

RESEARCH ARTICLE

<https://doi.org/10.46488/NEPT.2026.v25i04.D1917>

OPEN ACCESS

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

Linda, Vania Angelica Angdi and Linda Kusumaning Wedari†

Accounting Department, School of Accounting, Bina Nusantara University, Jakarta 11480, Indonesia

†Corresponding author: Linda Kusumaning Wedari; linda.wedari@binus.edu

ARTICLE HISTORY

Received: 02-03-2026

Revised: 18-04-2026

Accepted: 01-05-2026

KEYWORDS

Carbon intensity
Artificial intelligence-based digital transformation
Sustainable manufacturing
SDG 9
ESG

CITE THIS ARTICLE

Linda, Angdi, V. A. and Wedari, L. K., 2026. AI-driven digital transformation for sustainable manufacturing: Exploring the impact of carbon intensity and ESG through eco-innovation theory. *Nature Environment and Pollution Technology*, 25(4), D1917. <https://doi.org/10.46488/NEPT.2026.v25i04.D1917>

COPYRIGHT & LICENCE

© 2026 The Authors
Open Access under CC BY 4.0.

PUBLISHED BY



ABSTRACT

This study aims to examine the influence of carbon intensity and environmental, social, and governance (ESG) performance on the adoption of digital transformation from the perspective of eco-innovation theory to support sustainable production and decarbonization goals. A quantitative method was used to analyze 91 firm-year observations from manufacturing firms in Indonesia. The results show that firms with higher Scope 1 carbon intensity tend to adopt digital transformation because emissions are directly observable in operational activities, while high ESG performance can support improved performance through digital transformation adoption. The significant negative relationship between Scope 2 carbon intensity and digital transformation indicates that firms may use alternative non-digital solutions to reduce Scope 2 carbon intensity. These results support eco-innovation theory, which states that digital and non-digital innovations are essential for environmental sustainability and production efficiency, particularly in the manufacturing industry. This study provides practical insights for managers and policymakers on designing digital strategies that align with environmental conservation efforts and support 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). Artificial intelligence (AI), big data, blockchain, and the Internet of Things (IoT) are examples of technologies that firms are beginning to implement through digital transformation (hereafter DT) as a strategy to support efficiency and productivity while minimizing operational costs and optimizing resource 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 indicated by the increasing adoption index values each year.

Indonesia still faces a gap between digital awareness and its implementation. This is evident from the relatively low acceleration index shown in Fig. 1. These data demonstrate that firms in Indonesia still face various challenges in developing their technological capabilities, indicating that 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 on five priority sectors: food and beverage, textiles and clothing, automotive, chemicals,

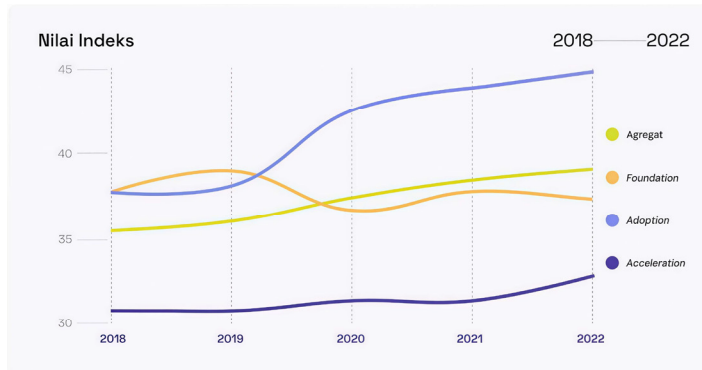


Fig. 1: Digital transformation index in the business pillar (Kementerian Komunikasi dan Digital RI 2024).

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 refers to processes that utilize existing digital technologies. DT has become an appropriate approach for helping a business entity improve efficiency and effectiveness, 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 through performance monitoring, thereby promoting more efficient, transparent, and accountable corporate operations (Zhang et al. 2025). Moreover, ESG implementation encourages more environmentally friendly practices and accountable governance. This condition is increasingly supported by greater data availability, transparency, and accessibility, enabling greater business openness and effectiveness (Zhang & Huang 2024). The integration of DT further supports the achievement of Sustainable Development Goal (SDG) 9, which emphasizes 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).

The manufacturing sector in Indonesia contributes significantly to carbon emissions, which are high due to its production activities, reaching 340.71 million tons of CO₂e in 2022 (Ahdiat 2024). The increasing carbon emissions have prompted the government to accelerate the development and enforcement of policies aimed at reducing 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, aiming to improve transparency and accountability concerning ESG performance as these elements are consistently reported (Otoritas Jasa Keuangan, 2017a). 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's 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 greater economic risks associated 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 because of its potential to improve firms' operational efficiency. Prior research has examined 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 emissions 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 emissions 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 of the contribution of each emission scope to DT. In addition, most prior research relies on theoretical frameworks 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 attempts to expand on existing discussions by adopting Scope 1 and Scope 2 carbon emission intensities and ESG performance as important factors that can encourage firms to adopt DT. Scope 1 and Scope 2 carbon emission intensities can represent the emission sources that are closest to a company's operational activities and can still be controlled directly. In the context of Indonesian manufacturing, emissions are 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 and Scope 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 following subsections provide a literature review on the relationship between carbon emissions, ESG performance, and DT. This 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.

1.1. 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 toward 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 the context of digital development, industry is increasingly demonstrating the potential of AI as a catalyst for energy efficiency, big data analysis, productivity enhancement, and decision-making that supports 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).

1.2. 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 and James (1996), which emphasizes business, technology, and operational practices that create economic value while reducing negative environmental impacts. 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. Digital technologies 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 are indirect emissions originating from electricity, steam, heat, or cooling purchased from external parties and used by the company (Emmanuel et al. 2023). In contrast to Scope 1 emission intensity, which is under a firm's direct operational control, Scope 2 emission intensity is 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 Scope 2 carbon intensity relates to a company's carbon performance, which depends on the energy used by the company 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 a direct factor) and electricity tariff structures (as an indirect factor), indicating that increases in Scope 2 emission intensity are also driven by external conditions that are difficult for firms to control. Firms 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 use and determine which assets consume more energy under certain conditions. This allows them to

take appropriate action to reduce energy consumption, such as switching off these assets when not in use (Griffin et al. 2014). Companies may focus on routine asset maintenance to maintain stable machine performance and reduce energy consumption, purchase renewable energy, or use other non-digital strategies to reduce emissions intensity rather than adopting DT, which also requires significant funding (Baniya & Giurco 2025). These initiatives may be preferable to DT initiatives.

Eco-innovation theory posits that environmental challenges and stakeholder and regulatory pressures 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 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 and to provide a benchmark for capital allocation, such as investment and credit risk assessment (Miller 2024). When a company achieves a high level of ESG performance, this can drive further performance improvement, which can be supported 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 performance (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 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 under 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, a cloud-based system 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 in a stable phase (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 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 to support 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 frameworks (Aldieri & Vinci 2021). From the perspective of 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 SDG 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 the period 2020–2024. Of 228 listed manufacturing companies in Indonesia, only 20 companies met the research criteria and were included in the analysis. Some data were excluded from the analysis due to missing or unavailable data, such as Scope 1 emissions, Scope 2 emissions, and ESG scores. Therefore, the total sample comprises 91 firm-year observations.

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 ₂ e/total assets) from the company
	Scope 2 Carbon Intensity	CISc2	Company's indirect carbon emission intensity; ln(total Scope 2 emissions in tons CO ₂ e/total assets) from the company
	ESG Score	ESG	ln(Environmental, 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)

2.2. Variables

2.2.1. Dependent Variable

Digital Transformation. Information on digital transformation keywords was 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 (Gao et al. 2024, Ma & Tao 2023, Wang et al. 2023a). Keywords were entered into a Python script to extract occurrences from each company's annual reports for 2020–2024, and the output was the frequency with which these keywords appeared 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 the 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, using the natural logarithm of the total keyword frequency.

2.1.2. Independent Variables

Scope 1 and Scope 2 Carbon Emission Intensity and ESG Score. This study collected Scope 1 and Scope 2 emissions data disclosed in the sustainability reports. Scope 1 carbon intensity was calculated by dividing natural logarithm of Scope 1 emissions (measured in tons of CO₂e) by total assets. Scope 2 carbon intensity was calculated by dividing natural logarithm of Scope 2 emissions (measured in tons of CO₂e) by total assets. ESG score data were obtained from the Refinitiv database, which indicates how well a company performed in terms of environmental, social, and governance (ESG) issues in a given year, using the natural logarithm of the ESG score, which is measured on a numerical scale

ranging from 0–100, where higher values indicate better ESG performance.

2.2.3. Control Variables

These variables were selected from prior research to improve the precision of the model's estimates and 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 the percentage of shares owned by institutions (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 time since the company's IPO (Listage) (Guo et al. 2025, Wang et al. 2023b), with all variables transformed using the natural logarithm. Table 1 provides the definitions and measurements of these variables.

This study uses the following regression model in the analysis:

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

Where:

- DT_{it} = Digital Transformation
- $CISc1_{it}$ = Carbon Intensity Scope 1
- $CISc2_{it}$ = Carbon Intensity Scope 2
- ESG_{it} = Environmental, Social, and Governance score
- IO_{it} = Institutional Ownership
- FS_Rev_{it} = Firm Size by Revenue
- DER_{it} = Debt-to-Equity Ratio
- $Listage_{it}$ = Listing Age
- $\alpha_1, \alpha_2 \dots \alpha_7$ = Regression coefficients
- ε = Error

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. 2023a)
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)

- i = Company
- t = Year

All variables in the regression model are measured using their respective natural logarithmic transformations as defined in Table 1. This study uses panel data analysis to examine the effects of carbon emission intensity and ESG performance on the level of digital transformation adoption in manufacturing companies during 2020–2024.

3. RESULTS AND DISCUSSION

3.1. Descriptive Statistical Analysis

Descriptive statistics for the variables used in this study are presented in Table 3, based on 91 firm-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 4868.385, which is relatively close to the median of 4534, 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 is above the median of 12.961, indicating comparatively high emission intensity among the sampled firms. 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. The mean of CISc2 is 6.109, which is notably higher than its median of 1.702, indicating that most firms rely heavily on carbon-intensive external energy sources. Elevated CISc2 values reflect a greater dependence on externally 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 0–100, where higher scores indicate stronger overall 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

Table 3: Descriptive statistics.

Variable	N	Mean	Median	Std. Dev.	Min	Max
DT	91	4868.385	4534	2285.847	1417	11954
CISc1(t CO ₂ e/IDR)	91	52.461	12.961	104.766	0.181	424.700
CISc2(t CO ₂ e/IDR)	91	6.109	1.702	11.606	0.008	57.199
ESG	91	57.763	58.59	16.658	23.79	88.59
IO (%)	91	0.879	0.951	0.203	0.033	0.993
FS_Rev (IDR billion)	91	57704.03	38651.36	61952.46	8800	330920
DER	91	0.919	0.756	0.897	0.129	6.466
Listage (Year)	91	28.571	31	7.835	2	43

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

*, **, and *** indicate significance at $p < 0.10$, $p < 0.05$, and $p < 0.01$, respectively.

operational activities, although the extent and consistency of implementation still vary among the firms.

Table 4 shows the Pearson correlation matrix for all variables. All correlations between the independent variables are below 0.6 (Hair et al. 2019), suggesting that multicollinearity is unlikely to be a concern; variance inflation factors (VIFs) were also examined to confirm this.

3.2. Regression Result Analysis

Table 5 presents the regression results from an ordinary least squares (OLS) model 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 coefficient with a statistically significant p-value of less than 0.001, 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 through enhanced emissions monitoring. From the eco-innovation theory perspective of Fussler and James (1996), 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 emissions through improved processes and managerial systems (Rennings 2000). Thus, firms can monitor emissions 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. This is consistent with previous research showing that digital technology can increase firm productivity (Xu et al. 2023, Zhou & Liu 2024). This finding provides empirical support for Hypothesis 1a.

In contrast, CISc2 has a significant negative coefficient with a p-value of 0.007, indicating that the increase in indirect emissions caused by purchasing electricity from third parties has a negative effect on digital transformation adoption. This suggests that firms with high dependence on external energy sources may prefer non-digital strategies as alternative approaches to reducing Scope 2 carbon emission intensity, rather than investing in digital solutions that require greater investment. From an eco-innovation theory perspective (Fussler & James 1996), firms tend to prioritize incremental innovation when facing high Scope 2 intensity (Zhai et al. 2022). Eco-innovation is not always realized through the adoption of advanced technology but also through improvements 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 with a p-value of less than 0.001, indicating that companies with good ESG performance tend to choose DT as a 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 the eco-innovation theory of Fussler and 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 one way a company can adopt digital technology to more systematically monitor environmental and social performance and improve

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: Symbols *, **, and *** indicate significance levels of 10%, 5%, and 1%, respectively. Values in parentheses indicate the p-value for each coefficient.

the quality of ESG disclosure (Yavari et al. 2023). Therefore, these results support Hypothesis 2.

3.3. Discussion

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

The positive impact of 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 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 stems not only from government regulations; during the COVID-19 pandemic, operational restrictions also accelerated the adoption of digital monitoring systems and process automation (Amankwah-Amoah et al. 2021).

In contrast to the Scope 1 result, Scope 2 carbon intensity has a significant negative effect on digital transformation adoption. These findings diverge from a portion of the literature that generally assumes that 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 instead involve 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). This extends 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 measures 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 rather 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 studies showing that digital transformation contributes 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 reported 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 adopting digital transformation in compliance with 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 a green finance framework that encourages the

use of sustainable financing instruments, including green bonds, to support environmentally friendly investments (Otoritas Jasa Keuangan 2017b). 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 eligible for green finance incentives do not understand or know their eligibility status and therefore 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.

4. 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. This is consistent with eco-innovation theory, which 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 issues of emissions and ESG performance play a significant strategic role. Both can be powerful drivers for companies to move toward DT, but under certain conditions they can also be a hindrance, especially for Scope 2 carbon intensity. Companies with high dependence on electricity 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 policymakers that carbon emission levels and ESG performance influence the speed at which firms adopt DT. For managers, these results indicate that DT can be part of the solution, rather than only 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 constraining DT investment. For companies, accelerating adoption can support carbon emissions management, strengthen ESG performance, and 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 include only manufacturing companies, so the results may 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 fully reflect 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 could also include additional variables (e.g., mediators or moderators) as well as extend the observation period to retest and expand the analysis, potentially benefiting corporate sustainability research.

5. ACKNOWLEDGEMENT

This study is based on the authors' thesis at Bina Nusantara University.

6. OPEN DATA STATEMENT

This study used data obtained from publicly available annual reports and sustainability reports of the sample companies, as well as proprietary data obtained from Refinitiv under license. The publicly available documents can be accessed through the respective companies' websites, while the Refinitiv data are subject to licensing restrictions and are not publicly available.

7. REFERENCES

- Ahdiat, A., 2024. Ini industri penyumbang emisi gas rumah kaca terbesar di Indonesia. Databoks. Available at: <https://databoks.katadata.co.id/lingkungan/statistik/b0d4d2a1d9aaa4c/ini-industri-penyumbang-emisi-gas-rumah-kaca-terbesar-di-indonesia>
- Aldieri, L. and Vinci, C.P., 2021. Eco-innovation in support of sustainable development goals. In: W. Leal Filho, A.M. Azul, L. Brandli, A. Lange Salvia and T. Wall (eds.) *Industry, Innovation and Infrastructure*. Encyclopedia of the UN Sustainable Development Goals. Springer, Cham. [DOI]
- Alrawadieh, Z., Alrawadieh, Z. and Cetin, G., 2020. Digital transformation and revenue management: Evidence from the hotel industry. *Tourism Economics*, 27(2), pp.328–345. [DOI]
- Alsanie, G., 2025. Investigating the impact of digitalization on resource use, energy use, and waste reduction towards sustainability: Considering environmental awareness as a moderator. *Sustainability*, 17(9), 4073. [DOI]
- Amankwah-Amoah, J., Khan, Z., Wood, G. and Knight, G., 2021. COVID-19 and digitalization: The great acceleration. *Journal of Business Research*, 136, pp.602–611. [DOI]
- Andrian, T. and Sudibyo, Y.A., 2019. Disclosure effect of carbon emission and corporate social responsibility to financial performance. *Journal of Economics and Sustainable Development*, 10(12), pp.87–94. [DOI]
- Baboe, K.C., Angelica, S.J.L. and Wedari, L.K., 2025. Sustainable empowerment: Digital transformation and carbon emissions as a catalyst for enterprise ESG performance. *International Journal of Sustainable Development and Planning*, 20(4), pp.1553–1561. [DOI]
- Baniya, B. and Giurco, D., 2025. Net zero energy buildings and climate resilience narratives – navigating the interplay in the building asset maintenance and management. *Energy Reports*, 13, pp.1632–1648. [DOI]
- Bhatia, M., Meenakshi, N., Kaur, P. and Dhir, A., 2024. Digital technologies and carbon neutrality goals: An in-depth investigation of drivers, barriers, and risk mitigation strategies. *Journal of Cleaner Production*, 451, 141946. [DOI]
- Bolognesi, E., Burchi, A., Goodell, J.W. and Paltrinieri, A., 2025. Stakeholders and regulatory pressure on ESG disclosure. *International Review of Financial Analysis*, 103, 104145. [DOI]
- Broadstock, D.C., Matousek, R., Meyer, M. and Tzeremes, N.G., 2020. Does corporate social responsibility impact firms' innovation capacity? The indirect link between environmental & social governance implementation and innovation performance. *Journal of Business Research*, 119, pp.99–110. [DOI]
- Chauhan, M. and Sahoo, D.R., 2024. Towards a greener tomorrow: Exploring the potential of AI, blockchain, and IoT in sustainable development. *Nature Environment and Pollution Technology*, 23(2), pp.1105–1113. [DOI]
- Chen, J., Gao, M., Ma, K. and Song, M., 2020. Different effects of technological progress on China's carbon emissions based on sustainable development. *Business Strategy and the Environment*, 29(2), pp.481–492. [DOI]
- Chen, J., Guo, Z. and Lei, Z., 2024. Research on the mechanisms of the digital transformation of manufacturing enterprises for carbon emissions reduction. *Journal of Cleaner Production*, 449, 141817. [DOI]
- Chen, X., Despeisse, M. and Johansson, B., 2020. Environmental sustainability of digitalization in manufacturing: A review. *Sustainability*, 12(24), 10298. [DOI]
- Cheng, S., Yang, Y. and Liu, J., 2014. Convergence of regional economic growth and carbon emission intensity in China. *Nature Environment and Pollution Technology*, 13(3), pp.623–628.
- CRSM Indonesia, 2024. Implementasi environmental, social and governance (ESG) 2024 survey nasional.
- da Cunha, Í. G.F., Policarpo, R.V.S., de Oliveira, P.C.S., Zanon, L.G. and do Nascimento Rebelatto, D.A., 2025. Exploring ESG indicators and the Sustainable Development Goals: A fuzzy multi-criteria approach to cause-and-effect analysis. *Business Strategy and Development*, 8(3). [DOI]
- Dan, E., Shen, J., Zheng, X., Liu, P., Zhang, L. and Chen, F., 2023. Asset structure, asset utilization efficiency, and carbon emission performance: Evidence from panel data of China's low-carbon industry. *Sustainability*, 15(7), 6264. [DOI]
- Desjardine, M.R., Li, B. and Shi, W., 2025. Information-based competition: The case of rival owners in rating agencies. *Academy of Management Journal*, 68(1), pp.221–256. [DOI]
- Emmanuel, Y.L., Adenikinju, O., Doorsamy, M., Ayoola, T.J., Oladejo, A.O., Kwarbai, J.D. and Otekunrin, A.O., 2023. Carbon emission disclosure and financial performance of quoted Nigerian financial services companies. *International Journal of Energy Economics and Policy*, 13(6), pp.628–635. [DOI]
- Fussler, C. and James, P., 1996. *Driving Eco-Innovation: A Breakthrough Discipline for Innovation and Sustainability*. Pitman, London.
- Gao, Y., Yang, H., Sun, X., Tian, X. and Xu, J., 2024. Corporate digital transformation and financing constraints: The moderating effect of institutional investors. *Heliyon*, 10(12), e33199. [DOI]
- Griffin, J.S., Thal, A.E. and Leach, S.E., 2014. Enhancing asset management through a better understanding of energy consumption. *International Journal of Strategic Property Management*, 18(3), pp.253–264. [DOI]
- Grishunin, S., Naumova, E., Burova, E., Suloeva, S. and Nekrasova, T., 2022. The impact of sustainability disclosures on value of companies following digital transformation strategies. *International Journal of Technology*, 13(7), pp.1432–1441. [DOI]
- Guo, L., Li, S., Liu, Y., Zhang, C. and Sang, B., 2025. The green ripple effect: How digital transformation reduces carbon emissions across industrial chains. *Discrete Dynamics in Nature and Society*, 2025, 9159803. [DOI]
- Guo, L. and Tang, M., 2024. How does digital transformation improve corporate carbon emission reduction performance? An empirical study on data from listed companies in China. *Sustainability*, 16(8), 3499. [DOI]
- Haas, C., Jahns, H., Kempa, K. and Moslener, U., 2023. Deep uncertainty and the transition to a low-carbon economy. *Energy Research & Social Science*, 100. [DOI]
- Hair, J.F., Black, W.C., Babin, B.J. and Anderson, R.E., 2019. *Multivariate Data Analysis* (8th ed.).
- Hoffmann, V.H. and Busch, T., 2008. Corporate carbon performance indicators: Carbon intensity, dependency, exposure, and risk. *Journal of Industrial Ecology*, 12(4), pp.505–520. [DOI]
- Hosnoffsky, V. and Junge, S., 2019. Does the market reward digitalization efforts? Evidence from securities analysts' investment recommendations. *Journal of Business Economics*, 89(8–9), pp.965–994. [DOI]
- IDX, 2023. Launching of Indonesia carbon exchange (IDXCarbon).
- Kementerian Komunikasi dan Digital RI, 2024. TDN 2024.
- Kementerian Perindustrian Republik Indonesia, 2018. Indonesia Industry 4.0 readiness index.

- Khan, Z.A. and Singh, S., 2023. Intellectual property rights regime in green technology: Way forward to sustainability. *Nature Environment and Pollution Technology*, 22(4), pp.2145–2152. [DOI]
- Khatib, S.F.A., Ismail, I.H.M., Salameh, N., Abbas, A.F., Bazhair, A.H. and Sulimany, H.G.H., 2023. Carbon emission and firm performance: the moderating role of management environmental training. *Sustainability*, 15(13), p.10485. [DOI]
- Kristianto, F.P., Ulfia, Y.N. and Galih Prakoso, 2025. Framework for digital transformation in Industry 4.0: Insights data driven analysis in the Indonesia manufacture sector. *Journal of Advances in Information and Industrial Technology*, 7(1), pp.45–60. [DOI]
- Li, J., 2024. A study on the mechanism of the impact of digital transformation in manufacturing enterprises on sustainable development performance. *International Journal of Environmental Impacts*, 7(1), pp.81–92. [DOI]
- Li, Q., Abdul Ghani Azmi, I. binti and Norman, A.A. binti, 2025. Enhancing sustainable innovation through workplace well-being and digital capability: A systematic literature review toward responsible and cleaner consumption. *Cleaner and Responsible Consumption*, 18. [DOI]
- Lin, P.T., Jin, Y., Gao, F., Yang, R. and Lin, Q., 2023. Institutional investors, CSR report readability and the moderating role of ESG performance. *SAGE Open*, 13(4). [DOI]
- Liu, Y., Kumar, S., Liu, H., Li, S. and Zhou, Z., 2025. ESG performance, digital transformation, and green innovation. *Humanities and Social Sciences Communications*, 12(1). [DOI]
- Ma, W., Sun, D., Deng, Y., Meng, X. and Li, M., 2021. Analysis of carbon emissions of prefabricated buildings from the views of energy conservation and emission reduction. *Nature Environment and Pollution Technology*, 20(1), pp.39–44. [DOI]
- Ma, Y. and Tao, P., 2023. A perspective on management myopia: The impact of digital transformation on carbon emission intensity. *Sustainability*, 15(12), 9417. [DOI]
- Matt, C., Hess, T. and Benlian, A., 2015. Digital transformation strategies. *Business & Information Systems Engineering*, 57(5), pp.339–343. [DOI]
- McDougall, M., Mooney, A. and Dunkley, E., 2025. BlackRock loses second Dutch pension mandate over sustainable investing concerns. *Financial Times* (December).
- Miller, N., 2024. ESG score. *Corporate Finance Institute* (July).
- Nareswari, N., Tarczynska-Luniewska, M. and Al Hashfi, R.U., 2023. Analysis of environmental, social, and governance performance in Indonesia: Role of ESG on corporate performance. *Procedia Computer Science*, 225, pp.1748–1756. [DOI]
- Otoritas, J.K., 2017a. Penerapan keuangan berkelanjutan bagi lembaga jasa keuangan, emiten, dan perusahaan publik. Available at: <https://keuanganberkelanjutan.ojk.go.id/keuanganberkelanjutan/id/regulation/detailregulation/3781/penerapan-keuangan-berkelanjutan-bagi-lembaga-jasa-keuangan-emiten-dan-perusahaan-publik>
- Otoritas, J.K., 2017b. Penerbitan dan persyaratan efek bersifat utang berwawasan lingkungan (green bond). Available at: <https://keuanganberkelanjutan.ojk.go.id/keuanganberkelanjutan/Peraturan/View/613/penerbitan-dan-persyaratan-efek-bersifat-utang-berwawasan-lingkungan-green-bond>
- Plathottam, S.J., Rzonca, A., Lakhnori, R. and Iloeje, C.O., 2023. A review of artificial intelligence applications in manufacturing operations. *Journal of Advanced Manufacturing and Processing*, 5(3). [DOI]
- Qian, Y., Liu, J., Shi, L., Forrest, J.Y.L. and Yang, Z., 2023. Can artificial intelligence improve green economic growth? Evidence from China. *Environmental Science and Pollution Research*, 30(6), pp.16418–16437. [DOI]
- Raman, R., Ray, S., Das, D. and Nedungadi, P., 2025. Innovations and barriers in sustainable and green finance for advancing Sustainable Development Goals. *Frontiers in Environmental Science*, 12, 1513204. [DOI]
- Ramli, K., 2023. Policy development to accelerate digital transformation. pp.11–36.
- Ren, L. and Cheng, Y., 2024. The impact and mechanism of ESG performance on corporate continuous innovation: Evidence from China. *Sustainability*, 16(17), 7562. [DOI]
- Rennings, K., 2000. Redefining innovation-eco-innovation research and the contribution from ecological economics. *Ecological Economics*, 32(2), pp.319–332. [DOI]
- Rohayati, Y. and Abdullah, A., 2024. Digital transformation for era Society 5.0 and resilience: Urgent issues from Indonesia. *Societies*, 14(12), 266. [DOI]
- Shang, Y., Raza, S.A., Huo, Z., Shahzad, U. and Zhao, X., 2023. Does enterprise digital transformation contribute to the carbon emission reduction? Micro-level evidence from China. *International Review of Economics & Finance*, 86, pp.1–13. [DOI]
- Song, W., Ren, S. and Yu, J., 2019. Bridging the gap between corporate social responsibility and new green product success: The role of green organizational identity. *Business Strategy and the Environment*, 28(1), pp.88–97. [DOI]
- Song, Y., Xie, Z. and Song, Y., 2025. The impact of digital transformation on carbon emission intensity. *International Review of Economics & Finance*, 102. [DOI]
- Sun, J., Ran, L. and Wang, B., 2025. ESG performance and digital transformation: Evidence from Chinese A-listed companies. *Sustainability*, 17(18), 8517. [DOI]
- Tang, J., Huang, K. and Xiong, A., 2025. Impact of digital transformation on corporate sustainability: Evidence from China's carbon emissions. *Energy Informatics*, 8(1). [DOI]
- United Nations, 2025. Goal 9: Build resilient infrastructure, promote sustainable industrialization and foster innovation. (September 10). Available at: <https://www.un.org/sustainabledevelopment/infrastructure-industrialization/>
- Vial, G., 2019. Understanding digital transformation: A review and a research agenda. *The Journal of Strategic Information Systems*, 28(2), pp.118–144. [DOI]
- Wade, M. and Shan, J., 2020. Covid-19 has accelerated digital transformation, but may have made it harder not easier. *MIS Quarterly Executive*, 19(3), pp.213–220.
- Wang, J., Hong, Z. and Long, H., 2023a. Digital transformation empowers ESG performance in the manufacturing industry: From ESG to DESG. *SAGE Open*, 13(4). [DOI]
- Wang, W., Hu, R., Zhang, C. and Shen, Y., 2023b. Impact of common institutional ownership on enterprise digital transformation—Collaborative governance or collusion fraud? *Heliyon*, 9(11), e21641. [DOI]
- Wang, Y. and Sun, L., 2025. The impact of digital transformation on firm performance - an empirical study based on business administration perspective. *Applied Mathematics and Nonlinear Sciences*, 10(1). [DOI]
- Xu, J., Yu, Y., Zhang, M. and Zhang, J.Z., 2023. Impacts of digital transformation on eco-innovation and sustainable performance: Evidence from Chinese manufacturing companies. *Journal of Cleaner Production*, 393. [DOI]
- Yang, P., Hao, X., Wang, L., Zhang, S. and Yang, L., 2024. Moving toward sustainable development: The influence of digital transformation on corporate ESG performance. *Kybernetes*, 53(2), pp.669–687. [DOI]
- Yavari, A., Mirza, I.B., Bagha, H., Korala, H., Dia, H., Scifleet, P., Sargent, J., Tjung, C. and Shafiei, M., 2023. ArtEMon: Artificial intelligence and Internet of Things powered greenhouse gas sensing for real-time emissions monitoring. *Sensors*, 23(18), 7971. [DOI]
- Yavuz, M.S., Tatli, H.S. and Bozkurt, G., 2025. Exploring the financial

- impact of digital transformation: A comprehensive analysis on firms. *Journal of Innovation and Knowledge*, 10(5). [DOI]
- Yin, F., Xiao, Y., Cao, R. and Zhang, J., 2023. Impacts of ESG disclosure on corporate carbon performance: Empirical evidence from listed companies in heavy pollution industries. *Sustainability*, 15(21), 15296. [DOI]
- Yue, S., Ye, G., Khalid, F. and Wang, T., 2025. From digital transformation to energy efficiency: Ownership concentration's hidden role in driving climate solutions. *Humanities and Social Sciences Communications*, 12(1). [DOI]
- Zhai, H., Yang, M. and Chan, K.C., 2022. Does digital transformation enhance a firm's performance? Evidence from China. *Technology in Society*, 68, 101841. [DOI]
- Zhang, C., Fang, J., Ge, S. and Sun, G., 2024. Research on the impact of enterprise digital transformation on carbon emissions in the manufacturing industry. *International Review of Economics & Finance*, 92, pp.211–227. [DOI]
- Zhang, J., Li, H. and Zhao, H., 2025. The impact of digital transformation on organizational resilience: The role of innovation capability and agile response. *Systems*, 13(2), 75. [DOI]
- Zhang, M. and Huang, Z., 2024. The impact of digital transformation on ESG performance: The role of supply chain resilience. *Sustainability*, 16(17), 7621. [DOI]
- Zhao, Q., Li, X. and Li, S., 2023. Analyzing the relationship between digital transformation strategy and ESG performance in large manufacturing enterprises: The mediating role of green innovation. *Sustainability*, 15(13), 9998. [DOI]
- Zhou, J. and Liu, W., 2024. Carbon reduction effects of digital technology transformation: Evidence from the listed manufacturing firms in China. *Technological Forecasting and Social Change*, 198. [DOI]