

Where:

- DT_{it} = Digital Transformation
- $CISc1_{it}$ = Carbon Intensity Scope 1
- $CISc2_{it}$ = Carbon Intensity Scope 2
- ESG_{it} = Environmental, Social, Governance score
- IO_{it} = Insitutional Ownership

- Fs_Rev_{it} = Firm Size by Revenue
- DER_{it} = Debt-to-Equity Ratio
- $Listage_{it}$ = Listing Age
- $\alpha_1, \alpha_2 \ldots \alpha_7$ = Reggression Coefficient
- ε = Error
- i = Company
- t = Year

This study uses panel data analysis to look at the effect of carbon emission intensity and ESG score performance on the level of digital transformation adoption in manufacturing companies during 2020-2024.

3. RESULTS

3.1 DESCRIPTIVE STATISTICAL ANALYSIS

Descriptive statistics for the variables used in this study are presented in Table 3, based on 91 company-year observations. These statistics provide an overview of the distribution of the dependent variable (DT), and the independent variables (CISc1, CISc2, and ESG) included in the analysis.

The Digital Transformation (DT) variable is measured as a composite indicator representing the extent to which firms adopt and integrate digital technologies into their operational and strategic processes. The mean DT value of 4.868,385, which is relatively close to the median of 4.534, indicates that the DT distribution is balanced around its central tendency. Regarding the independent variables, CISc1 represents the intensity of direct carbon emissions, measured as the volume of greenhouse gas emissions relative to a firm's total assets, thereby capturing the carbon intensity of a firm's operational activities. CISc1 has a mean value of 52.461 which indicates that the mean of CISc1 is positioned above the median 12.961, indicating sampled firms records comparatively higher emission intensity. Higher CISc1 values indicate greater carbon emissions per unit of assets, reflecting more carbon-intensive assets utilized in operations and lower resource-use efficiency. Similarly, CISc2 represents the intensity of indirect carbon emissions arising from the consumption of externally generated energy, scaled by a firm's total assets. Mean of CISc2 is 6.109, which is notably higher than its median of 1.702, which indicates that most firms rely heavily on carbon-intensive external energy sources. Elevated CISc2 values reflect a greater dependence on external supplied energy with higher emission factors, implying limited efficiency in energy sourcing, and a slower transition toward renewable or low-carbon energy alternatives (Ma et al., 2021).

The ESG performance variable is measured on a standardized scale ranging from 0 to 100, where the higher scores indicate stronger and better comprehensive environmental, social, and governance practices. The mean ESG score of 57.763 lies slightly above the midpoint of the scale, indicating that firms in the sample exhibit a moderate level of ESG performance. This suggests that firms have begun to integrate environmental, social, and governance aspects into their operational activities, although the extent and consistency of implementation still vary among the firms.

Table 3: Descriptive statistics

Table 4 shows Pearson's correlations matrix for all variables. The correlation between variables shows less than 0.6 (Hair et al., 2019), meaning none of the correlations between independent variables are at levels that would cause multicollinearity to be of concern, but variance inflation factors are checked to be more assured of this.

Table 4: Pearson correlation matrix

Variables	DT	CISc1	CISc2	ESG	IO	Fs_Rev	DER	Listage
DT	1.0000							
CISc1	0.1319	1.0000						
CISc2	0.0215	0.3209***	1.0000					
ESG	0.5818***	-0.0470	0.2693*	1.0000				
IO	0.0870	-0.0823	-0.0351	-0.2213**	1.0000			
FS_Rev	0.1749*	-0.2565**	-0.1773	0.1914*	-0.1512	1.0000		
DER	0.0298	0.0697	0.0352	0.3746***	-0.1865*	-0.4396***	1.0000	
Listage	-0.0581	0.1550	0.1827*	0.2497**	-0.2446**	0.1913*	0.3094***	1.0000

*, **, *** Correlation is significant at the $P < 0.10$, $P < 0.05$, $P < 0.01$

3.2 REGRESSION RESULT ANALYSIS

Table 5 presents the regression results using Ordinary Least Squares (OLS) investigating the effects of carbon intensity (Scope 1 and Scope 2) and ESG performance on digital transformation. The results demonstrate that CISc1 has a positive and statistically significant P-value of 0.000, indicating that firms with higher levels of direct emissions (scope 1 emissions) are likely to intensify their adoption of digital transformation as a strategic measure to improve operational efficiency by enhanced emission monitoring. Based on Fussler & James (1996)'s perspective on eco-innovation theory, digital transformation is viewed as a form of environmentally friendly technological innovation that helps firms reduce their environmental impact without sacrificing economic performance. Eco-innovation theory states that innovation aims not only to increase production efficiency but also to reduce resource consumption and emission through improved processes and managerial systems (Rennings, 2000). Thus, firms can help to monitor emission consumption in real time, identify operational inefficiencies more accurately and quickly, and optimize production processes sustainably by adopting technologies such as AI, IoT, data analytics, and automation. It is consistent with previous research which states the role of digital technology in increasing company productivity (Xu et al., 2023; Zhou & Liu, 2024). This finding provides empirical **support Hypothesis 1a.**

In contrast, CISc2 shows a significant negative coefficient at P-value of 0.007, indicating that the increase in indirect emissions caused by purchasing electricity from third parties has negative effect on digital transformation adoption. This suggests that firms with high external energy sources may prefer choosing non-digital strategies as an alternative solution of scope 2 carbon emission intensity reduction, rather than investing in digital solutions which require greater cost. From an eco-innovation theory perspective (Fussler & James, 1996), firms tend to prioritize incremental innovation when facing scope 2 intensity (Zhai et al., 2022). Eco-innovation is not always realized through the adoption of advanced technology, but also through improvement to more energy-efficient operational processes (Song et al., 2018). firms can explore other avenues for operational adjustment beyond digital transformation, so digital transformation is not the only way for firms to reduce emissions. This result **supports Hypothesis 1b.**

The ESG variable showed a significant positive effect at P-value of 0.000, indicating that companies with good ESG performance tend to choose DT as the strategic response to maintain and continue to improve their ESG performance. This suggests that companies with good sustainability practices view DT adoption as a tool to support transparency and better governance. From the perspective of eco-innovation theory Fussler & James, (1996), sustainability-oriented companies view digital transformation as a form of managerial and technological innovation to improve economic performance, strengthen transparency and accountability, and enhance governance effectiveness (Yang et al., 2024). Data analytics is a one-way company that adopts digital technology to more systematically monitor environmental and social performance and improve the quality of ESG disclosure (Yavari et al., 2023). Therefore, these results **support Hypothesis 2.**

Table 5: Baseline regression results

Variables	**DT**
CISc1	0.082***
	(0.000)
CISc2	-0.080***
	(0.007)
ESG	1.101***
	(0.000)
IO	0.294***
	(0.008)
FS_Rev	0.295
	(0.667)
DER	-0.137
	(0.138)
Listage	-0.790**
	(0.071)
_cons	4.174***
	(0.003)
N	91
adj. R^2	0.500
F-Statistic	13.83 (0.000)
VIF	1.67

Note: symbol *, **, *** indicate significance levels of 10%, 5%, and 1% respectively. The values in parentheses indicate the P-value for each coefficient.

4. DISCUSSION

This research was conducted to analyze the impact of carbon intensity from scope 1 and scope 2, as well as ESG performance on the adoption of digital transformation. The study found that carbon intensity from scope 1, scope 2, and ESG performance significantly affects digital transformation.

The positive impact scope 1 carbon intensity on digital transformation indicates that manufacturing firms in Indonesia with higher levels of direct emissions are more likely to adopt digital transformation for process efficiency and operational decarbonization. These results are consistent with prior findings indicating that emissions drive firms to adopt digital transformation (DT) and implement digital-based operational monitoring (Chauhan & Sahoo, 2024; Zhou & Liu, 2024). Firms have full control over internal emission sources, enabling more effective efficiency-oriented policies. Digital systems are used to monitor production machine performance and operational vehicle fuel consumption at the operational level. This allows for more measurable emission control and supports the optimization of combustion processes and energy use in production facilities (Xu et al., 2023; Zhou & Liu, 2024). Pressure not only stems from government regulations, but another example is seen during COVID-19 pandemic, where operational restrictions accelerated the adoption of digital monitoring systems and process automation (Amankwah-Amoah et al., 2021).

Contradictory results to scope 1, scope 2 carbon intensity significant negative impacts the adoption of digital transformation. These findings diverge from a portion of the literature that generally assumes thar pressures related to environmental concerns stimulate innovation; however, the results of this study indicate that, in the context of Scope 2 emissions, firms' responses do not necessarily take the form of digitalization, but rather through relatively more direct and efficient non-digital measures to reduce scope 2 emissions, such as asset maintenance and renewable energy purchases (Baniya & Giurco, 2025; Griffin et al., 2014). In line with eco-innovation theory, corporate environmental initiatives are not necessarily implemented through digital solutions but can also be achieved through non-digital innovations such as energy source substitution, improvements in asset efficiency, and the adoption of renewable energy (Fussler & James, 1996), Thereby extending the literature by emphasizing that the relationship between pressures related to environmental concerns and innovation is contingent upon the characteristics of the emission sources (Baniya & Giurco, 2025). Companies tend to adopt non-digital forms that can provide more immediate results in reducing scope 2 emissions because investments in digital transformation are riskier and have long-term impacts. The impact of the pandemic also caused companies to face economic uncertainty, leading them to focus more on cost reductions than investing in sustainable technologies. Meanwhile, increased scope 2 emissions from environmentally unfriendly energy sources can increase operational costs, potentially forcing companies to delay or limit investments in digital transformation. Throughout the pandemic, the government also focused on supporting the clean energy transition and encouraging sustainable investment (Haas et al., 2023).

Furthermore, the result of this study indicates a positive relationship between companies' ESG performance and digital transformation adoption. This finding suggests that companies with strong environmental, social, and governance practices, as well as strong sustainability commitments, create a more conducive organizational environment for strategic decision-making, including investments in digital transformation, which is consistent with prior studies that position ESG as an indicator of organizational readiness to adopt technological innovation (Sun et al., 2025). These results are consistent with previous study showing that digital transformation contribute to improved corporate environmental performance, broadening the understanding that the impact of digitalization extends beyond the environmental to encompass social and governance dimensions within the ESG framework (Liu et al., 2025; Yang et al., 2024; Baboe et al., 2025). Companies with stable governance structures typically have more long-term-oriented internal controls, making them more likely to view digitalization as a strategic solution to improve operational performance and corporate sustainability. The positive relationship between ESG performance and digital transformation adoption is consistent with the findings of Sun et al. (2025) who stated that good ESG performance and firms in stable periods tend to encourage the adoption of digital transformation.

Digital technology adoption is influenced by regulatory and stakeholder pressures, as well as by a firm's ability to address and adapt to these external demands. Companies in Indonesia have begun implementing the adoption of digital transformation in compliance to Ministerial Regulation No. 21 of 2020 concerning the measurement of industry readiness for the transformation to Industri 4.0 through Indonesia Industry 4.0 Readiness Index (INDI 4.0). This study confirms that effective DT requires a balance between regulatory pressures and organizational readiness for sustainability (Rennings, 2000).

The Financial Services Authority (OJK) is also involved in developing green finance framework that encourages the use of sustainable financing instruments, including green bonds, to support environmentally friendly investments. (Otoritas Jasa Keuangan, 2017). However, regulatory pressure and policy support are not always accompanied by corporate readiness to design, manage, and implement sustainable investments, as evidenced by the low level of green finance utilization by entities that are otherwise eligible. Moreover, companies with eligibility of green finance incentives do not understand and know their eligibility status, that they cannot utilize this opportunity. This situation demonstrates that green finance may serve as a driver of eco-innovation and digital transformation, but its effectiveness depends heavily on a company's internal capabilities, particularly ESG readiness as a foundation for integrating digital transformation into business processes (Raman et al., 2024). These findings underscore that the presence of regulatory frameworks and sustainable financing instruments must be complemented by firms' organizational and ESG readiness for the impetus toward green innovation and digital transformation to be effectively translated into operational practices.

5. CONCLUSIONS

This study examines how scope 1 carbon emission intensity, scope 2 carbon emission intensity, and ESG performance influence the firm's decision to adopt DT. The results indicate that these factors act as strategic determinants, shaping corporate digitalization in different ways depending on the source and controllability of emissions. Consistent with eco-innovation theory, that views DT as a strategic driver that improves energy management, reduces resource inefficiencies, and improves overall sustainability performance, thereby strengthening competitive advantage. Companies do not simply respond to regulations reactively; they use DT as a proactive adaptation mechanism to manage emission sources that are entirely within their control. These findings extend the literature by demonstrating that emission controllability, rather than merely emission magnitude, is a critical factor in shaping firms' digital investment decisions.

The issue of emissions and ESG performance plays a significantly strategic role. Both can be powerful drivers for companies to move towards DT, but under certain conditions they can also be a hindrance, especially for scope 2 carbon intensity. Companies with high electricity energy dependency tend to delay DT adoption due to substantial energy requirements and cost pressures. As a result, firms face a trade-off between improving efficiency through digitalization and limited financial capacity driven by high energy costs.

The issue is not just about compliance but about how firms determine their long-term direction and priorities. This study provides a clear picture for managers, businesspeople, and policy makersthat carbon emission levels and ESG quality performance influence the speed at which firms adopt DT. For managers, these results could serve as a reminder as part of the solution, not just a technological trend, through real-time monitoring of emissions and energy consumption, identification of operational inefficiencies, and strengthening reporting quality and internal controls to enhance sustainability transparency. In contrast, to mitigate scope 2 emissions intensity, managers need to prioritize energy efficiency and electricity consumption management to avoid contraining DT investment. For companies, accelerating the adoptioncan support carbon emissions management and strengthen ESG performance, enhance investment competitiveness. Companies also need to accelerate energy efficiency programs, optimize electricity use, and transition to cleaner energy sources to prevent energy costs from becoming a limiting factor for digital investment. For policymakers, the regulatory framework should incentivize the adoption of digital solutions,, while simultaneously encouraging improvements in the quality of governance and ESG reporting. The negative impact of scope 2 indicates the need for policy interventions on the energy side, such as electricity efficiency programs and support for the clean energy transition.

However, this study has several limitations. First, the data used onlyincludes manufacturing companies, so the resultsmay not be generalizable to other sectors that have different operational patterns and emission levels. Second, the measurement of DT is based on how often terms related to digitization appear in the company's annual report. While this approach captures managerial emphasis and disclosure intensity and is generally considered reliable due to its replicability and data availability, it may not be fully reflecting the depth, quality, or actual implementation level of DT initiatives and may be influenced by differences in disclosure practices across firms. Therefore, future research is encouraged to employ more granular DT indicators, for example by using dummy variables capturing specific digital initiatives, to improve measurement precision. Future research also could include additional variables (e.g., mediators or moderators) as well as extend the research observations to retest and expand the research to potentially benefit company sustainability.

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