The Digital Economy Matters for GTFP: Evidence from Regions in Indonesia

Melisa Octora[1*], Khoirunurrofik[2]

[1,2]*Master in Economic Planning and Development Policy Study Program, Faculty of Economics and Business, Universitas Indonesia; Depok, Indonesia*

*Corresponding Author E-Mail: melisaoctora@gmail.com

ABSTRACT

The advancement of the digital economy has transformed productivity patterns and created opportunities to support sustainable development, with Green Total Factor Productivity (GTFP) serving as a key indicator that incorporates resource efficiency and environmental considerations. This study aims to examine the effect of the digital economy on GTFP. This study used a multi-year panel dataset, where GTFP is measured through the Malmquist–Luenberger Productivity Index with a Slack-Based Measurement Data Envelopment Analysis (SBM-DEA) approach, and the impact of the digital economy is analyzed using a Two-Way Fixed Effect regression model. The findings show that the digital economy has a significant positive effect on GTFP, with stronger impacts in more developed regions. These results indicate that digital economic development can enhance green productivity by improving human capital and supporting environmentally oriented economic activities. Therefore, policies that integrate digital transformation, human development, and environmental regulation are essential to maximize sustainable productivity and strengthen progress toward long-term sustainable development goals.

Keywords: *Digital Economy, Green Productivity, Green Total Factor Productivity, Human Development Index, Sustainable Development Goals.*

Submitted:
December 22, 2025

Revised:
January 18, 2026

Accepted:
February 27, 2026

Published Online:
February 28, 2026

INTRODUCTION

Indonesia has experienced economic growth. However, according to the Yale Center for Environmental Law & Policy, the country ranked 164th out of 180 countries in the 2022 Environmental Performance Index, with a score of 28.2 points. This score reflects an increase of 10.30 points over the past ten years. Based on data from Statistics Indonesia (*Badan Pusat Statistik*/BPS) (2022), Indonesia's GDP per capita rose by IDR 9.47 million, from IDR 31.06 million in 2012 to IDR 40.52 million in 2019. Nevertheless, carbon dioxide (CO_2) emissions also increased by 0.30 metric tons per capita, from 1.90 metric tons in 2012 to 2.20 metric tons in 2019. This condition has prompted Indonesia and other countries to pay closer attention to environmental impacts, as air pollution significantly contributes to social and economic costs and exacerbates global warming (Pirmana et al., 2021; Syuhada et al., 2023). Green Total Factor Productivity (GTFP) has gained attention as a strategy to balance economic growth and environmental protection in sustainable global development. In Indonesia, green development has been a national priority according to the National Medium-Term Development Plan (*Rencana Pembangunan Jangka Menengah Nasional*/RPJMN) 2014–2019. Many regions contribute significantly to economic expansion but also exacerbate pollution and environmental problems, making the study of GTFP essential for achieving sustainable development nationally and globally.

Improving GTFP has been the subject of numerous studies. The digital economy's recent explosive growth has opened up new avenues for promoting green development throughout Indonesia. The digital economy is a contemporary economic paradigm that aims to achieve both economic growth and environmental sustainability by combining

JIAKES

Jurnal Ilmiah Akuntansi Kesatuan
Vol. 14 No. 1, 2026
pp. 327-340
IBI Kesatuan
ISSN 2337 – 7852
E-ISSN 2721 – 3048
DOI: 10.37641/jiakes.v14i1.4851

efficiency and fairness (Youssef, 2022; Liu et al., 2024). During the COVID-19 epidemic, when mobility limitations brought attention to digital dependence, its significance grew. Indonesia accounted for 40% of ASEAN's digital economy, which was valued at USD 194 billion in 2022, according to Kompas (2025). This indicates the sector's considerable potential for expansion.

Empirical studies indicate a relationship between the digital economy and green productivity. The digital economy currently plays a crucial role in driving economic growth while improving environmental sustainability. Lyu et al. (2023) and Lan and Tang (2023) concluded that the digital economy significantly enhances industrial GTFP. Similarly, Kong and Li (2022) and Huang et al. (2023) found that the digital economy positively impacts urban green efficiency. Liao (2023) asserted that the digital economy effectively promotes green economic development by advancing industrial structures and fostering regional innovation output. Meanwhile, Imansyah et al. (2023) reported that the digital economy significantly influences both economic growth and CO_2 emissions in Indonesia.

The impact of the digital economy on the green economy and its role in promoting sustainability remain underexplored at the regional level in Indonesia (Sulisnaningrum et al., 2023). While Chinese studies have examined this within the manufacturing sector, Indonesian research has mainly focused on the Information and Communication Technology sector's effects on economic growth, CO_2 emissions, and income distribution, often neglecting digital infrastructure due to regional disparities. Studies measuring the digital economy by transaction value or business numbers show positive effects on economic growth, but generally overlook environmental impact (Oloyede et al., 2023; Yasmeen et al., 2024).

This study examines the impact of the Digital Economy (DE) on green economic productivity by considering economic growth and environmental factors, including inputs, outputs, and unintended effects of economic activities in Indonesia. The analysis utilizes econometric models applied to district and municipal data from 2012 to 2019. While earlier research has mostly concentrated on the case of China, this study takes a fresh approach by examining the connection between the digital economy and green economic output in the context of Indonesia. This study makes use of Indonesian data with a regional focus. This study offers fresh perspectives on the development and enhancement of sustainable development theory within the framework of the digital economy. This study provides useful resources for advancing the growth of the digital economy in the quest for sustainability by concentrating on the various features of districts and municipalities.

LITERATURE REVIEW & HYPOTHESIS DEVELOPMENT

The Influence of the Digital Economy on Green Total Factor Productivity

The concept of a green economy emphasizes increasing productivity while ensuring environmental protection. Green Total Factor Productivity (GTFP) is a key indicator of high-quality economic growth, supporting green growth models and the transition toward sustainable development (Ahmed, 2012; Li et al., 2022; Hao et al., 2023). Originating from the 1992 Earth Summit and developed in 1994, green productivity promotes a balance between economic growth and environmental preservation (Rusiawan et al., 2015; Adamowicz, 2022; Jabeen & Khan, 2022). When a region achieves efficient GTFP, it demonstrates the potential for green economic growth, highlighting the importance of sustainable development and adaptation to evolving economic dynamics (Lan & Tang, 2023).

Several studies have examined the relationship between the digital economy and green economic productivity. Huang et al. (2023) found positive effects in eastern, central, and northeastern China, particularly in larger cities and regions with stricter environmental regulations. Kong and Li (2022) identified three channels: improving human capital, industrial restructuring, and technological innovation. Liao (2023) emphasized its role in industrial transformation and regional innovation, with impacts varying across regions.

Previous studies on the digital economy and green productivity have primarily focused on China, leaving research in Indonesia relatively limited. This gap provides an opportunity to explore Indonesia's unique regional economic dynamics. Gati (2023) examined the impact of digital infrastructure from 2011 to 2021, showing that Base Transceiver Stations (BTS), mobile phone usage, and internet connectivity positively influenced per capita income. However, the study concentrated on inclusive economic growth and did not address environmental impacts.

H1: The digital economy has a significant positive effect on green total factor productivity in Indonesia

Human Development Index as a Mediating Variable

The concept of the digital economy was first introduced by Tapscott (1996) and later adopted by governments and academics worldwide. It describes a socio-economic system encompassing information, ICT, digital goods and services distribution, and communication capabilities. Measurement of the digital economy often uses Principal Component Analysis (PCA), a statistical method that reduces data dimensions by transforming correlated variables into uncorrelated principal components (Huang et al., 2023). This approach enables researchers to construct comprehensive digital economy indices by combining multiple technological and economic indicators into a single measurable framework. Consequently, PCA improves analytical accuracy and allows for more robust comparisons of digital development across regions and over time.

The digital economy has the potential to impact GTFP by influencing the makeup of human capital. The New Economic Growth Theory states that human capital can boost company productivity, which can increase GTFP, as well as propel technical innovation and the spread of information and creative ideas. Human capital refers to the quality of human resources acquired through education (Lachler & Aschauer, 1998; Rafid, 2023; Sumual et al., 2024). On the other hand, digitalization also expands access to educational resources and promotes innovation across various forms and types of education. This condition enables people to access higher-quality educational resources, thereby contributing to the improvement of human capital (Brabazon, 2002; Bykova et al., 2024; Nwachukwu, 2024; Efendi et al., 2025). One way to measure human capital is through the education sector, as suggested by Todaro (2000). Human capital in education can be assessed using education indices derived from the Human Development Index (HDI) (Guijarro et al., 2022; Grisolia et al., 2022). The quality of human capital in a certain area increases with educational attainment. Because human capital has a major impact on both production and technological efficiency, it is crucial to take it into account when analyzing how the digital economy affects UGTFP.

H2: Human development index mediates the relationship between the digital economy and green total factor productivity in Indonesia by influencing human capital.

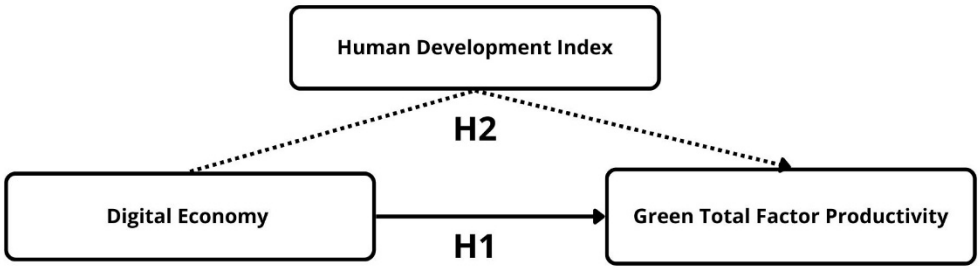

Figure 1. Conceptual Framework

The study's conceptual framework, which suggests that the digital economy directly affects green total factor productivity, is depicted in Figure 1. Furthermore, the Human

Development Index is positioned as an intervening element that enhances the sustainability benefits of digital economic growth by strengthening the relationship between the digital economy and green total factor productivity.

RESEARCH METHODS

This study uses panel data from 458 regencies/municipalities in Indonesia covering the periods 2012–2015 and 2017–2019. The year 2016 is excluded due to missing capital expenditure data, while DKI Jakarta is omitted because it does not report separate regency/municipality-level capital expenditure. Other regencies/municipalities with substantial data gaps are also excluded, and 2020 is omitted to avoid distortions related to the COVID-19 pandemic. To handle missing values transparently, extensive gaps were removed entirely from the sample, while minor gaps (less than 10% per variable across the panel) were addressed using linear interpolation; the proportion of interpolated observations remained below 8% overall, and preliminary checks confirmed that results were qualitatively unchanged when using complete-case analysis alone. Data are sourced from Statistics Indonesia, the Ministry of Finance of the Republic of Indonesia, the National Socio-Economic Survey (*Survei Sosial Ekonomi Nasional*/Susenas), the Village Potential Statistics (*Potensi Desa*/Podes), Mapid, the Ministry of Environment and Forestry (*Kementerian Lingkungan Hidup dan Kehutanan*/KLHK), the Ministry of Public Works and Housing (*Kementerian Pekerjaan Umum dan Perumahan Rakyat*/KemenpuPR), and the Investment Coordinating Board (*Badan Koordinasi Penanaman Modal*/BKPM).

The Malmquist–Luenberger Productivity Index (MLPI), combined with Slack-Based Measurement Data Envelopment Analysis (SBM-DEA), is employed to calculate Green Total Factor Productivity (GTFP). Following Chung (1997), the MLPI quantifies productivity change while incorporating undesirable outputs through a directional distance function with the vector g = (0, y, -b), thereby capturing movements toward the global frontier that simultaneously increase desirable outputs and reduce undesirable outputs under constant inputs. To mitigate the well-documented risk of linear programming infeasibility in conventional cross-period MLPI calculations, particularly when technology frontiers shift or undesirable outputs change proportionally, this study integrates undesirable outputs directly within the non-oriented SBM-DEA framework (Tone, 2015), which avoids infeasibility issues more robustly than radial models and ensures consistent intertemporal comparability across the panel. The SBM-DEA model is specified as follows:

$$\rho^k = \min\left(\frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{\bar{s_i}}{z_{io}}}{1+\frac{1}{s1+s2}\left(\sum_{r=1}^{s1}\frac{s_r^g}{y_{g,ro}}+\sum_{r=1}^{s2}\frac{s_r^b}{y_{b,ro}}\right)}\right) \quad (1)$$

Subject to:

$$x_0 = X\lambda + s^- \quad (2)$$

$$y_o^g = Y^g\lambda - s^g \quad (3)$$

$$y_o^b = Y^b\lambda - s^b \quad (4)$$

$$s^- \geq 0, s^g \geq 0,\ s^b \geq 0, \lambda\, 0 \quad (5)$$

Where $x_o, y_o^b,$ and y_o^b represent the target values of inputs and outputs. Meanwhile, $X\lambda, Y^g\lambda,$ and $Y^b\lambda$ denote the initial values of inputs and outputs. The slack variables s^-, s^g, s^b represent input excess, undesirable output excess, and insufficient desirable output, respectively.

In measuring GTFP, this study adopts NO_2 concentration per capita as the sole undesirable output, primarily due to the consistent availability of granular, regency/municipality-level data from Mapid and KLHK throughout the study period, unlike CO_2 emissions or $PM_{2.5}$, which are frequently available only at provincial or national aggregates or through less reliable disaggregation methods for subnational units

in Indonesia. Input variables include labor (employed population from BPS), capital expenditure (realized local government capital expenditure in million IDR from BPS and Ministry of Finance), and electricity consumption per capita (from Susenas). The desirable output is real GRDP at constant prices (from BPS). Although a single undesirable output limits the comprehensiveness of environmental cost representation, NO_2 serves as a relevant proxy for air pollution externalities in the Indonesian context, particularly in urban and industrial areas where traffic and combustion sources dominate; future extensions could incorporate multiple pollutants when finer-grained subnational data become available. The digital economy index (DG or ED) is constructed using Principal Component Analysis (PCA) on three sub-indicators: the number of internet users, the number of computer owners, and the number of Base Transceiver Station (BTS) units per regency/municipality (Gati, 2023; Huang et al., 2023; Lyu et al., 2023; Johnson & Wichern, 2002). The Human Development Index (HDI) acts as the mediating variable, while control variables include transportation infrastructure (total road length in good condition per population from KemenpuPR), the Air Quality Index (IKU from KLHK), real GRDP per capita, and realized FDI in million IDR (from BKPM).

The empirical analysis applies the Two-Way Fixed Effects regression model to estimate the direct effect of the digital economy on GTFP, specified as:

$$GTFP_{it} = \alpha_0 + \beta_1 ED_{it} + \beta_2 X_{it} + \mu_t + \lambda_i + \varepsilon_{it} \quad (6)$$

Furthermore, to analyze the effect of the digital economy on GTFP with the mediation of the Human Development Index, a mediation effect estimation will be added as follows:

$$IPM_{it} = \alpha_0 + \beta_1 ED_{it} + \beta_2 X_{it} + \mu_t + \lambda_i + \varepsilon_{it} \quad (7)$$
$$GTFP_{it} = \alpha_0 + \beta_1 ED_{it} + \beta_2 IPM_{it} + \beta_3 X_{it} + \mu_t + \lambda_i + \varepsilon_{it} \quad (9)$$

Subsequently, the empirical specification is extended by estimating the effects of each sub-indicator of the digital economy variable.

$$GTFP_{it} = \alpha_0 + \beta_1 Int_{it} + \beta_2 Komp_{it} + \beta_2 BTS_{it} + \beta_2 X_{it} + \mu_t + \lambda_i + \varepsilon_{it} \quad (10)$$

In all specifications, GTFP is the dependent variable, ED (or its sub-components: Int, Comp, BTS) is the key independent variable, X represents control variables, λ t and λ i capture time and regional (province-level) fixed effects to control for unobserved heterogeneity, and ε is the error term.

RESULTS

It is possible to draw the conclusion that both the digital economy and green productivity in Indonesia were on the rise between 2012 and 2019, based on an analysis of both. These two aspects appear to be mutually reinforcing, where improvements in digital infrastructure and access contributed to the enhancement of green productivity across regions. However, despite this positive trend, a decline in green productivity occurred in 2019. This downturn may be attributed to several factors, such as challenges in adopting environmentally friendly technologies, economic constraints, or policy fluctuations.

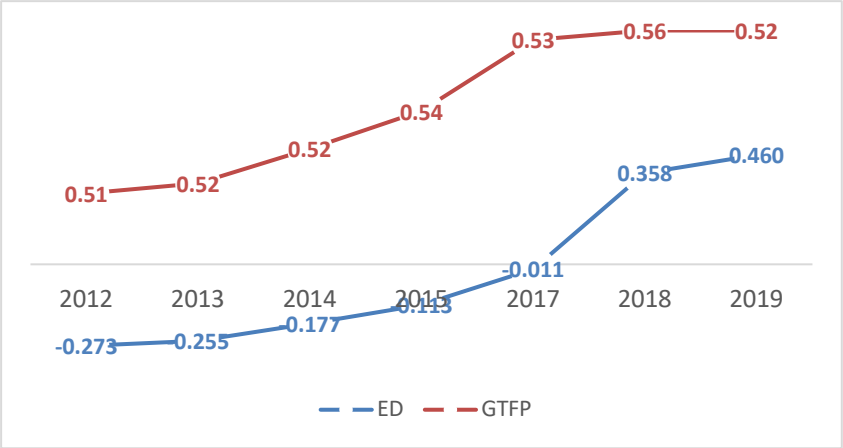

Figure 2. Trend of Digital Economy and Green Productivity from 2012 to 2019

Based on Figure 2, GTFP, represented by the orange line, shows a consistent upward trend. Starting from an average productivity value of 0.51 in 2012, GTFP increased steadily, reaching its peak at 0.56 in 2018, although it experienced a slight decline to 0.52 in 2019. This trend reflects a positive development in green productivity throughout the analysis period. Meanwhile, the blue line, which represents the digital economy, began with an average value of -0.273 in 2012. Although it remained negative until 2016, the Digital Economy Index (DE) increased significantly, turning positive at 0.358 in 2018 and further rising to 0.460 in 2019.

The graph illustrates that while GTFP continued to show positive growth, the digital economy also advanced, shifting from a negative to a positive trend. This indicates the potential for the digital economy to increasingly contribute to green productivity. A linear relationship between the digital economy and GTFP has been observed (Liao, 2023). Therefore, the development of the digital economy can promote green productivity. A more holistic and sustainable approach is needed to integrate digital technologies with environmental sustainability initiatives to maintain green productivity in the future.

An analysis of green productivity across various regions in Indonesia from 2012 to 2019 reveals significant disparities in regional performance. The Java region recorded relatively stable growth during this period, reflecting consistent efforts in the implementation of sustainable practices. In contrast, the Sulawesi region exhibited year-to-year fluctuations, indicating ongoing challenges in achieving green productivity. Meanwhile, the regions of Sumatra, Kalimantan, as well as Nusa Tenggara, Papua, and West Papua experienced a decline in green productivity in 2019. These findings highlight the need for greater policy attention and targeted initiatives to support the growth of green productivity in these areas.

Figure 3 illustrates changes in Green Total Factor Productivity (GTFP) across regions and time periods (left panel) and the proportion of input slack capital expenditure, electricity consumption, labor, and NO_2 per capita that contributes to inefficiency in each region (right panel). Green productivity in each region, which fluctuated between 2012 and 2019, can be enhanced by addressing the slack in each input variable. An analysis of the average slack across regencies and municipalities shows that Kalimantan exhibits the highest slack, indicating unutilized potential that has not been productively optimized. This is followed by Java, Sumatra, Sulawesi, and finally the regions of Nusa Tenggara, Papua, and West Papua, highlighting regional disparities in green productivity efficiency.

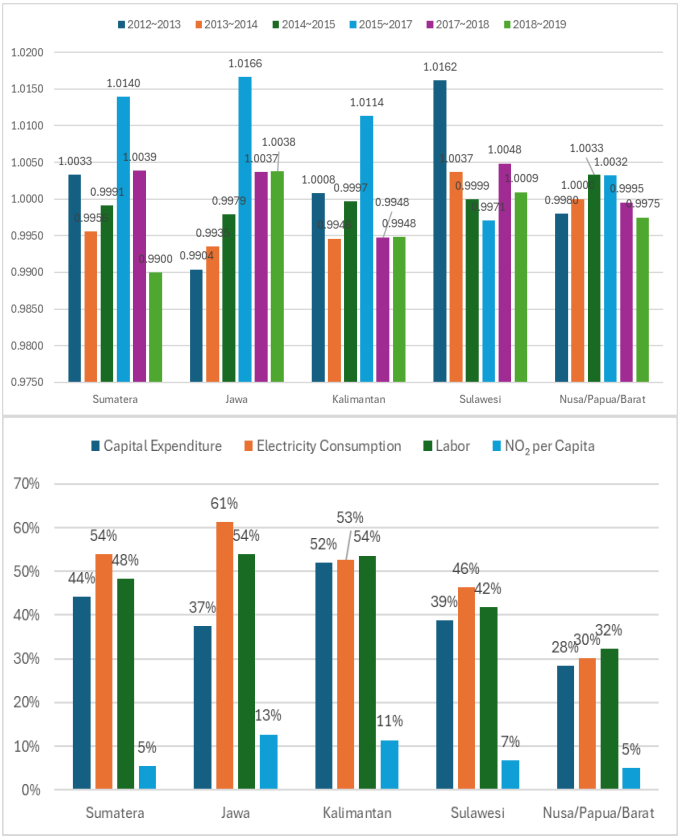

Figure 3. Green Productivity Trends and Input Slack Composition by Region in Indonesia (2012–2019)

Table 1 displays the baseline regression results of DG's impact on GTFP. The regression results without any control variables are displayed in the first column. Using a two-way fixed effects model that concurrently accounts for time and geographical fixed effects, columns two through five show the regression findings with control variables introduced one at a time. Each empirical result demonstrates how the model reliably captures the impacts under various setting.

Table 1. Estimation Results of the Effect of the Digital Economy on GTFP in Indonesia from 2012 - 2019

Variable	**GTFP (1)**	**(2)**	**(3)**	**(4)**	**(5)**
Digital Economy	0.0247***	0.0231***	0.0200***	0.0153**	0.0153**
	(0.00617)	(0.00650)	(0.00655)	(0.00700)	(0.00700)
Trans		0.00441***	0.00381***	0.00374***	0.00377***
		(0.00136)	(0.00137)	(0.00137)	(0.00137)
IKU			0.00173***	0.00175***	0.00175***
			(0.000499)	(0.000499)	(0.000499)
GDRP				2.62e-11*	2.62e-11*
				(1.38e-11)	(1.38e-11)
FDI					-9.40e-12
					(1.09e-11)
Time FE	Yes	Yes	Yes	Yes	Yes
Prov FE	Yes	Yes	Yes	Yes	Yes
_cons	0.516***	0.551***	0.403***	0.394***	0.394***
	(0.00559)	(0.0121)	(0.0442)	(0.0445)	(0.0445)
N	3206	3176	3176	3176	3176
R2_w	0.0264	0.0314	0.0357	0.0370	0.0372
Standard errors in parentheses					
* p<0.10, ** p<0.05, *** p<0.01					

According to Table 1, estimation results, the digital economy has a statistically significant and positive impact at the 5% significance level ($\alpha = 0.05$). This demonstrates

that Indonesia's GTFP has improved as a result of the digital economy. These findings are consistent with studies by (Lan & Tang, 2023; Lyu et al., 2023), which suggests that the digital economy can reduce transaction search and friction costs, thereby enhancing GTFP. Knowledge and technology are shared through data processing, effectively eliminating information barriers among communities (Connelly et al., 2011). The digital economy offers several substantial benefits in enhancing GTFP, particularly in supporting sustainable development. With the convenience brought by digital transactions such as e-commerce and online payments, economic activities become more efficient and resource-saving. Moreover, the advancement of digital technologies opens up opportunities for innovations that promote energy conservation and emissions reduction (Lee et al., 2023). More ecologically friendly manufacturing and consumption methods, such as the utilization of renewable energy combined with smart technologies, are made possible by digital technology.

The regression results show that several control variables have a significant impact on GTFP. First, a 1% increase in road length per capita leads to an increase in GTFP by 0.0000441 points. Sustainable transportation infrastructure supports green economic growth by reducing environmental impacts, improving logistics efficiency, and enhancing quality of life. This finding is consistent with Cheng et al. (2023), who argue that improvements in transportation infrastructure positively and significantly affect GTFP by reducing transportation and production factor transaction costs, and by accelerating the diffusion of knowledge and technology. Additionally, Pratama and Khoirunurrofik (2023) find that road infrastructure improvements significantly lower transportation costs for firms, enabling more efficient allocation of resources and ultimately increasing labor productivity. Infrastructure also creates opportunities to modernize the growth of the agricultural sector, improve the quality of life for communities, and support diverse rural development, thereby contributing to the achievement of all Sustainable Development Goals (SDGs) (Prus & Sikora, 2021). Transportation infrastructure facilitates the movement of production factors across regions and reduces transport costs in green development (Lian et al., 2019).

Second, the Air Quality Index (AQI) has a positive and significant effect, with a coefficient ranging from 0.00173 to 0.00175. The digital economy contributes technically to regulatory enforcement by establishing environmental monitoring systems, strengthening the targeted tracking of highly polluting industries and enterprises through the collection and integration of real-time, efficient, and open environmental monitoring data (Lan & Tang, 2023). With government intervention, regions can effectively allocate resources to green transformation and clean energy sectors, thus improving the efficiency of resource allocation. Third, GRDP per capita shows a positive, although small, effect on GTFP. This result aligns with the findings of Lian et al. (2024), which confirm a significant positive relationship. Although the impact is relatively modest, it suggests that regional economic growth still contributes to green economic efficiency, even if the effect is not large in scale. Fourth, Foreign Direct Investment (FDI) does not show a significant effect on GTFP, indicating the presence of structural barriers or other factors that affect the effectiveness of such investments. This finding is consistent with Lian et al. (2019), who note that FDI may have a negative impact, as increased investment could potentially lead to higher pollution levels.

According to Table 2 estimation results, the digital economy's regression coefficient on the HDI is 0.0585, and its regression coefficient on GTFP is 0.0141, both of which are statistically significant at the 5% level. This shows that GTFP increases by 0.00209 points for every point rise in HDI. This improvement highlights the importance of education quality, health, and income in enhancing green productivity. In the digital era, education systems increasingly focus on developing complex and practical professional skills. Digital education also plays a vital role in equalizing access to learning, enabling lifelong education through technologies such as online learning, artificial intelligence, and real-time translation (Kong & Li, 2022). These technologies expand public access to diverse knowledge sources, improve workforce skills, and optimize human resource allocation.

With a more skilled labor force, the adoption of clean and environmentally friendly technologies becomes more feasible, helping firms conserve energy and reduce pollution. Moreover, a high-quality workforce contributes to fostering environmental awareness and values within society, encouraging a balance between economic development and environmental protection, and enhancing green economic efficiency.

Table 2. Estimation of the Mediating Effect

Variable	HDI	GTFP
Digital Economy	0.0585***	0.0141**
	(0.0212)	(0.00700)
HDI		0.00209***
		(0.00632)
Trans	0.0113***	0.00353***
	(0.00416)	(0.00137)
IKU	-0.00581***	0.00187***
	(0.00151)	(0.000499)
GDRP	4.42e-11	2.53e-11*
	(4.18e-11)	(1.38e-11)
FDI	2.50e-11	-9.92e-12
	(3.29e-11)	(1.08e-11)
Time FE	Yes	Yes
Prov FE	Yes	Yes
_cons	66.69***	-0.999**
	(0.135)	(0.424)
N	3176	3176
R2_w	0.955	0.0411
Standard errors in parentheses		
* p<0.10, ** p<0.05, *** p<0.01		

The study then calculates and contrasts how each element of the digital economy affects GTFP. The number of internet users, computer users, and BTS infrastructure are among the elements examined. It is possible to determine which digital economy component has the biggest influence on GTFP in Indonesia based on the estimation results shown in Table 2. This offers a more thorough comprehension of how each element contributes to green productivity.

Table 3. Estimation of the Effect of Digital Economy Sub-Indicator on GTFP from 2012 to 2019

Variable	GTFP (1)	(2)	(3)
Int	4.82e-08*		
	(2.59e-08)		
Comp		2.72e-08	
		(9.81e-08)	
BTS			0.000100* *
			(0.0000495)
Trans	0.00373***	0.00389***	0.00340**
	(0.00136)	(0.00136)	(0.00138)
HDI	0.0211***	0.0214***	0.0211***
	(0.00632)	(0.00635)	(0.00632)
IKU	0.00183***	0.00199***	0.00195***
	(0.000503)	(0.000498)	(0.000495)
GRDP	2.50e-11*	3.36e-11**	2.97e-11**
	(1.40e-11)	(1.39e-11)	(1.31e-11)
FDI	-9.80e-12	-9.94e-12	-1.00e-11
	(1.08e-11)	(1.09e-11)	(1.08e-11)
Time FE	Yes	Yes	Yes
_cons	-1.016**	-1.046**	-1.033**
	(0.424)	(0.425)	(0.423)
N	3176	3176	3176
r2_w	0.0409	0.0397	0.0411
Standard errors in parentheses			
* p<0.10, ** p<0.05, *** p<0.01			

According to the analytical results shown in Table 3, GTFP in Indonesia is positively and statistically significantly impacted by the number of internet users and BTS infrastructure, at the 1% and 5% significance levels, respectively. These findings indicate that improved internet access and the development of telecommunication infrastructure play an important role in supporting green productivity growth. A stronger BTS infrastructure enhances digital connectivity, while the increasing number of internet users reflects broader access to information and technology. Together, these factors contribute to productivity and innovation across various sectors, ultimately promoting sustainable economic growth in Indonesia. Regions that are more advanced in terms of digital infrastructure development are better positioned to benefit from the digital dividend, thereby contributing more significantly to green growth in their respective areas (Ren et al., 2023).

On the other hand, the number of computer users does not show a significant impact on GTFP in Indonesia. Although computer usage may support digital economic activities to some extent, its contribution to green productivity remains limited. This suggests that computer use alone is insufficient to drive sustainable productivity and innovation without broader digital infrastructure support, such as internet access and BTS coverage. Therefore, greater investment in digital technology, particularly in enhancing internet connectivity and BTS infrastructure, has a stronger impact in accelerating the transition toward a sustainable green economy in Indonesia.

Table 4. Estimation of the Impact of Sub-indicators DE on GTEP by Region, 2012-2019

	Sumatera			Jawa, Bali			Kalimantan			Sulawesi			Nusa, Papua, Papua Barat		
Int	-4.83e-08			0.000000179***			-0.000000487**			-0.000000241			-0.000000849***		
	(7.97e-08)			(3.20e-08)			(0.000000186)			(0.000000196)			(0.000000284)		
Comp		-0.000000402			0.000000377***			-0.00000173**			-0.00000131***			-0.00000157*	
		(0.000000279)			(0.000000112)			(0.000000536)			(0.000000491)			(0.000000878)	
BTS			0.000240**			0.000230***			0.000107			-0.000258			-0.000329
			(0.0000977)			(0.0000703)			(0.000180)			(0.000239)			(0.000297)
HDI	0.0279***	0.0296***	0.0246**	0.0237**	0.0229*	0.0254*	0.00721	0.0145	0.0129	0.0616***	0.0665***	0.0622***	-0.00498	-0.00512	-0.00472
	(0.0107)	(0.0108)	(0.0109)	(0.0129)	(0.0132)	(0.0131)	(0.0138)	(0.0136)	(0.0138)	(0.0177)	(0.0176)	(0.0177)	(0.0182)	(0.0184)	(0.0186)
IKU	0.00457***	0.00459***		0.000876	0.00172	0.00181	0.00261	0.00196	0.00209	0.00162	0.000738	0.00167	-0.000713	0.0000349	-0.000163
	(0.000754)	(0.000749)		(0.00111)	(0.00111)	(0.00111)	(0.00189)	(0.00187)	(0.00190)	(0.00175)	(0.00178)	(0.00175)	(0.00215)	(0.00217)	(0.00217)
GDRP	1.37e-09	1.18e-09	-8.34e-10	6.65e-12**	1.97e-11	2.60e-11*	1.67e-09*	1.94e-09*	1.76e-09*	1.90e-09***	1.84e-09***	1.89e-09***	2.45e-09***	2.29e-09**	2.26e-09**
	(1.31e-09)	(1.29e-09)	(1.28e-09)	(1.41e-11)	(1.41e-11)	(1.36e-11)	(8.32e-10)	(8.28e-10)	(8.41e-10)	(5.15e-10)	(5.11e-10)	(5.15e-10)	(9.21e-10)	(9.26e-10)	(9.28e-10)
PMA	1.89e-09	1.57e-09	2.91e-09	2.92e-09	2.55e-09	2.70e-09	1.00e-09	1.89e-09	1.46e-09	-7.61e-12	-6.23e-12	-7.46e-12	3.39e-09	4.97e-09	4.09e-09
	(4.41e-09)	(4.41e-09)	(4.48e-09)	(1.83e-09)	(1.86e-09)	(1.86e-09)	(4.87e-09)	(4.84e-09)	(4.92e-09)	(1.05e-11)	(1.05e-11)	(1.05e-11)	(5.22e-09)	(5.25e-09)	(5.27e-09)
Trans	-0.000445	-0.000388	0.00117				0.00173	0.00292	0.000560	0.00413	0.00509	0.00422	0.00284	0.000841	0.000909
	(0.00213)	(0.00210)	(0.00217)				(0.00291)	(0.00294)	(0.00300)	(0.00358)	(0.00357)	(0.00360)	(0.00514)	(0.00511)	(0.00520)
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
cons	-1.787**	-1.877**	-1.115	-1.306*	-1.354	-1.497*	-0.307	-0.663	-0.675	-3.625**	-3.815***	-3.669***	1.046	1.006	0.964
	(0.725)	(0.727)	(0.729)	(0.895)	(0.909)	(0.906)	(0.928)	(0.913)	(0.931)	(1.188)	(1.180)	(1.188)	(1.187)	(1.199)	(1.211)
N	1036	1036	1036	847	847	847	350	350	350	504	504	504	463	463	463
r2_w	0.125	0.126	0.0940	0.118	0.0940	0.0932	0.154	0.164	0.135	0.110	0.122	0.109	0.0764	0.0627	0.0579
Standard errors in parentheses															
* p<0.10, ** p<0.05, *** p<0.01															

The influence of the digital economy on GTFP in several Indonesian regions was estimated and compared as part of the investigation. The principal islands of Sumatra, Java, and Bali, Kalimantan, Sulawesi, and Nusa Tenggara/Maluku/North Maluku/Papua/West Papua were used to classify the areas. The estimation results displayed in Table 4 demonstrate that the influence is not uniformly spread throughout Indonesia, since the contribution of digital economy components to GTFP differs among areas. This analysis emphasizes regional variations in the digital economy's contribution, especially with regard to green production.

DISCUSSION

This study reveals that the digital economy impacts Green Total Factor Productivity (GTFP) differently across Indonesian regions, emphasizing the role of regional characteristics, infrastructure, and human capital. In Sumatra, BTS infrastructure expansion positively affects GTFP by enhancing connectivity and economic efficiency, while internet and computer usage show no significant effect, indicating that access alone

is insufficient. HDI positively influences GTFP, highlighting the role of education, health, and welfare in leveraging digitalization for sustainable growth. These findings align with Gati (2023) and Huang et al. (2023), suggesting that policymakers should promote infrastructure, digital literacy, and environmentally conscious technology adoption.

In Java and Bali, all digital economy indicators, including internet users, computer users, and BTS infrastructure, significantly enhance GTFP. Coefficients indicate that high levels of technological penetration, supported by robust HDI scores, contribute to regional green productivity growth. These results reflect findings from Kong and Li (2022) and Lyu et al. (2023), who reported that mature human capital and technological infrastructure in Chinese provinces significantly improved green total factor productivity. Java's well-established digital ecosystem and local government support further reinforce the adoption of green technologies, driving innovation across agriculture, industry, and services. This suggests that regions with integrated digital infrastructure, capable human resources, and supportive policies can effectively translate digitalization into sustainable economic productivity.

In contrast, Kalimantan demonstrates the negative effects of internet and computer usage on GTFP, while HDI does not show a significant impact. This indicates that increased access to digital technologies does not necessarily translate into productive or environmentally sustainable activities, consistent with Brabazon (2002), who warned that digital access alone does not guarantee productive outcomes. High potential for environmental degradation, logistical challenges, and limited public awareness of sustainability further constrain the region's ability to benefit from digitalization. Similarly, Sulawesi shows that computer use negatively affects GTFP, while other digital indicators are insignificant. These findings suggest that uneven infrastructure distribution, digital skill gaps, and low technological absorption hinder the effectiveness of the digital economy in promoting green productivity, echoing observations by Sulisnaningrum et al. (2023) regarding Southeast Asia.

The eastern regions of Indonesia, including Nusa Tenggara, Papua, and West Papua, also experience negative effects of internet usage and BTS infrastructure on GTFP. Limited digital infrastructure, low digital literacy, complex geography, and minimal investment restrict the potential for digital technologies to enhance productivity and environmental efficiency. Statistics Indonesia data indicate persistently low Information and Communication Technology Development Index scores in these regions (2017–2019), underscoring the urgent need for targeted digital capacity building. These outcomes mirror findings in Kalimantan, suggesting that in resource-based and geographically challenged regions, infrastructure alone is insufficient without complementary human capital and policy interventions (Ahmed, 2012; Lan & Tang, 2023).

The study highlights the heterogeneous effects of the digital economy across Indonesian regions, emphasizing the need for tailored policy approaches. In non-resource-based regions with strong economic activity, such as Java and Sumatra, policies should focus on enhancing digital infrastructure, attracting skilled digital labor, and promoting green technology adoption to sustain GTFP growth. Conversely, in resource-dependent regions, particularly in Eastern Indonesia, strategies should reduce reliance on natural resources, improve digital literacy, and integrate smart technologies into production models to support sustainable practices (Lyu et al., 2023; Liu et al., 2024). The findings reinforce prior research showing that digital economy development alone does not guarantee green productivity gains; benefits are mediated by human capital, institutional support, and environmental awareness (Huang et al., 2023; Lee et al., 2023). Overall, effective policy must consider regional disparities in infrastructure, human capital, and environmental conditions, integrating digital expansion with sustainable development goals to maximize green economic growth across Indonesia (Imansyah et al., 2023; Ren et al., 2023).

CONCLUSION

This study demonstrates that the digital economy significantly influences GTFP in Indonesia between 2012 and 2019, both directly and indirectly through improvements in the HDI. Nationally, internet usage and BTS infrastructure positively enhance GTFP, while computer usage shows no significant effect. Regional analyses reveal substantial heterogeneity: Java and Bali benefit from all digital economy components, whereas Sumatra shows gains mainly from BTS infrastructure and HDI, and regions such as Kalimantan, Sulawesi, and Eastern Indonesia face limited or negative effects due to uneven infrastructure, low human capital, and low digital literacy. Control variables, including per capita income, Air Quality Index, and road infrastructure per capita, positively affect GTFP, while foreign direct investment demonstrates negligible or negative impacts. These findings underscore that digitalization alone is insufficient; the effectiveness of the digital economy in promoting green productivity depends on complementary factors such as human capital, environmental awareness, and supportive policies.

The study's implications highlight the importance of integrating digital infrastructure expansion with human resource development and environmental regulation. Policymakers should focus on enhancing telecommunications in underdeveloped and frontier regions, promoting digital literacy, and adopting smart and green technologies, while resource-dependent regions require stronger environmental governance and incentives for sustainable practices. Limitations include the measurement of GTFP based solely on NO_2 emissions, suggesting the need for future research incorporating additional indicators, such as CO_2 emissions from manufacturing, for a more comprehensive assessment. This study provides empirical evidence of how digitalization, human development, and environmental management interact to influence green productivity, informing policies to maximize the digital economy's role in sustainable growth across Indonesia.

FUNDING STATEMENT: This research did not receive any specific grant from funding agencies in the public, commercial, or not - for - profit sectors.

CONFLICTS OF INTEREST: The author declares no conflict of interest.

DECLARATION OF GENERATIVE AI STATEMENT: During the preparation of this work, the author used Turnitin, Grammarly, and ChatGPT to improve sentence structure and overall clarity. All content was then reviewed, edited, and refined by the author, who takes full responsibility for the accuracy, integrity, and originality of the final publication.

REFERENCES

[1] Adamowicz, M. (2022). Green deal, green growth, and green economy as a means of support for attaining the sustainable development goals. *Sustainability*, *14*(10), 59-61.

[2] Ahmed, E. M. (2012). Green TFP intensity impact on sustainable East Asian productivity growth. *Economic Analysis & Policy*, *42*(1), 66-75.

[3] Brabazon, T. (2002). *Digital hemlock: Internet education and the poisoning of teaching*. Sydney: UNSW Press.

[4] BPS. (2022). *Ekonomi Indonesia 2019 tumbuh 5,02 persen.* Retrieved on June, 15, 2025, from https://www.bps.go.id/id/pressrelease/2020/02/05/1755/ekonomi-indonesia-2019-tumbuh-5-02-persen.html

[5] Bykova, V., Khasanova, M., & Polonkoeva, F. (2024). The role of human capital in economic development: an analysis of factors contributing to economic growth. *Reliability: Theory & Applications*, *19*(81), 1676-1682.

[6] Cheng, Z., Li, X., Zhu, Y., & Wang, M. (2023). The effects of agglomeration externalities on urban green total-factor productivity in China. *Economic Systems*, *47*(2), 101-125.

[7] Connelly, B. L., Certo, S. T., Ireland, R. D., & Reutzel, C. R. (2011). Signaling theory: A review and assessment. *Journal of Management*, *37*(1), 39–67.
[8] Efendi, B., Nasution, D. P., Rusiadi, R., & Pratiwi, D. (2025). The impact human development index and industrial labor on economic growth in North Sumatra Province. *Jurnal Ilmiah Akuntansi Kesatuan*, *13*(3), 643-654.
[9] Gati, S. A. (2023). The effect of telecommunications infrastructure on inclusive economic growth in Indonesia 2011− 2021. *International Journal of Innovative Technologies in Social Science*, *2*(5), 38-49.
[10] Grisolia, G., Lucia, U., & Torchio, M. F. (2022). Sustainable development and workers ability: considerations on the education index in the human development index. *Sustainability*, *14*(14), 83-92.
[11] Hao, X., Wang, X., Wu, H., & Hao, Y. (2023). Path to sustainable development: Does digital economy matter in manufacturing green total factor productivity?. *Sustainable Development*, *31*(1), 360-378.
[12] Huang, L., Zhang, H., Si, H., & Wang, H. (2023). Can the digital economy promote urban green economic efficiency? Evidence from 273 cities in China. *Ecological Indicators*, *155*(4), 110-127.
[13] Imansyah, M. H., Hartono, D., Putranti, T., & Muzdalifah, M. (2023). The impacts of digital economy on green economy: The indonesian miyazawa model. *Polish Journal of Environmental Studies*, *32*(2), 1609-1619.
[14] Jabeen, A., & Khan, S. A. (2022). Economic growth, social inclusion, and environmental protection: assessing the existence of green growth in Pakistan. *Environmental Science and Pollution Research*, *29*(44), 66675-66688.
[15] Johnson, R. A., & Wichern, D. W. (2002). *Applied multivariate statistical analysis*. New Jersey: Pearson.
[16] Kompas. (2025). Indonesia Diproyeksi Sumbang 40 Persen Pertumbuhan Ekonomi Digital di ASEAN Tahun 2030. Retrieved on December 15, 2025, from https://nasional.kompas.com/read/2025/10/17/19283661/indonesia-diproyeksi-sumbang-40-persen-pertumbuhan-ekonomi-digital-di-asean.
[17] Kong, L., & Li, J. (2022). Digital economy development and green economic efficiency: Evidence from province-level empirical data in China. *Sustainability*, *15*(1), 3-13.
[18] Lachler, U., & Aschauer, D. A. (1998). *Public investment and economic growth in Mexico*. New York: The World Bank.
[19] Lan, Q., & Tang, W. (2023). Research on the impact of digital economy on industrial green total factor productivity analysis based on Chinese provinces. *Economic Research-Ekonomska Istraživanja*, *36*(3), 114-127.
[20] Lee, C.-C., He, Z.-W., & Yuan, Z. (2023). A pathway to sustainable development: Digitization and green productivity. *Energy Economics*, *124*(5), 106-112.
[21] Li, J., Chen, L., Chen, Y., & He, J. (2022). Digital economy, technological innovation, and green economic efficiency, Empirical evidence from 277 cities in China. *Managerial and Decision Economics*, *43*(3), 616–629.
[22] Liao, W. (2023). How does the digital economy affect the development of the green economy? Evidence from Chinese cities. *PloS One*, *18*(8), 898-906.
[23] Liu, L., Pang, Y., & Liu, B. (2024). Research on the impact and mechanism of digital economy on China's urban green total factor productivity. *Scientific Reports*, *14*(1), 227-256.
[24] Liu, Y., Dong, F., Yu, J., & Liu, A. (2024). Examining the impact of digital economy on environmental sustainability in China: Insights into carbon emissions and green growth. *Journal of the Knowledge Economy*, *15*(4), 18044-18080.
[25] Lyu, Y., Wang, W., Wu, Y., & Zhang, J. (2023). How does digital economy affect green total factor productivity? Evidence from China. *Science of the Total Environment*, *857*(12) 159-178.
[26] Youssef, A. M. A. R. (2022). The role of the digital economy in sustainable development. *International Journal of Humanities and Language Research*, 5(2), 13–25.
[27] Nwachukwu, G. O. (2024). Human capital development: A driver for educational improvement in Nigeria. *British journal of education*, *12*(6), 30-39
[28] Oloyede, A. A., Faruk, N., Noma, N., Tebepah, E., & Nwaulune, A. K. (2023). Measuring the impact of the digital economy in developing countries: A systematic review and meta-analysis. *Heliyon*, *9*(7), 78-88.
[29] Pirmana, V., Alisjahbana, A. S., Yusuf, A. A., Hoekstra, R., & Tukker, A. (2021). Environmental costs assessment for improved environmental-economic account for Indonesia. *Journal of Cleaner Production*, *280*(12), 124-131.
[30] Pratama, D., & Khoirunurrofik, K. (2023). Peran infrastruktur transportasi terhadap produktivitas tenaga kerja industri manufaktur di Indonesia. *Jurnal Ekonomi Dan Pembangunan*, *31*(1), 123-133.
[31] Prus, P., & Sikora, M. (2021). The impact of transport infrastructure on the sustainable development of the region, Case study. *Agriculture*, *11*(4), 279-289.
[32] Rafid, M. (2023). Relationship analysis and concept of human capital theory and education. *EDUCATUM: Scientific Journal of Education*, *1*(1), 26-31.
[33] Ren, Y., Tian, Z., & Liu, C. (2023). Impact of the digital economy on urban green growth: Empirical evidence from China. *Plos One*, *18*(12), 296-312.

[34] Rusiawan, W., Tjiptoherijanto, P., Suganda, E., & Darmajanti, L. (2015). Assessment of green total factor productivity impact on sustainable Indonesia productivity growth. *Procedia Environmental Sciences*, *28*(3), 493–501.

[35] Sulisnaningrum, E., Mutmainah, S., Bawono, S., & Drean, B. (2023). Investigating the impact of ICT developments on the environment in the digital economy and green economy in Southeast Asia. *International Journal of Professional Business Review*, *8*(5), 10-19.

[36] Sumual, T., Lumapow, H., & Rotty, V. (2024). The role of human capital investment in improving the quality of human resources (hr) in education in the digital era. *Asian Journal of Engineering, Social and Health*, *3*(11), 2520-2528.

[37] Syuhada, G., Akbar, A., Hardiawan, D., Pun, V., Darmawan, A., Heryati, S. H. A., ... & Mehta, S. (2023). Impacts of air pollution on health and cost of illness in Jakarta, Indonesia. *International Journal of Environmental Research and Public Health*, *20*(4), 29-36.

[38] Tapscott, D. (1996). Six themes for new learning from: the digital economy: promise and peril in the age of networked intelligence. *Educom Review*, *31*(5), 52–54.

[39] Todaro, M. P. (2000). Migration and Development. *Population and Development Review*, *26*(3), 611-622.

[40] Tone, K. (2015). Dealing with undesirable outputs in DEA: A slacks-based measure (SBM) approach. *GRIPS Discussion Papers*, *1*(7), 154-166.

[41] Tsai, W.-H., Lee, H.-L., Yang, C.-H., & Huang, C.-C. (2016). Input-output analysis for sustainability by using DEA method: A comparison study between European and Asian countries. *Sustainability*, *8*(12), 12-30.

[42] Xu, K., Bossink, B., & Chen, Q. (2019). Efficiency evaluation of regional sustainable innovation in China: A slack-based measure (SBM) model with undesirable outputs. *Sustainability*, *12*(1), 31-44.

[43] Yasmeen, R., Tian, T., Yan, H., & Shah, W. U. H. (2024). A simultaneous impact of digital economy, environment technology, business activity on environment and economic growth in G7: Moderating role of institutions. *Heliyon*, *10*(12), 34-40.