

THE DIGITAL ECONOMY AND GREEN ECONOMIC GROWTH IN INDONESIA: SPATIAL SPILLOVER AND NONLINEAR EFFECTS

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ABSTRACT

Introduction/Main Objectives: This study aims to investigate the digital economy and its spatial effects on green economic growth in Indonesia. It also explores nonlinear or U-shaped effects of the digital economy. **Background Problem:** The research addresses the background problem of balancing economic growth and environmental sustainability, emphasizing the spatial interdependencies in the digital economy's impact on green economic growth. Understanding these spatial effects is crucial for designing effective regional policies. **Novelty:** The novelty of this study lies in its examination of the impact of the digital economy on green economic growth using an aggregate index constructed using the Entropy value method. Furthermore, spatial effects are incorporated to account for interdependencies among regions. **Research Methods:** Spatial analysis using the spatial Durbin model with random-effects models is employed to analyze the data. **Findings/Results:** Empirical findings from this study indicate a negative impact of the digital economy on green economic growth in Indonesia. Moreover, the study confirms the presence of a nonlinear relationship, specifically a U-shaped effect between the digital economy and the environment-economy index. The coefficients of spatial effects, encompassing both the digital economy and green economic growth, demonstrate significant influences on this relationship. **Conclusion:** Currently, Indonesia finds itself in the early evolutionary stage of digitalization, which has potential to improve the green economy in the longer term. Optimizing the digital economy is imperative to mitigating unsustainable outputs and inputs in the manufacturing process. Furthermore, achieving a sustainable economy necessitates considering the effects of other regions on local green economies, emphasizing the importance of understanding spatial interdependencies.

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INTRODUCTION

In the current dynamic global landscape, the significance of environmental conservation has become widely acknowledged due to escalating concerns around climate change, biodiversity loss, pollution, and resource depletion (Jovane et al., 2008). These pressing issues have garnered substantial attention from individuals, governments, and organizations worldwide, prompting the establishment of international agreements that seek to address environmental protection and the mitigation of harmful practices to achieve sustainable development. Prominent examples of such agreements include the UN Framework Convention on Climate Change (1992), the Kyoto Protocol (1997), and the Paris Agreement (2016) (Nukusheva et al., 2021). However, achieving a balance between economic development and environmental sustainability remains a complex challenge, particularly for developing economies striving for rapid growth while managing environmental risks.

Amid these global sustainability efforts, the digital economy has emerged as a key driver of sustainable development, especially green economic growth, by means of optimizing economic processes, increasing efficiency, and supporting low-carbon development (Zhang et al., 2022; Luo et al., 2022). Leveraging digitalization, automation, and data-driven innovations, economies can transition towards greener and more sustainable growth models. While numerous studies have examined this relationship, most have focused on China (Zhang et al., 2018; Xu et al., 2022; Chang & Li, 2022; Feng et al., 2023), leaving limited insights into other developing economies.

Indonesia, as one of the largest developing economies in Southeast Asia, has experienced rapid digital transformation in recent years, driven by the expansion of digital platforms, fintech, and e-commerce. However, unlike

China, where studies have extensively analyzed the environmental impact of digitalization, research exploring the influence of Indonesia's digital economy on green economic growth remains scarce. This study addresses the urgent need to formulate policies that ensure digitalization supports sustainable economic development rather than exacerbating environmental degradation.

Empirical studies, particularly in China, have explored the role of digitalization in promoting green development. Zhang et al. (2018) highlighted regional variations in the effects of technological innovations on urban green development, while Xu et al. (2022) focused on the spatial spillover effects in the relationship between the digital economy and environmental pollution. Employing the spatial Durbin model (SDM), Chang and Li (2022) investigated the impact of digitalization on carbon emissions, revealing complex spatial interdependencies. Even more recently, a study by Feng et al. (2023) further demonstrated a nonlinear (U-shaped) relationship between expansion of the digital economy and green growth, suggesting that the benefits of digitalization may only materialize beyond a certain threshold.

Despite these extensive studies in China, research on the digital economy's role in green economic growth in Indonesia remains limited. Existing studies set in Indonesia, such as Imansyah et al. (2023) and Islam et al. (2023), have primarily focused on ICT infrastructure without considering the role of the digital economy more comprehensively. Furthermore, existing research largely ignores spatial spillover effects and potential nonlinearities in the relationship between the digital economy and green growth. Seeking to address these gaps, this study examines the impact of the digital economy on green economic growth in Indonesia using an aggregate index, while also analyzing

the presence of spatial spillover effects that may influence this relationship. Additionally, mindful of the U-shaped relationship between digitalization and green growth demonstrated by Feng et al. (2023), which suggests that early digital adoption may initially increase pollution before leading to long-term environmental benefits, this research investigates whether a similar nonlinear effect exists in the Indonesian context. Moreover, this study employs an entropy-weighted digital economy index and the spatial Durbin model to capture regional connectedness, thus offering a more comprehensive analysis of the digital economy's role in green economic growth.

To the best of author's knowledge, this is the first study to examine the impact of the digital economy on green economic growth in Indonesia, taking into account spatial effects and nonlinear relationships. While most studies utilize principal component analysis (PCA) to construct an index, this study takes a different approach by using the entropy weight method (EWM) (Fu et al., 2021; Corrocher & Ordanini, 2002) to ensure objective weights are assigned to each indicator. Unlike PCA, which reduces dimensionality by extracting principal components, potentially leading to loss of valuable information, EWM retains the full informational content of each indicator to provide a more data-driven and transparent weighting mechanism (Cao et al., 2022). Additionally, EWM is more adaptable to datasets with varying scales and does not require orthogonality assumptions, making it particularly suitable for constructing indices that integrate heterogeneous economic and environmental indicators. The resulting index provides a comprehensive assessment of the digital economy's influence on green economic growth while accounting for potential nonlinear effects. Additionally, by incorporating spatial factors, this research contributes to a

more comprehensive understanding of how regional interdependencies are shaping the relationship between the digital economy and green economic growth in Indonesia.

Specifically, this paper makes several contributions. First, it provides empirical evidence from the Indonesian context, offering valuable insights for policymakers, businesses, and stakeholders seeking to promote green economic growth through the digital economy. Second, it addresses a critical research gap by investigating the complex dynamics between the digital economy and regional sustainability in Indonesia, incorporating spatial effects and potential nonlinear relationships. The findings offer a deeper understanding of the factors driving green economic growth and emphasize the need for tailored policies and strategies. Additionally, the study includes the impact of COVID-19 on the green economy as a control variable, shedding light on post-pandemic challenges and opportunities for sustainable development.

LITERATURE REVIEW

1. Digital Economy Effects on the Green Economy

Extensive research has been conducted on the correlation between the digital economy and green economic growth. Evident across these studies is a prevailing belief regarding the digital economy's potential to foster and enhance green economic growth (Chang & Li, 2022; Cao et al., 2022; Feng et al., 2023). Relatedly, in the mid-twentieth century, neo-classical economist Solow (1957) theorized that capital and labor are interchangeable, with capital exerting a horizontal influence on growth while technological progress facilitates sustained vertical economic growth.

The impact of the digital economy on green economic growth can be explained through

several pathways. Firstly, digital technologies enhance resource efficiency by optimizing production processes and reducing waste, resulting in more sustainable resource use and a reduced environmental footprint. For example, advanced data analytics and automation technologies help companies identify inefficiencies and streamline operations, minimizing resource consumption and emissions (Demartini et al., 2019). Secondly, the digital economy fosters innovation in green industries by accelerating the development and adoption of clean technologies and sustainable practices through digital platforms and tools. This has positive effects on areas such as renewable energy, smart grids, and energy-efficient systems. Collaboration, knowledge-sharing, and investment in green technologies are facilitated within the digital economy, driving the growth of sustainable industries (Feng et al., 2023). Lastly, the digital economy enables and encourages sustainable consumption patterns and behavior change. Through digital platforms and tools, individuals and businesses gain the ability to make environmentally conscious choices. E-commerce platforms provide access to sustainable products and services, while smart devices and applications aid in monitoring and managing energy consumption. Digital technologies offer information, incentives, and opportunities for sustainable decision-making, promoting a shift towards greener lifestyles and business practices (Midden et al., 2008). Collectively, these pathways contribute to the promotion of green economic growth.

The impact of the digital economy on carbon emissions has been examined in China. Using panel data from 282 cities over the period of 2011 to 2019, Chang and Li (2022) revealed the digital economy is playing a significant role in promoting China's transformation into a low-carbon economy. Their findings highlight the

strategic interaction between carbon emissions and the digital economy, underscoring the potential of digital advancements for driving sustainable, low-carbon development. Similarly, Hao et al. (2023) have identified a positive relationship between digitalization and green economic growth in China, with green technology innovation, an advanced industrial structure, and industrial rationalization emerging as important factors. Promoting digitalization and greening is therefore crucial for sustainable economic development.

Furthermore, Hao et al. (2023) and Feng et al. (2023) have explored the non-linear effects of digitalization on green economic growth in China. Their research reveals a significant positive relationship, highlighting the presence of non-linear dynamics and underscoring the importance of promoting digitalization and greening for sustainable economic development. Building on their findings, our study aims to explore the non-linear effects of the digital economy on green development.

A systematic process can be applied to understand the non-linear effects of the digital economy on the green economy (Hilty et al., 2006). Initially, as the digital economy expands, it may have negative impacts on the environment. This can be attributed to factors such as increased electronic waste, energy consumption, and resource-intensive practices associated with digitalization. These effects may potentially harm environmental sustainability. However, as the digital economy progresses and certain conditions are met, a turning point is reached. At this stage, the positive impacts of the digital economy on the green economy start to outweigh the negative effects, as explained by environmental Kuznets curve (EKC) theory (Zhong et al., 2022). This shift can be attributed to advancements in technology and innovation, which lead to improved energy efficiency,

resource optimization, and the development of green technologies. Additionally, changes in consumer behavior and consumption patterns, such as the adoption of product-to-service models or reduced material intensity, contribute to the positive non-linear effects.

2. Spatial-Spillover Effects of the Green Economy

Existing research on spatial spillover effects in the green economy has integrated new economic geography with the concept of spatial convergence in economic growth quality (Hao et al., 2023; W. Wang et al., 2022). New economic geography postulates that economies with similar initial conditions and economic structures undergo endogenous evolutionary divergence within the spatial dimension (Kong et al., 2022). As the field of spatial economics has gained increasing recognition, the significance of geographic factors in analyzing economic growth convergence has also garnered greater attention. The subsequent emergence of the theory of spatial convergence of economic growth, rooted in new economic geography, acknowledges the spatial interaction among separate economies and subsequent spillover effects on economic development.

Furthermore, spatial spillover effects play a crucial role in the development of local green economies, as emphasized by Chang and Li (2022). Resource-rich cities serve as catalysts, transmitting knowledge, information, and green innovation to neighboring regions. Through this exchange, new avenues for green economic growth emerge, fostering interconnected networks of sustainability. In this way, the dynamics of spatial spillover contribute to the promotion of local green economies and pave the way for sustainable low-carbon development.

The spatial dimension also plays a pivotal role in the realm of technological innovation diffusion, facilitating spillover effects from the digital economy onto green economic growth (Zhao et al., 2019). Spatial spillover of technological innovation contributes to enhanced productivity and resource sharing, while also potentially addressing disparities in green growth across different spatial dimensions. However, Cao et al. (2022) found mixed evidence regarding indirect or spatial spillover effects. While several spatial effects were statistically significant, some variables did not show significant indirect effects. This can be attributed to insufficient financial support and a relatively low level of technological innovation development in China, posing challenges in fully leveraging the positive spillover effects of technological innovation to promote coordinated regional green growth. There are thus mixed results regarding the spatial effects of the digital economy on green growth.

The positive spatial effects of the digital economy on green economic growth can be explained through several underlying mechanisms. Firstly, the digital economy facilitates the exchange of information and knowledge transfer across geographic regions, enabling the dissemination of innovative ideas, best practices, and green technologies and encouraging the adoption of sustainable practices in local green economies (Han & Liu, 2022). Secondly, the digital economy fosters collaboration and networking among businesses, researchers, and policymakers, creating an ecosystem that supports green innovation and entrepreneurship (Ihsanudin & Rahayu, 2019). In turn, this collaborative environment promotes the development and scaling of green technologies, contributing to sustainable economic growth in interconnected regions.

Lastly, the digital economy enables teleworking, reducing the need for physical commuting and resulting in lower carbon emissions and improved environmental sustainability (Hook et al., 2020). More specifically, digital platforms allow individuals to work from any location, reducing transportation-related carbon emissions and supporting sustainable practices. These mechanisms collectively drive the spatial effects of the digital economy on green economic growth, highlighting the importance of understanding and harnessing the potential of digital technologies for sustainable development. By leveraging the spatial advantages of the digital economy, which include information exchange, collaboration, and teleworking, regions can experience positive impacts on their green economic growth trajectory.

METHOD, DATA, AND ANALYSIS

1. Data Sources

Secondary data is utilized in this study in the form of cross-sectional panel data encompassing all 34 provinces of Indonesia as well as time series data spanning 2018 to 2020. Including all 34 provinces provides a complete and nationally representative analysis of how the digital economy has influenced green economic growth across diverse regional contexts. The specific research period was selected due to the limited availability of the data required to construct the digital economy index from one of the primary sources—Statistics Indonesia (BPS). Specifically, the primary sources of data are BPS, providing comprehensive economic information; GeoQuery, offering geospatial data and CO₂ emissions data; and Bank Indonesia, which provides data on indicators of financial development. By combining these diverse sources, the study aims to gather a comprehensive and reliable dataset that facilitates investigation of

the relationship between the digital economy and green economic growth in the spatial context under examination.

2. Research Variables

The selection of the variables used in this study is based on economic and environmental theories, as well as empirical findings from prior research. The dependent variable, green economic growth, is measured using a composite index constructed with the entropy weight method (EWM) and incorporating indicators related to economic productivity, environmental sustainability, and energy efficiency (Cao et al., 2022). This approach ensures a multidimensional assessment of green growth that aligns with the sustainable development framework introduced earlier (Solow, 1991).

The main independent variable, the digital economy, is captured through an aggregate digital economy index covering digital infrastructure, digital usage, digital skills, and economic contribution. This variable is expected to influence green economic growth through two possible channels. First, according to endogenous growth theory (Romer, 1990), digitalization fosters technological innovation and efficiency improvements that can enhance sustainable economic development (Popov et al., 2022). Second, based on the environmental Kuznets curve (EKC) hypothesis, the relationship between digitalization and green growth may follow a U-shaped pattern, where early digitalization initially increases environmental pressure before contributing to sustainability in the longer term through green technology adoption (Feng et al., 2023). To test this nonlinearity, a squared term of the digital economy index is included in the model.

Given the potential for regional interdependencies, this study also examines spatial spillover effects, recognizing that economic and

environmental outcomes are not isolated within administrative boundaries (Xu et al., 2022; Chang & Li, 2022). A spatial Durbin model (SDM) is employed to assess whether the digital economy in one region influences green economic outcomes in neighboring regions.

Control variables are included to account for additional macroeconomic factors that influence green economic growth. Economic growth is incorporated following EKC theory, according to which higher income levels can support cleaner production methods (Grossman & Krueger, 1995). Financial development is also considered as access to finance can facilitate green investments and innovation (Wang et al., 2022) while inflation is included to control for macroeconomic stability as price fluctuations can affect investment in green technologies.

3. Model specification

Based on the preceding literature review, this paper investigates the influence of the digital economy on green economic growth within a spatial context. The research model adopted in this study draws from the work of Feng et al. (2023) and Wang et al. (2022), combining both nonlinear and spatial effects to examine the relationship between the digital economy and the green economy. When dealing with varying degrees of spatial correlation, traditional panel models such as ordinary least squares (OLS) regressions may not be suitable (Cao et al., 2022). This is because spatial dependence can lead to interdependence between error terms in linear regression models, resulting in biased estimation outcomes. Therefore, this study opts for spatial regression models to appropriately account for spatial effects.

Spatial interactions are introduced into the linear model using a spatial lag (error) model, leading to the formulation of a spatial Durbin model (SDM) (Wang et al., 2022). The

theoretical framework on which the SDM is based postulates that the observed values of the dependent variables are not solely shaped by the corresponding variables in neighboring regions, but also by the independent variables present in those same regions (Cao et al., 2022). This innovative approach allows for a holistic exploration of the critical factors influencing the dependent variables, taking into account both endogenous and exogenous perspectives from a wider spatial context. The SDM also acknowledges that the impact of explanatory variables on the dependent variables includes both direct and feedback effects from spatial spillovers (LeSage & Pace, 2009). To achieve accurate analysis, the partial differential method can decompose spatial spillover effects into direct, indirect, and total effects.

By employing this approach, the study seeks to capture the spatial dynamics inherent in the relationship between the digital economy and green economic growth, thereby enhancing the accuracy and validity of the findings. More specifically, drawing insight from the estimation method utilized by Yang et al. (2022), this study applies a random-effects Spatial Durbin Model (SDM) to panel data. The model specification is presented as follows:

$$\begin{aligned}
 GEG_{it} = & \beta_0 + \rho \sum_{j=1}^n W_{ijt} GEG_{it} + \beta_1 DEI_{it} + \\
 & \beta_2 DEI_{it}^2 + \beta_3 \sum_{i \neq j}^N W_{ijt} DEI_{it} + \\
 & \beta_4 \sum_{i \neq j}^N W_{ijt} DEI_{it}^2 + \sum_{k=1}^n \delta_{it} X_{it} + \\
 & \varepsilon_{it}
 \end{aligned} \tag{1}$$

Here, i denotes province; t denotes year; GEG denotes the green economic growth index; DEI denotes the digital economy index; X represents the control variables, including inflation ($LNCPI$), economic growth ($LNGRDP$), financial development (FD), and dummy covid ($DCOVID$); ρ is the coefficient of spatial-spillover of green economic growth; β_0, \dots, β_n

and W_{it} denote coefficients of each variable and the spatial weight matrix, respectively; and ε_{it} denotes the error term.

The spatial weight matrix plays a critical role in spatial measurements, enabling examination of the spatial relationships and roles between diverse regions (W. Wang et al., 2022). To this end, the study employs the queen contiguity weight matrix, which draws upon the weighting methodology utilized by Z. Wang et al. (2019) and Pirciog et al. (2023). Additionally, as a robustness check for the benchmark models, the geographical distance weight matrix, calculated using the Euclidean measurement, is also employed (W. Wang et al., 2022). The weight matrix is presented as follows.

$$W = \begin{cases} 0, & i=j \\ 1/d_{ij}^2, & i \neq j \end{cases} \quad (2)$$

4. Variable Description

The variables are described as follows:

(1) Green economic growth (the dependent variable): According to the Organisation for Economic Co-operation and Development (OECD), the concept of green growth entails fostering economic growth and development while simultaneously ensuring the continued

provision of diverse resources and environmental services from natural assets, thus contributing to human well-being (Cao et al., 2022). An international standard for measuring green economic growth across countries remains lacking. This is due to the inherent externalities and spatial heterogeneity associated with this distinct form of economic growth compared to conventional growth. Consequently, this research endeavors to establish an index system for evaluating green economic growth in the 34 provinces of Indonesia, drawing upon the study conducted by W. Wang et al. (2022) as a reference. The green economy index in this study comprises three dimensions: input, desired output, and undesired output, with specific indicators outlined in Table 1. To build an aggregate index, this study uses the entropy weight method (EWM) so that each indicator has an objective weight (Cao et al., 2022; Feng et al., 2023; W. Wang et al., 2022).

(2) Digital economy (key explanatory variable): Valenduc and Vendramin (2016) described the digital economy as an economic sector utilizing digital technology to design and transform strategic resources more

Table 1. Indicators in Index System for Provincial Green Economic Growth

Indicator Types	Indicator Composition	Indicator Definitions
Input	Capital stock	Gross fixed capital formation by province
	Energy consumption	Electricity consumption by province
	Labor	Working population 15 years of age and over
Desired output	Gross regional domestic product (GRDP)	GRDP in 2010 base year by province
Undesired output	Environmental pollution	Carbon dioxide (CO2) emissions

efficiently in the production chain to obtain greater returns at zero or semi-zero marginal costs so as to create high-quality economic development. This definition has been adapted by the OECD (2020) to encompass all economic activities that use digital in the input process to obtain high demand. In order to obtain a comprehensive understanding of the digital economy, this study constructs a digital economy index. Building upon the work of W. Wang et al. (2022), the index encompasses four dimensions: digital infrastructure, digital use, digital skills, and the economic and technological foundation. While the first three dimensions have been previously captured by the ICT development index formulated by Statistics Indonesia (BPS), this research introduces the economic and technological foundation dimension to augment the ICT index and establish a comprehensive digital economy index. Similar to the construction of the green economy index, the digital economy index is derived using the EMW technique (Cao et al., 2022; Feng et al., 2023; W. Wang et al., 2022). The indicators are specified in Table 2.

The steps for building an index using EMW are as follows.

- i. To ensure consistency among indicators across different dimensions, it is imperative to employ a normalization process as outlined below.

For positive indicators

$$x_{ij}, \text{ set } x'_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (3)$$

For negative indicators

$$x_{ij}, \text{ set } x'_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (4)$$

$i = 1, 2, \dots, n; m; j = 1, 2, \dots, n$, where I denotes the number of observations and j denotes the number of indicators.

- ii. Calculating the proportion of each indicator j .

$$p_{ij} = \frac{x'_{ij}}{\sum_{i=1}^m x'_{ij}} \quad (5)$$

- iii. Formulating the entropy value of the indicator j .

$$e_{ij} = -k \sum_{i=1}^m p_{ij} \ln(p_{ij}), k = \frac{1}{\ln(m)} > 0 \quad (6)$$

Table 2. Indicators in the Index System used to Measure the Provincial Digital Economy

Indicator Types	Indicator Composition	Indicator Attributes
Digital infrastructure	Fixed telephone subscribers	+
	Mobile phone customers	+
	International internet bandwidth	+
	Computer ownership by household	+
	Internet access by household	+
Digital use	Internet users	+
	Fixed broadband internet subscribers	+
	Active mobile broadband internet subscribers	+
Digital skill	Average length of time at school	+
	Secondary gross participation rate	+
	Tertiary gross participation rate	+
The economic-technological foundation	GRDP in 2010 base year	+
	Wages on average by provinces	+
	Tertiary sector contribution of GRDP	+

iv. Calculating the weight of each indicator.

$$w_j = \frac{1-e_j}{\sum_{j=1}^n (1-e_j)} \quad (7)$$

v. Formulating the composite index of all indicators.

$$z = \sum_{j=1}^n w_j x'_{ij} \quad (8)$$

(3) Control variables: In order to mitigate potential biases arising from omitted variables and enhance the comprehensiveness of the estimation of the digital economy's impact on green economic growth, several control variables are incorporated into the model. First, provincial GDP represents economic development. In turn, economic development, regional social inclusiveness, and carbon emission efficiency are interconnected. Further, in regions with a robust economy, a larger share of income is dedicated to environmental governance and green research and development, thereby fostering a path towards low-carbon and sustainable development (Xiang et al., 2022). Controlling for GDP ensures that variations in green economic growth are not solely attributed to differences in economic scale but rather reflect the influence of digitalization. Second, measurement of inflation is represented by the proxy of the consumer price index (CPI). The relationship between inflation and sustainable growth is multifaceted. On one hand, elevated levels of inflation lead to a decline in consumer purchasing power and subsequently reduced energy consumption, thereby positively influencing environmental quality (Bilal et al., 2022). Conversely, a rise in inflation can signal uncertainty, leading to the delay of investment projects aimed at transitioning from non-renewable energy sources to sustainable renewable energy generation (Ullah et al., 2020). By including inflation as

a control variable, the model minimizes bias by ensuring that the estimated effect of the digital economy on green economic growth is not confounded by fluctuations in price stability. Third, the financial development variable is proxied by the ratio of total credit to GRDP. Sustainable and equitable economic progress is supported by the allocation of capital to renewable energy, integration of ESG criteria, and enabling of inclusive financial systems (Xiang et al., 2022). Including financial development as a control variable therefore helps prevent potential distortions in estimating the relationship between the digital economy and green economic growth. The three control variables are logarithmically transformed. Additionally, to account for the impact of the COVID-19 pandemic during the research period, a dummy COVID-19 variable is incorporated specifically for the year 2020. The COVID-19 pandemic had a temporary positive impact on the green economy by reducing CO₂ emissions (Borojo et al., 2022). This reduction can be attributed to the decreased activity in industry, transportation, the power sector, and international aviation.

RESULT AND DISCUSSION

This study utilizes panel data from 34 provinces in Indonesia (2018–2020) to analyze the relationship between the digital economy and green economic growth. Composite indices for both variables are constructed using the entropy weight method (EWM) to ensure objective weighting. The research model builds on Feng et al. (2023) and Wang et al. (2022), incorporating nonlinear and spatial effects. Following Yang et al. (2022), the study employs random effects and spatial Durbin models (SDM) to estimate the impact of digitalization, accounting for spatial dependencies and spillover effects across

regions. This approach provides a comprehensive framework for understanding the broader economic and environmental dynamics of digitalization.

1. Descriptive Statistics

Table 3 presents comprehensive descriptive statistics for the variables utilized in the study, detailing their mean, standard deviation, minimum, and maximum values. The analysis reveals that the green economic growth index (GEG), representing the overall sample, attains an average value of 0.514, with a minimum of 0.426 and a maximum of 0.635. The standard deviation of 0.042 signifies considerable disparities in green economic growth levels across the different regions. Regarding the digital economy index (DEI), the average value, a key explanatory variable, stands at 0.384. The DEI values range from 0.224 to 0.747, exhibiting a standard deviation of 0.099. The wide range in DEI values is indicative of substantial variations in the digital economy among provinces, even surpassing the variation in green economic growth. The study incorporates three control variables, namely gross

domestic product, consumer price index, and financial development. All control variables are subjected to logarithmic transformations to enhance stability in their variations. Similar to the primary variable, the control variables exhibit regional and temporal variations within a range that avoids extreme values.

The correlation matrix reveals the relationship between the independent variables. Table 4 shows that the correlation values between the variables are all below 0.6, indicating a low level of correlation. This suggests that multicollinearity is not a significant concern in the empirical analysis (Ratner, 2009).

In order to provide a comprehensive overview of the distribution of green economic growth and the digital economy across Indonesian provinces, spatial maps for the year 2020 are presented in Figures 1 and 2. The classification divisions in these maps have been determined using Jenks' natural breaks calculation, following the methodology employed by Wang et al. (2022). The spatial maps illustrate the distribution of each variable, categorized as low, medium, or high development.

Table 3. Summary statistics

	mean	sd	min	max	observation
<i>GEG</i>	0.514	0.042	0.416	0.635	102
<i>DEI</i>	0.384	0.099	0.224	0.747	102
<i>LNCPI</i>	4.629	0.021	4.594	4.677	102
<i>LNGRDP</i>	18.872	1.142	17.036	21.331	102
<i>LNFD</i>	3.090	0.429	2.161	4.614	102

Table 4. Matrix of correlation

	<i>GEG</i>	<i>DEI</i>	<i>LNCPI</i>	<i>LNGRDP</i>	<i>LNFD</i>
<i>GEG</i>	1.000				
<i>DEI</i>	0.202	1.000			
<i>LNCPI</i>	-0.233	0.269	1.000		
<i>LNGRDP</i>	0.266	0.311	-0.029	1.000	
<i>LNFD</i>	-0.204	-0.383	-0.056	0.077	1.000

Figure 1 reveals that three provinces, namely DKI Jakarta, East Java, and East Kalimantan exhibit high levels of green economic growth. However, as of 2020, eight provinces in Indonesia are still demonstrating lower levels of green economic growth compared to the majority of provinces, which are achieving higher and medium development levels. This indicates that the pursuit of a sustainable economy, as reflected in the green economic growth index, remains unevenly distributed across the country. The coexistence of high economic growth and limited environmental awareness underscores the need for greater focus on the provinces with lower levels of development to prevent them from lagging behind other regions, and to foster overall sustainable economic growth.

As depicted in Figure 2, the majority of provinces in Indonesia, specifically 21 out of 34, have attained higher and medium levels of digital economy development. Conversely, there are 13 provinces exhibiting lower levels of digital economy development. This disparity underscores the uneven progress of the digital economy across all regions, highlighting substantial untapped potential for further digital advancement. A notable challenge identified to the development of the digital economy in Indonesia is the incongruity between high internet penetration and the persistently low levels of digital literacy among the population (Rumata & Sastrosubroto, 2021). Efforts to bridge this gap and enhance digital literacy are imperative for facilitating more inclusive and comprehensive digital economic growth in the country.

Figure 1. Green economic growth index in Indonesia, 2020



Figure 2. Digital economy index in Indonesia, 2020



2. Benchmark regression analysis

The aim of this study is to investigate the impact of the digital economy on green economic growth across 34 provinces in Indonesia. The random-effects method is employed as the estimation approach, following the methodology outlined by Yang et al. (2022). The utilization of this method is justified by the presence of unobserved variables that contribute to regional disparities in the dependent variable, namely green economic growth. These disparities can arise from variations in economic structure and governmental policies pertaining to environmental protection across provinces (Liu et al., 2019).

Table 5 presents the estimation results from the digital economy model, in both linear and non-linear specifications, showing the digital economy's influence on green economic growth.

To ensure the robustness of the findings, the estimation is conducted using different control variables in each column. The results indicate a significant negative relationship between the digital economy and green economic growth in Indonesia. Specifically, an increase of 1 unit in the digital economy index corresponds to an average decrease of 1.5 units in the green economic growth index. Moreover, the analysis reveals that the squared digital economy, representing the non-linear coefficient, exhibits a positive and significant effect on green economic growth in Indonesia. Regarding the control variables, inflation shows a negative and significant association with green economic growth, while economic growth and the dummy variable for the COVID-19 pandemic exhibit significant positive effects. However, financial development is found to be statistically insignificant.

Table 5. Regression results for the effect of the digital economy on green economic growth

Variables	Dependent variable: GEG			
	I	II	III	IV
<i>DEI</i>	-0.879*** (0.319)	-0.596*** (0.139)	-1.072*** (0.221)	-0.535*** (0.125)
<i>DEI</i> ²	1.035*** (0.334)	0.774*** (0.139)	1.278*** (0.235)	0.732*** (0.147)
<i>LNGRDP</i>	0.010*** (0.004)			0.009** (0.003)
<i>LNCPI</i>		-0.795*** (0.247)		-0.815*** (0.234)
<i>LNFD</i>			-0.015 (0.012)	-0.003 (0.007)
<i>DCOVID</i>	0.030 (0.000)	0.058 (0.000)	0.030 (0.000)	0.058*** (0.011)
ρ	0.412*** (0.104)	0.431*** (0.099)	0.431*** (0.099)	0.315*** (0.082)
σ^2	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)
<i>N</i>	102	102	102	102
<i>R</i> ²	0.353	0.563	0.290	0.042

3. Analysis of Spatial Effects

Table 5 presents the ρ values, which display a positive and statistically significant coefficient at the 1% significance level, indicating the presence of spatial effects on green economic growth. This suggests that the development of the green economy in one province can have a positive influence on the green economy in neighboring provinces. Therefore, the impact on green economic growth is not limited to local effects but also extends to the surrounding areas, reflecting the interdependence of environmental economic factors. The spatial Durbin model method is employed to examine these spatial spillover effects and understand the relationship between the digital economy, control variables, and the green economy. This approach allows for the decomposition of effects into direct and indirect, as illustrated in Table 6. This decomposition enables the assessment of the marginal effects between variables based on spatial interactions and provides insights into the spatial spillover effects on the green economy (LeSage

& Pace, 2009). The results highlight the significance of spatial effects, particularly in the context of indirect effects.

The impact of the digital economy, both direct and indirect, on the green economy is significantly negative. The expansion of the digital economy from neighboring areas has a detrimental effect on the local green economy, equivalent to a decrease of approximately 0.667 units. Moreover, the non-linear effects of the digital economy are evident in spatial spillover, where an increase of one unit in the digital economy in a neighboring province has a positive impact on local green economic growth, increasing it by approximately 0.732 units.

Regarding the control variables result, the positive effect of economic growth on the green economy is consistent with empirical findings by Tawiah et al. (2021) and Yang et al. (2022). Higher economic growth incentivizes investment and research and development (R&D) efforts that support environmental economics and related developments. On the other hand,

Table 6. Decomposition results for the spillover effect of the digital economy on green economic growth

Variables	Dependent variable: GEG		
	Direct	Indirect	Total
<i>DEI</i>	-0.613*** (0.159)	-0.667** (0.316)	-1.281*** (0.451)
<i>DEI2</i>	0.816*** (0.189)	0.732* (0.380)	1.547*** (0.545)
<i>LNGRDP</i>	0.008** (0.004)	-0.011** (0.005)	-0.004 (0.008)
<i>LNCPI</i>	-0.931*** (0.204)	-0.922*** (0.253)	-1.852*** (0.275)
<i>LNFD</i>	-0.002 (0.006)	0.008 (0.012)	0.006 (0.013)
<i>DCOVID</i>	0.060*** (0.012)	0.019 (0.040)	0.080* (0.047)
<i>N</i>	102	102	102
<i>R</i> ²	0.627	0.627	0.627

inflation, as a macroeconomic variable reflecting economic uncertainty, hampers investment, particularly in the conversion of non-renewable resources into renewable production, resulting in a decline in the green economy (Ullah et al., 2020). Furthermore, the identified positive impact of the pandemic crisis period on green economic growth is also supported by research by Borojo et al. (2022). The restrictions imposed during the pandemic led to reduced mobility and production activities, resulting in decreased energy consumption and thereby promoting green economic growth.

4. Discussion

The results in Table 5 indicate that the digital economy has a significant negative initial impact on green economic growth, suggesting that increased digitalization contributes to higher environmental degradation in its early stages. These findings contradict prevailing research support for a positive effect of the digital economy on enhancing green economic growth (Ma and Zhu, 2022; Wang et al., 2022; Han & Liu, 2022). Moreover, they indicate that in the midst of rapid digitalization, the development of a healthy environment is not an economic consideration, thereby increasing environmental risks (Vishnevsky et al., 2021).

The current research results align with findings reported by Tang et al. (2023) that demonstrate negative effects of the digital economy on the green economy. This can be explained by the growth substitution effect, where an expansion in the digital economy stimulates revenue growth in the economic sector, leading to production expansion. Simultaneously, the energy plundering effect occurs, resulting in increased consumption of polluting energy sources. These dynamics are consistent with Indonesia's status as a developing country in the early stages of digitalization.

During this nascent stage, digitalization necessitates increased usage of information and communication technology (ICT), which in turn leads to greater energy demand, predominantly derived from non-renewable resources (Fagas et al., 2017). The result is increased CO₂ emissions from heightened energy consumption, ultimately leading to unsustainable economic growth. This observation is further supported by empirical findings from Lange et al. (2020), who demonstrated that when energy efficiency measures do not accompany ICT, ICT capital accumulation can impede the green economy due to increased energy consumption. These circumstances align with the Jevons Paradox, which highlights the counterintuitive relationship between efficiency improvements and resource consumption arising from digitalization's impact on the environment. Additionally, there are indications that digital technology contributes to market disintegration and monopolistic market power, which hinder the attainment of green technology (Xiang et al., 2022). Overall, these inconsistencies contribute to unsustainable growth patterns.

The results in Table 5 also indicate that the squared term of the digital economy variable has a significant positive effect on green economic growth, further supporting the presence of a U-shaped relationship between the digital economy and the green economy. As the digital economy advances and matures, resource utilization for digitalization can become more efficient, enabling the implementation of low-carbon production activities and subsequent reduction of emissions. This facilitates the achievement of economic growth while maintaining environmental stability (Xiang et al., 2022). Additionally, the evolving relationship between the developing digital economy and green economic growth will influence people's behavior and attitudes, guiding their decisions towards a sustainable economy (Ciocoiu, 2011).

Consequently, the digital economy could likely have an overall positive impact on green economic growth in Indonesia. Positive effects can be maximized by addressing issues such as resource allocation inefficiency and digital platform monopolies (Xiang et al., 2022). This finding aligns with research conducted by Xiang et al. (2022) in China who demonstrate that in the early stage of digital development the abundance of digital resources is not conducive to low-carbon inclusive growth.

In terms of spatial effects, Table 6 reveals that the digital economy's impact on green economic growth extends beyond provincial boundaries, highlighting the presence of significant spillover. This suggests that digitalization in one region not only affects the local environmental and economic outcomes but also influences green economic growth in neighboring provinces. These spatial spillover follow a nonlinear pattern, with expansion in neighboring provinces then positively contributing to local green economic growth. This underscores the importance of coordinating regulations for digital economy development in surrounding areas to ensure a high-quality local environment that supports sustainable growth. The existence of spatial spillover effects between the digital and green economy is also corroborated by previous studies (Hao et al., 2023; Xu et al., 2022; Chang & Li, 2022; Zhang et al., 2018).

The identified spatial spillover effect is reasonable given the characteristics of the digital economy, which enables information sharing and overcomes distance and time barriers (Hao et al., 2023). Specifically, two mechanisms contribute to the presence of spatial effects: the dissemination of knowledge regarding clean technology, facilitated without the need for physical infrastructure in a specific location, and

interaction among platform users, who can collectively monitor environmental quality and efficiency. Jiao et al. (2018) have also noted that technology diffusion across regions expands alongside societal mobility and industrial migration. As a result, spatial spillover effects from digitalization transcend geographical limitations, further enhancing environmentally-based sustainable growth.

5. Robustness Checks

Two robustness checks are employed in this study to ensure the reliability and validity of the empirical findings obtained from the estimation discussed earlier. The first test involves modifying the spatial weight approach by transitioning from the previously used queen continuity method to the Euclidean distance method. The adoption of this weighting method is consistent with several prior studies (Zhang et al., 2018; W. Wang et al., 2022). The second robustness test utilizes an alternative spatial method known as the spatial autoregressive (SAR) model. The results of both tests are presented in Table 7. They are consistent in confirming the existence of a U-shaped effect of the digital economy on green economic growth, as well as the presence of spatial spillover effects. These findings provide further validation of, and consistency to the empirical benchmark regression results.

Additionally, the control variables exhibit similar patterns across both the primary and robustness tests. Economic growth and the COVID-19 dummy variable maintain their significant positive effects on green economic growth, while inflation remains negatively associated with such growth. However, financial development, which was statistically insignificant in the primary estimation, remains insignificant in the robustness checks.

Table 7. Robustness Check Results

Variables	Robustness:				Robustness:			
	After change in spatial weight method				Using SAR			
	I	II	III	IV	I	II	III	IV
<i>DEI</i>	-1.022*** (0.311)	-0.643*** (0.162)	-1.172*** (0.230)	-0.638*** (0.156)	-0.685*** (0.150)	-0.512*** (0.133)	-0.765*** (0.140)	-0.492*** (0.125)
<i>DEI</i> ²	1.187*** (0.333)	0.822*** (0.164)	1.389*** (0.244)	0.833*** (0.187)	0.807*** (0.147)	0.681*** (0.130)	0.924*** (0.147)	0.640*** (0.145)
<i>LNGRDP</i>	0.011** (0.005)			0.007 (0.005)	0.006* (0.004)			0.005 (0.004)
<i>LNCPI</i>		-0.369 (0.310)		-0.410 (0.264)		-1.111*** (0.260)		-1.078*** (0.269)
<i>LNFD</i>			-0.013 (0.010)	-0.002 (0.007)			-0.005 (0.012)	-0.000 (0.010)
<i>DCOVID</i>	0.045 (0.000)	0.062*** (0.018)	0.043 (0.000)	0.061 (0.000)	0.014*** (0.003)	0.048*** (0.010)	0.014*** (0.003)	0.047*** (0.010)
ρ	0.416* (0.222)	0.297* (0.162)	0.455*** (0.152)	0.299** (0.146)	0.513*** (0.089)	0.365*** (0.084)	0.528*** (0.079)	0.366*** (0.086)
σ^2	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)
<i>N</i>	102	102	102	102	102	102	102	102
<i>R</i> ²	0.476	0.577	0.421	0.636	0.234	0.541	0.255	0.526

CONCLUSION AND SUGGESTIONS

This study has examined the impact of the digital economy on green economic growth in Indonesia, incorporating spatial and nonlinear effects. The findings confirm a U-shaped relationship, indicating that early-stage digitalization negatively affects the green economy due to increased resource consumption and pollution. However, as digitalization advances, it fosters green economic growth by enhancing energy efficiency, optimizing production processes, and supporting sustainable innovation. These results align with previous studies emphasizing the step-order effect of digitalization in economic transformation.

A key contribution of this study is the identification of spatial spillover effects, which demonstrate that a province's green economic growth is influenced not only by its own digital economy but also by digital advancements in

surrounding regions. This finding underscores the importance of regional cooperation in promoting digitally-driven sustainability policies. Unlike the focus of most existing research on national or sectoral impacts, this study provides a spatially interconnected perspective, highlighting the broader economic and environmental implications of digitalization.

To achieve the goal of green economic growth, stakeholders should prioritize the development of a digital economy that optimizes and streamlines economic resources and structures, while also supporting low-carbon development. This necessitates both a well-organized regulatory framework and government guidance to stimulate technological innovation and establish the foundation for a mature digital economy in Indonesia. Ultimately, this will have a positive impact on creating an environmentally-focused economy. Additionally, investment in the digital economy, both direct and indirect,

should be promoted. Direct investment should focus on accelerating environment-based platforms while indirect investment should prioritize research and development (R&D) for energy-efficient applications. These measures will support the optimization of the digital economy towards green economic growth and encourage sustainable behaviors. The study's confirmation of spatial spillover effects between the green economy and the digital economy underscores the importance of regulators considering not only local environmental and digitalization effects, but also the need to collaborate with neighboring provincial regulators in implementing coordinated environmental policies. This coordination is essential to optimizing the development of the green economy.

While this study provides important insights into the relationship between the digital economy and green economic growth, several limitations should be acknowledged. First, the study focuses on Indonesia, which may limit the generalizability of the findings to other countries with different digitalization levels, regulatory environments, and economic structures. Future research could extend this analysis through a cross-country framework to explore whether similar patterns hold in different contexts. Second, the entropy-weighted digital economy index used in this study captures multiple dimensions of digitalization. However, alternative methods, such as machine learning-based approaches, could further refine the measurement and provide deeper insights. It is thus recommended that future studies compare different index construction techniques to enhance robustness. Additionally, future research should further explore the role of digital technology in upgrading industry structures, as digital transformation can accelerate the transition towards intelligent and environ-

mentally sustainable manufacturing. Recent discussions highlight the interaction between digital green innovation and supply chain integration, emphasizing how digitalization can enhance resource efficiency, minimize carbon footprints, and create more resilient production systems. Moreover, future research could explore the role of human capital (education, workforce skills, and innovation capacity) and regional competitiveness (infrastructure, institutional strength, and economic diversification) in shaping the effectiveness of the digital economy on green economic growth, thereby providing a more comprehensive policy framework for sustainable development.

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