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Research article

Digital financial inclusion and its dual impact on economic and environmental outcomes in ASEAN countries

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Abstract: We examined the influence of digital financial inclusion (DFI) on economic growth and environmental sustainability in ASEAN nations from 2005 to 2022. Employing advanced econometric techniques such as Pooled Ordinary Least Squares (POLS), Two-Stage Least Squares (2SLS), and Generalized Method of Moments (GMM), we uncovered compelling findings: DFI boosts the economy but at an environmental cost. This surprising outcome poses a significant challenge for policymakers striving to balance economic benefits with ecological health. Our study calls for strategic government action to reconcile these critical areas, ensuring sustainable regional development.

Keywords: automatic teller machine; ASEAN countries; carbon dioxide emission; debit cards; digital financial inclusion; gross domestic product

JEL Codes: F36, O16, Q56

1. Introduction

Economic growth is a paramount goal worldwide, especially critical in developing regions that battle against deep-rooted issues like unemployment and poverty, alongside pressing environmental concerns such as pollution and climate change. Home to 8.6% of the global population, Southeast Asia faces stark realities: Around 36 million people within the ASEAN region subsist below the international poverty line (Rahman et al., 2022). Despite being the fifth-largest global economy in 2019 with a GDP

of USD 3.2 trillion, ASEAN has seen a slowdown in GDP growth in recent years, a downturn driven by internal and external factors (Nasution et al., 2022). Concurrently, environmental challenges have surged to the forefront, becoming a pivotal topic of discussion. Today, the economic and environmental dilemmas confronting many countries are starkly visible in the ASEAN region, where nearly 90% of energy demands are met through the combustion of fossil fuels (Munir et al., 2020).

Research such as that by Grossman and Krueger (1995) suggests that Carbon dioxide (CO_2) levels increase until a certain income threshold is reached, which reflects the traditional Environmental Kuznets Curve (EKC) showing a U-shaped relationship between economic growth (EG hereafter) and environmental quality. Initially, EG escalates due to ecological pressures but subsequently declines (Georgiev & Mihaylov, 2015). It is important to investigate whether EG is a substantial contributor to carbon dioxide emissions, especially when it comes to the digital financial sector. As we step into the modern world, where global economies are intrinsically connected through digital development, digital financial inclusion (DFI) has emerged as a major driver of change. It enables settlement systems based on cutting-edge technologies to improve access to financial services, leading to economic growth/development and addressing environmental issues. Research by authors like Ozili (2018) and Mention (2019) underscores that this digital transition not only facilitates equitable financial opportunities but also fosters innovation and directs investments toward sustainable projects, especially in underprivileged areas (Xi & Wang, 2023) like ASEAN.

DFI and environmental sustainability (ES) intersection is a complex and under-researched domain. Zhang et al. (2021) posit that financial progress, often synonymous with economic growth, correlates with increased CO_2 emissions. The environmental impacts of financial inclusion (FI), however, remain under-researched (Khan & Ozturk, 2021). This paradox is elucidated by Usman et al. (2021), who highlight the potential for FI to either enhance or degrade environmental quality. Moreover, Damrah et al. (2022) underscore the critical trade-off between promoting economic development and ensuring environmental sustainability. They note a positive association between pollution emissions, economic activities, and financial sector development, as evidenced by Zhang et al. (2021). Given the diverse economic landscapes within ASEAN nations, characterized by varying levels of FI, analyzing the nexus between FI, the ES, and EG assumes heightened significance in this context.

Despite the burgeoning research in this field, a pivotal research lacuna persists, particularly regarding the intricate nexus between DFI, EG, and environmental stewardship within the ASEAN context. Ahmad et al. (2022), Sharif et al. (2023), and Saydaliev and Chin (2022) have delved into the overarching relationship among these facets. However, the granularity of DFI's influence on EG within these nations remains insufficiently examined.

Our main aim of this paper is to address the two issues regarding the ASEAN region:

1. To examine the mechanism of how DFI enhances the EG in ASEAN countries.
2. To examine the ASEAN region's nexus between DFI and ES.

We address the gaps by examining the DFI on EG and CO_2 in the ASEAN countries context. We consider several control variables that are scarce under one umbrella in this region, including internet penetration rates, fossil fuel energy, industrial sector's contribution, and foreign direct investment, which need more exploration, as stated by Xuan et al. (2024) and inflation rate. Given the current global scope of DFI across societal segments, it is crucial to determine its significance in enhancing environmental sustainability, particularly within ASEAN nations. Utilizing advanced econometric methods, such as Pooled OLS, 2SLS, and GMM—this research offers detailed insights that could significantly impact policy development.

The organization of this paper is as follows: In Section 2, we offer a comprehensive analysis of the literature, establishing a foundation for ensuing discussions. In Section 3, we delineate the methodologies employed, whereas in Section 4, we explore the data analysis and our significant discoveries. In Section 5, we conclude the study by addressing the derived conclusions, broader ramifications, and the limitations of the study.

2. Literature review and hypothesis development

DFI is a game-changer and cost-effective measure primarily delivering financial services through mobile devices (Amaliah et al., 2024). DFI represents a wide scope through tailor-made programming to achieve developmental outcomes, bridging the gap for the unbanked, providing exposure to financial inclusion (FI), and contributing to economic development. Although FI and EG have attained significant attention from the researchers, the relationship between DFI and EG remains underexplored. The nexus between FI and EG is examined and interpreted as closely related (Kim et al., 2018). DFI encompasses various financial services such as Internet banking, mobile apps, and insurance payment. DFI leverages technologies to transform traditional financial services into automated processes. It utilizes big data analysis to gather insights and reduces the information asymmetry risk by improving transparency and offering personalized financial solutions. These advancements help incorporate a significant portion of the financially excluded population into the formal financial system (Xi & Wang, 2023). This fosters greater economic participation and promotes inclusive growth by enabling access to financial services for underserved populations (Daud, 2023; Feng & Zhang, 2023; Liu et al., 2021; Shen et al., 2021).

Economic growth and sustainability have become crucial topics, as they are key to ensuring the health and wealth of the upcoming generation (Zhang et al., 2024). Environmental degradation threatens biodiversity and is a significant concern for economic development. Environmental sustainability (ES) is increasingly tied to technological advancement, given that technological innovations often have positive and negative repercussions for society (Bakhsh et al., 2024). Financial inclusion (FI) is also integral in promoting ES by facilitating access to technologies that reduce CO_2 (Yang et al., 2022; Zhuo et al., 2023). While Oanh (2024) found, through advanced technologies, that FI positively impacts environmental quality, this improvement may paradoxically lead to economic decline in specific contexts. Despite extensive research on the correlation between financial growth and economic growth (Alam et al., 2022; Aluko & Obalade, 2020; Çetin et al., 2023; Shahbaz et al., 2020) and its environmental implications (Wang et al., 2023; Xu et al., 2022), a significant gap persists in comprehending how financial investment directly affects critical environmental indicators such as carbon emissions and fossil fuel usage.

We address these gaps by examining DFI's role in shaping EG and ES activities within the ASEAN region.

2.1. Overview of the Literature

Table 1 presents a compilation of researchers who have utilized economic and environmental variables. Ding et al. (2022), Godil et al. (2020), and Wang et al. (2022) concluded that DFI positively influences GDP and CO_2 emissions. Camba and Camba Jr (2020) and Haini (2022) identified a significant correlation between internet penetration and economic growth in ASEAN countries.

Furthermore, Edquist and Bergmark (2024) quantified this relationship, noting that a 10% increase in internet penetration could reduce CO_2 emissions by 7%. Elfaki et al. (2021) have also shown that industrialization positively impacts GDP. This observation is supported by Sikder et al. (2022), who reported that a 1% increase in industrialization might result in a 0.23% increase in CO_2 emissions. Rehman et al. (2019) observed that while renewable energy positively impacts Pakistan's GDP, CO_2 emissions—despite their environmental implications—are linked to economic growth. In contrast, using fossil fuel energy has a detrimental effect on the country's economic performance. Concurrently, Martins et al. (2019) and Ibrahiem and Hanafy (2020) found that CO_2 emissions adversely affect fossil fuel energy, suggesting a complex interplay between energy consumption and environmental impacts. In Nigeria, Adaramola and Dada (2020) observed that inflation negatively impacts GDP, a conclusion further supported by Tien (2021). Furthermore, Setyadharma et al. (2021) expanded on this by suggesting that both in the short and long term—inflation could also influence air pollution levels—indicating that economic factors like inflation may have broader environmental repercussions.

Table 1. Overview of empirical outcomes.

Sr No.	Variables	Expected Effect on		Paper References
		GDP	CO_2	
1	Digital Financial Inclusion	Positive[1]	Positive[2]	Wang et al. (2022); Xi and Wang (2023) [1,2]
2	Internet Penetration	Internet penetration is the engine of economic growth[1], Positive Effect[2]	10% increase in Internet Penetration reduces 7% CO_2 [3]	Camba and Camba Jr (2020); Edquist and Bergmark (2024); Haini (2022) [1,2,3]
3	Industrialization	Postive[1]	1% Increase in Industrialization 0.23% increase CO_2 [2]	Elfaki et al. (2021); Sikder et al. (2022) [1,2]
4	Fossil Fuel Energy Consumption	Negative[1]	Negative [2,3]	Ibrahiem and Hanafy (2020); Martins et al. (2019); Rehman et al. (2019) [1,2,3]
5	Foreign Direct Investment Inflow	Positive[1]	Negative [2]	Acquah and Ibrahim (2020); Islam et al. (2021) [1,2]
6	Inflation	Negative[1,2]	Low inflation is suitable for the environment[3]	Adaramola and Dada (2020); Setyadharma et al. (2021); Tien (2021) [1,2,3]

Source: Author Himself (1= First reference; 2= Second Reference; 3= Third Reference)

2.2. DFI and EG

Prominent global organizations have provided definitions for the concept of FI. According to the World Bank, FI involves households and businesses accessing and using various financial services (Jiang & Liu, 2022; Van et al., 2021; Yang et al., 2023). Recently, there has been growing interest in the relationship between FI and EG, with researchers examining its impact across economies and time frames (Ofoeda et al., 2022). Research indicates that FI is critical in poverty alleviation, reducing inequality, and fostering EG (Mahmood et al., 2022; Ouechtati, 2020). Zhang and Qu (2024) examined the influence of industrialization and Internet growth on economic growth. They found that these factors adversely affect China's air quality index and people's health. Several key factors influence the nexus between the FI and EG. Inclusive financial systems, which broaden access to capital, loans, and savings, enable societal groups to start businesses, invest in education, and expand their economic activities, thus driving economic growth (Azimi, 2022; Manasseh et al., 2023). One critical component of FI is the Insurance market, which fosters economic stability by reducing financial risks and

promoting long-term investment. Studies suggest a bidirectional relationship exists between stock market development, the insurance market, and EG, where improvement in one area positively impacts the others, as highlighted by the ASEAN Regional Forum (Erlando et al., 2020).

Numerous research scholars underscore the significance of FI for economic stability, establishing it as a crucial factor in fostering financial growth (Antwi et al., 2024; Daud & Trinugroho, 2024; Siddiki & Bala-Keffi, 2024). DFI also plays a pivotal role in economic stability, particularly in countries such as Indonesia (Amaliah et al., 2024; Riggs et al., 2018) and China (Xi & Wang, 2023), as well as in both high and low-income nations (Daud, 2023). Conversely, a study by Vukovic et al. (2024) suggests that while financial technologies have a neutral impact on financial stability, they significantly enhance FI in BRICS countries. Basnayake et al. (2024) conducted a study on the Asia-Pacific region using 2014, 2017, and 2021 data, revealing that DFI significantly enhances the EG by expanding financial access and improving resource efficiency. However, the researchers primarily focus on the linear impact of DFI, thereby leaving significant research gaps in understanding its nuanced relationships with other important economic indicators, such as foreign direct investment and inflation across Asian countries. To address these gaps, we incorporate a comprehensive set of control variables like foreign direct investment, industrialization, and internet penetration. We aim to provide a more accurate and detailed analysis of how DFI impacts the EG and other significant parameters by including these diverse control variables. Consequently, we propose the hypothesis as:

Hypothesis 1: A positive association exists between digital financial inclusion and economic growth.

2.3. Nexus between DFI and CO_2

The relationship between DFI and CO_2 emissions is being increasingly investigated, in contrast to the more thoroughly examined connection between DFI and EG. Theoretical approaches indicate that financial investment can exert dual effects on environmental quality. It provides individuals and businesses improved access to financial services, hence promoting investments in green technologies. The enhanced accessibility and efficacy of investments facilitate the promotion of ecologically sustainable behaviors (Le et al., 2020). Conversely, some contend that financial development may adversely affect the environment (Wang et al., 2022).

Furthermore, financial inclusion is essential for attaining economic sustainability in emerging nations like Pakistan (Ansari et al., 2024). Multiple studies demonstrate that the correlation between financial development and environmental sustainability implies that financial development may reduce CO_2 emissions by promoting technological innovation, leading to diminished energy consumption (Hafeez et al., 2022; Khan et al., 2021; Wang et al., 2020). Conversely, research by Guan and Zhao (2024) indicates that while financial inclusion (FI) significantly promotes economic growth and enhances quality of life, its impact on environmental sustainability (ES) requires further examination.

Digital financial inclusion has garnered considerable focus due to its possible impact on CO_2 emissions; the literature indicates that this effect ranges from positive to U-shaped connections (Lee et al., 2022; Zhang & Liu, 2022). Khan and Ozturk (2021) discovered that financial development can reduce pollution by examining data from 88 emerging nations from 2000 to 2014. Their findings indicate that robust financial systems can alleviate the environmental impacts of economic growth and globalization. Additionally, such financial systems may provide capital for renewable energy projects and incentivize businesses to adopt sustainable practices. Conversely, Mukalayi and Inglesi-Lotz (2023) examined the relationship between DFI and CO_2 using data from 1990 to 2019 from various regions

like MANA, Asia-Pacific, and Latin America. They found that DFI is associated with increased energy consumption and CO_2 emission while identifying research gaps, including nonlinear and causal relationships. Similarly, Khan et al. (2023) found that DFI significantly and positively impacts CO_2 emission. The study explored that DFI has a significant and positive impact on the CO_2. The study emphasized the need for more comprehensive research incorporating additional variables to achieve more accurate and nuanced findings. Based on this premise, the following hypothesis is proposed:

Hypothesis 2: There is a negative correlation between Digital financial inclusion and CO_2 emissions, indicating that improved access to financial services may enhance environmental sustainability.

3. Research methodology and modeling approach

We utilize a dataset comprising information from 10 ASEAN nations spanning the years 2005 to 2022. The dataset encompasses 18 years (2005–2022) and includes 10 ASEAN countries; nonetheless, the sample size (N=10) may constrain the robustness of certain inferences, particularly for the impact of outliers. Nonetheless, the magnitude of the cross-sectional data and the duration of the time series are adequate to identify significant trends and correlations, rendering dynamic panel data analysis suitable for this research. The development of digital financial infrastructure is pivotal in today's economy, acting as a key enabler of economic progression.

DFI emerges as a crucial element, spurring innovation in the financial realm and addressing the investment needs of specialized markets. Consequently, it significantly improves the caliber of economic expansion (Chinoda & Kapingura, 2023; Khera et al., 2022; Xi & Wang, 2023; Xu et al., 2023).

The fundamental structure of the models is presented in equation (1,2) and pertinent studies (Ozturk & Ullah, 2022). Focusing on similar variables, Table 1 illustrates the anticipated positive and negative impacts on GDP and CO_2.

$$GDP_{it} = \propto + \beta_1 + \beta_2 DFI_{it} + \beta_3 IPR_{it} + \beta_4 ISC_{it} + \beta_5 FFEC_{it} + \beta_6 FDII_{it} + \beta_7 IR_{it} + \alpha_i + \varepsilon_{it} \quad (1)$$

$$CO_{2,it} = \propto + \varphi_1 + \varphi_2 DFI_{it} + \varphi_3 IPR_{it} + \varphi_4 ISC_{it} + \varphi_5 FFEC_{it} + \varphi_6 FDII_{it} + \varphi_7 IR_{it} + \alpha_i + \varepsilon_{it} \quad (2)$$

We explore how digital financial inclusion (DFI) influences GDP and CO_2 emissions, as Equations 1 and 2 elaborate. We examine various factors, including the internet usage rate, industrial sector contributions, fossil fuel usage, foreign direct investment, and inflation (Le et al., 2020; Zaidi et al., 2021). In this analysis, DFI is represented by two proxies: The accessibility of ATMs and the utilization of debit cards (Le et al., 2020; Shen et al., 2021). The employment of ATMs and debit cards as alternatives to DFI is especially suitable for ASEAN countries, where digital financial services are rapidly expanding, although access to traditional financial services remains limited in certain areas. These measures precisely represent the degree of digital financial inclusion, which is crucial for assessing the impact of financial services on economic growth and sustainability in the region.

We use dynamic panel data models to effectively capture cross-sectional and temporal variation. Methods including Pooled OLS (POLS), Two-Stage Least Squares (2SLS), and Generalized Method of Moments (GMM) are utilized to mitigate endogeneity, unobserved heterogeneity, and serial correlation, thereby enhancing the comprehension of the interconnections among DFI, economic growth, and environmental sustainability (Osabohien et al., 2022; Ozturk & Ullah, 2022; Paul et al., 2021; Tauqir et al., 2022).

The chosen approaches are employed to examine the dynamic relationships among DFI, GDP, and CO_2 emissions.

Fixed-Effects (FE) and Random-Effects (RE) models are frequently utilized in panel data analysis, as they possess particular constraints pertinent to our research. FE models effectively account for time-invariant unobserved heterogeneity; nevertheless, they are inadequate in resolving endogeneity resulting from dynamic interactions and simultaneity among variables such as DFI, GDP, and CO_2 emissions. Furthermore, FE models do not permit the incorporation of time-invariant variables, which may be relevant to our investigation. Random effects models, conversely, posit that the unobserved effects are uncorrelated with the explanatory variables. This assumption is frequently impractical in economic data, as omitted variables may correlate with the predictors, resulting in biased and inconsistent estimations. Considering the potential for correlations within our dataset of several ASEAN members, RE models may yield unreliable estimates. The integration of POLS, 2SLS, and GMM provides a more resilient framework for our investigation. POLS offers a foundational comprehension, 2SLS mitigates endogeneity via instrumental variables, and GMM additionally enables dynamic interactions and unobserved heterogeneity without the rigid assumptions necessitated by FE and RE models. This methodological trifecta guarantees that our estimates are consistent and dependable, accurately reflecting the intricate relationship among DFI, economic growth, and environmental sustainability.

To address these issues, we integrate Pooled OLS (POLS), Two-Stage Least Squares (2SLS), and Generalized Method of Moments (GMM). POLS provides a basic understanding of the relationships but overlooks cross-sectional heterogeneity and temporal dependencies, which can bias the results (Gujarati et al., 2009). While 2SLS mitigates endogeneity through instrumental variables, it assumes homogeneity of effects over time, a presumption that may not hold in our context. GMM, however, is more flexible, as it accounts for dynamic relationships, unobserved heterogeneity, and endogeneity, making it particularly suitable for capturing the long-term effects of DFI on economic and environmental outcomes. Given the "small T, large N" configuration of our dataset (18 years and 10 ASEAN countries), GMM is the most appropriate method for addressing the complexities of endogeneity, serial correlation, and cross-sectional heterogeneity in this study.

The methods mentioned earlier primarily address static correlations. To enhance comprehension of the dynamic effects of financial inclusion (FI) on CO_2 emissions and economic growth, we employ the Generalized Method of Moments (GMM). FI, as an inherently endogenous variable—supported by research from Geng and He (2021); Khera et al. (2021); Ren et al. (2023); Renzhi and Baek (2020)—requires a more robust analytical approach in the context of panel data. Our dataset, which spans 18 years (T=18) and includes 10 ASEAN countries (N=10), follows a "small T, large N" configuration that is particularly suited for GMM. This method is effective in handling datasets with short time series but large cross-sectional variation, enabling consistent estimation even in the presence of endogeneity, serial correlation, and cross-sectional heterogeneity. To address these challenges, we employ system GMM, a method that has proven to be well-suited for such data structures (Ozturk & Ullah, 2022). One of the main issues facing this study is the possible endogeneity of DFI, GDP, and CO_2 emissions. The system method is particularly appropriate to address this problem since it utilizes lagged variables as instruments in order to correct the possible endogeneity. Through the utilization of internal instruments, GMM alleviates potential biases stemming from simultaneity and unobserved heterogeneity, yielding more dependable estimations of the correlations among DFI, economic growth, and environmental sustainability.

$$GDP_{it} - \propto + \lambda_1 GDP_{it-1} + \beta_1 DFI_{it} + \beta_2 IPR_{it} + \beta_3 ISC_{it} + \beta_4 FFEC_{it} + \beta_5 FDII_{it} + \beta_6 IR_{it} + \alpha_i + \varepsilon_{it} \quad (3)$$

$$CO_{2,it} - \propto + \lambda_1 CO_{2,it-1} + \varphi_1 DFI_{it} + \varphi_2 IPR_{it} + \varphi_3 ISC_{it} + \varphi_4 FFEC_{it} + \varphi_5 FDII_{it} + \varphi_6 IR_{it} + \alpha_i + \varepsilon_{it} \quad (4)$$

In specifications 3 and (4), digital financial inclusion, the main variable is an endogenous variable in the literature (Ozturk & Ullah, 2022). When working with panel data, issues like serial correlation and heterogeneity arise, which are addressed using system GMM. The Arellano and Bond (1991) method is similarly adopted to examine the impact of digital financial inclusion on economic development and CO_2 emissions. GMM is valued for addressing both endogeneity and the challenges posed by limited data points. As an instrumental variable technique, GMM is considered superior to 2SLS. Roodman (2009) notes that GMM is particularly effective with datasets characterized by a small temporal dimension and a large cross-sectional dimension, which suits our dataset. This approach is also supported in the literature by Ozturk and Ullah (2022), and Wang (2019). Diagnostic tests were conducted to validate the GMM estimations. The Arellano-Bond AR (2) test assessed second-order serial correlation in first-differenced errors, whereas the Sargan test validated the exogeneity of the instruments. No substantial autocorrelation was detected, hence confirming the robustness of the GMM estimates. It is important to note that while the data's structure strengthens the results, factors like limited observations might influence the robustness of the relationships explored in this study.

We utilize a panel dataset from 2005 to 2022 to examine the impacts of DFI and economic expansion on environmental quality within the ASEAN nations. Table 2 systematically outlines definitions, variable abbreviations, and data sources.

Table 2. Definitions of indicators and associated data sources.

Indicator	Abbreviation	Explanation	References
Gross Domestic Production Growth Rate	GDP	Annual percentage increase in GDP	Ozturk & Ullah, 2022
Carbon Dioxide Emissions	CO_2	CO_2 emissions (kilotons)	Ozturk & Ullah, 2022
Automated Teller Machines	ATMD	Automated teller machines (per 100,000 persons)	Le et al., 2020; Shen et al., 2021
Debit Card	DC	Debit Card (+ age of 15 years)	Le et al., 2020; Shen et al., 2021
Internet Penetration Rate	IPR	% of the population using the Internet	Le et al., 2020; Zaidi et al.,2021
Industrial Sector Contribution	ISC	Industrial sectors' contribution to GDP (+construction)	Le et al., 2020; Zaidi et al.,2021
Fossil Fuel Energy Usage	FFEC	% of energy consumption from fossil fuels	Le et al., 2020; Zaidi et al.,2021
Foreign Direct Investment Inflow	FDII	FDI net inflows as a percentage of GDP	Le et al., 2020; Zaidi et al.,2021
Inflation Rate	IR	Annual percentage variation in consumer price indices	Le et al., 2020; Zaidi et al.,2021

Source: World Bank, IMF, ASEAN Statistics

The data has been sourced from extensive databases provided by the World Bank (WDI), the International Monetary Fund (IMF), and ASEAN statistical resources. Environmental quality is quantified through CO_2 emissions, recorded in kilotons, while the annual GDP growth rate gauges EG. To assess digital financial inclusion (DFI), we utilize two specific indicators for the analysis: The

density of automated teller machines (ATMs) per 100,000 adults and the total number of debit cards within the ASEAN region. Prevailing research predominantly entails financial indices that reflect the influence of conventional financial services—often overlooking the digital facet of FI. The concept of FI, however, extends to the adoption and usage of financial products and services—which are vital for sustainable economic progress. FI facilitates enhanced access to education (SDG-4), healthcare (SDG-3), and housing and creates avenues for business and employment opportunities (SDG-8)—thereby playing a significant role in alleviating poverty (SDG-1), Inequality reduction (SDG-10), and fostering economic advancement (Arner et al., 2020; Danladi et al., 2023; Emara & Mohieldin, 2020; Essel-Gaisey & Chiang, 2022; Ferrata, 2019; Jan et al., 2023; Kara et al., 2021; Kuada, 2019; Ma'ruf & Aryani, 2019; Pandey et al., 2022; Valencia et al., 2021). The advancement of financial services into the digital realm has significantly amplified the reach and efficacy of FI, overcoming geographical constraints and temporal limitations traditionally associated with accessing financial amenities. In light of this evolution, this analysis incorporates DFI metrics than conventional indicators. Drawing on the methodologies of Khera et al. (2021), Liu et al. (2022), and Shen et al. (2021), we adopt ATM prevalence and DC user as proxies for DFI.

In alignment with recent scholarly contributions by Mallela et al. (2023) and Zaidi et al. (2021), our analytical model integrates a suite of control variables to augment its robustness. These variables include the internet penetration rate, quantified as the percentage of the population with internet access, and the scale of industrial activity, measured by the industry's value added to GDP. Furthermore, the analysis encompasses the construction sector and the extent of fossil fuel dependency, gauged by the percentage of energy consumption derived from fossil fuels. Foreign direct investment is measured as net inflow expressed as a percentage of GDP. Additionally, changes in consumer price indices reflect the annual inflation rate. Table 3 displays the descriptive statistics and correlation matrix for key variables, including GDP growth rate—CO_2 emissions, and other relevant factors. Descriptive statistics reveal a wide range of data points, with GDP growth rates varying from −2.128 to 18.005. Additionally, the distribution exhibits diverse shapes, as indicated by Skewness and kurtosis values. The correlation matrix reveals that the variables within the model exhibit low to moderate correlations. However, the negative correlation between GDP and ISC indicates that as ASEAN nations diversify and expand, the industrial sectors relative contribution declines in favor of services-oriented industries. The inverse correlation between CO_2 and FDII may indicate that elevated carbon emissions dissuade environmentally aware investors that emphasize sustainability and favor investments in greener economies (Xie et al., 2020). Furthermore, the inverse relationship between DC and FFEC suggests that enhanced digital financial services promote more efficient economic transactions and energy utilization, thereby diminishing dependence on fossil fuels (Adha et al., 2024). Similarly, the negative correlation between the IPR and the IR suggests that increased internet accessibility improves market efficiency and information dissemination, perhaps aiding in mitigating inflation rates (Çoban, 2022). Last, the inverse relationship between ISC and FFEC indicates that an increase in the industrial sector's GDP contribution may lead to a transition towards more sustainable energy practices, consequently diminishing fossil fuel usage. These arguments elucidate the complex interplay among economic growth, environmental considerations, technical infrastructure, and financial situations in ASEAN nations. As there is no individual correlation coefficient exceeding the high multicollinearity threshold, the model's reliability regarding multicollinearity concerns is validated.

Table 3. Descriptive statistics and correction matrix.

	GDP	CO_2	ATMD	DC	FDII	FFEC	IPR	IR	ISC
Descriptive statistics									
Mean	6.264	2881.391	61.017	14.592	5.619	52.383	59.289	8.230	30.449
Median	6.374	2806.422	61.803	14.615	5.822	53.376	58.434	8.600	31.290
Maximum	18.005	4981.922	99.675	24.725	9.979	79.961	99.707	14.890	49.733
Minimum	−2.128	1001.330	21.224	5.052	1.024	20.140	20.019	1.017	10.103
Std. Dev.	3.636	1069.092	23.183	5.508	2.539	16.705	24.895	3.857	11.116
Skewness	0.216	0.143	−0.018	0.022	−0.115	−0.214	−0.010	−0.132	−0.046
Kurtosis	2.737	1.954	1.811	1.938	1.862	1.961	1.710	1.995	1.862
Observations	180	180	180	180	180	180	180	180	180
Correction analysis									
GDP	1								
CO_2	0.061	1							
ATMD	0.393	0.110	1						
DC	0.245	−0.003	0.164	1					
FDII	0.158	−0.079	0.011	0.078	1				
FFEC	−0.193	−0.086	0.021	−0.074	−0.006	1			
IPR	0.657	−0.043	0.047	0.032	0.007	0.050	1		
IR	−0.094	−0.112	−0.120	−0.006	−0.002	0.029	−0.084	1	
ISC	−0.235	0.099	−0.056	−0.064	−0.003	−0.032	0.048	−0.038	1

Source: Compiled by author

Table 4 confirms the lack of acute multicollinearity in the estimation parameters, as indicated by Variance Inflation Factor (VIF) values remaining below the critical threshold of 10, thereby preserving the statistical integrity of the regression estimates.

Table 4. Variance inflation factor.

Variable	VIF	1/VIF
ATMD	1.060	0.943
DC	1.050	0.957
IR	1.030	0.967
ISC	1.020	0.978
FFEC	1.020	0.981
IPR	1.020	0.982
FDII	1.010	0.987
Mean VIF	1.03	

Source: Compiled by author

4. Findings and discussion

In this study, our objective is to extend the investigation on the effect of DFI on the EG and CO_2 emissions in ASEAN economies. Cross-sectional dependence tests are summarized in Table 5 and provide no indications of cross-sectional dependence of the economies we are dealing with. Table 6 presents the results of the heterogeneity test, indicating no significant slope heterogeneity, demonstrating that the impact coefficients remain uniform across cross-sections. To accurately estimate the selected variables, we implement econometric methods such as Pooled Ordinary Least Squares (POLS), Two-Stage Least Squares (2SLS), and Generalized Method of Moments (GMM). Each method is applied to two distinct models using ATMs and DC as proxies for DFI. POLS, 2SLS,

and GMM are all robust methodologies, although each is accompanied by distinct assumptions that affect the outcomes. POLS presumes the absence of unobserved heterogeneity or endogeneity, rendering it beneficial as a comparative baseline. Two-Stage Least Squares (2SLS) mitigates potential endogeneity through the use of valid instrumental variables, whereas Generalized Method of Moments (GMM) enhances efficiency and robustness, particularly in the context of heteroskedasticity and autocorrelation. These assumptions facilitate consistent and efficient estimations, hence augmenting the robustness of our findings across models. The methodology section elucidates that these methods were selected according to the data structure and the necessity to tackle particular econometric issues, ensuring the dependability of our results.

Table 5. Cross-Sectional dependence test.

	GDP	ATMD	DCU	FDII	FFEC	IPR	IR	ISC	IWR	RIE
Cross-Sectional Independence	0.036	2.497	1.638	−1.686	2.175	2.711	2.475	0.801	−0.706	−1.129
P-values	0.515	0.994	0.949	0.046	0.985	0.997	0.993	0.789	0.24	0.13
	CO_2	ATMD	DCU	FDII	FFEC	IPR	IR	ISC	IWR	RIE
Cross-Sectional Independence	0.289	2.497	1.638	−1.686	2.175	2.711	2.475	0.801	1.481	−1.352
P-values	0.614	0.994	0.949	0.046	0.985	0.997	0.993	0.789	0.931	0.088

Source: Author compiled

Table 6. Test for slope heterogeneity.

Models	Statistics	Values	p-value
GDP	Delta	0.195	0.845
	Delta adj.	0.313	0.754
CO_2	Delta	0.809	0.419
	Delta adj.	1.297	0.195

Source: Author Compiled

The analysis will first focus on interpreting the results related to economic development, followed by an assessment of the environmental model.

The results presented in Table 7 show the relationship between DFI and GDP within ASEAN countries, demonstrating that both ATM density (ATMD) and Debit Card (DC) significantly and positively influence GDP. A 1% increase in ATMs correlates with a 0.145% rise in GDP growth according to the POLS model and a 0.186% increase according to the 2SLS method. Nonetheless, this favorable correlation is inverted in the GMM model, suggesting that the effect of ATMs on GDP may fluctuate based on the estimate technique employed. Conversely, DC consistently exhibits a substantial positive impact on GDP across all models, with increments of 0.281% (POLS), 0.404% (2SLS), and 0.456% (GMM). These empirical results corroborate our hypothesis (1). Among the control variables, the internet penetration rate is a crucial determinant of economic growth across all estimation techniques, affirming its role as a pivotal factor in economic development. Foreign direct investment inflow also markedly enhances economic growth, reinforcing its status as a cornerstone of economic expansion. The inflation rate exhibits a notable positive effect on economic growth, implying that rising inflation could boost consumer spending as prices are expected to climb, thus driving economic activity. Surprisingly, industrialization exhibits a negative yet significant effect, indicating that a heavy

reliance on manufacturing at the expense of more advanced technological industries could lead to economic stagnation in ASEAN nations. The findings are consistent with research that underscores the critical role of financial technologies in driving economic growth across different regions. For instance, Sreenu (2024) highlights how digital technologies have significantly taken the Indian economy to the next level—enhancing access to financial services and operational efficiencies. Similarly, studies by Liu et al. (2021) and Xi and Wang (2023) show that through increased financial inclusion, enhanced economic stability, and inclusive economic growth, digital financial sustainability advanced economic quality in the China region. DFI is also gaining recognition as an important economic development driver, especially in the lower-middle-income ASEAN countries: Cambodia, Indonesia, Laos, Myanmar, the Philippines, and Vietnam (Ong et al., 2023).

Table 7. DFI and EG (OLS, 2SLS, GMM).

Variables	OLS		2SLS		GMM	
	Coefficient	p-value	Coefficient	p-value	Coefficient	p-value
ATMD	0.145	0.000***	0.186	0.004**	0.154	0.104
DC	0.281	0.000***	0.404	0.211	0.456	0.000***
FDII	0.26	0.000***	0.233	0.008**	0.231	0.003***
FFEC	−0.047	0.000***	−0.045	0.001***	−0.043	0.000***
IPR	0.096	0.000***	0.094	0.000***	0.094	0.000***
IR	0.124	0.003**	0.151	0.022**	0.129	0.097*
ISC	−0.071	0.000***	−0.061	0.011**	−0.063	0.009***
Observations	180		180		180	
R-squared	0.845		0.791		0.807	
Sargen Test			0.44			
AR (2)					1.44	
Instrument rank			8		8	

Source: Compiled by author Note: *** indicates $p < 0.01$; ** indicates $p < 0.05$; and * indicates $p < 0.1$.

The advancement of DFI is closely tied to the growth of the financial sector. As the number of commercial bank branches increases, FI will be enhanced and customer volumes will be boosted. Existing customers draw in new ones, positively impacting the country's economy. This expansion not only strengthens the financial sector by generating more revenue but also creates new employment opportunities, supporting Sustainable Development Goal 8 (SDG-8), which focuses on promoting sustained, inclusive economic growth and decent work for all (Yap et al., 2023). Additionally, this growth contributes to poverty reduction, aiding in the achievement of SDG-1 (Ozili, 2023), and helps reduce inequality, aligning with SDG-10 (Ozili, 2022), thereby improving tax revenues. The increase in infrastructure, such as ATMs and the usage of debit cards, also supports economic stability through digitalization.

Financial inclusion is regarded as a fundamental element of economic progress, enhancing individuals' quality of life. Financial institutions are progressively providing a range of services, such as Internet banking, cash deposit machines, ATM access, and digital account opening, which collectively enhance economic growth (Liu et al., 2021). Consequently, financial development is crucial for stimulating economic growth (Emara & El Said, 2021). We corroborate other studies highlighting the significance of financial inclusion (FI) in fostering economic growth and promoting quality of life (Ratnawati, 2020). Figure 1 illustrates the variations in the variables measured across all ASEAN countries in this study.

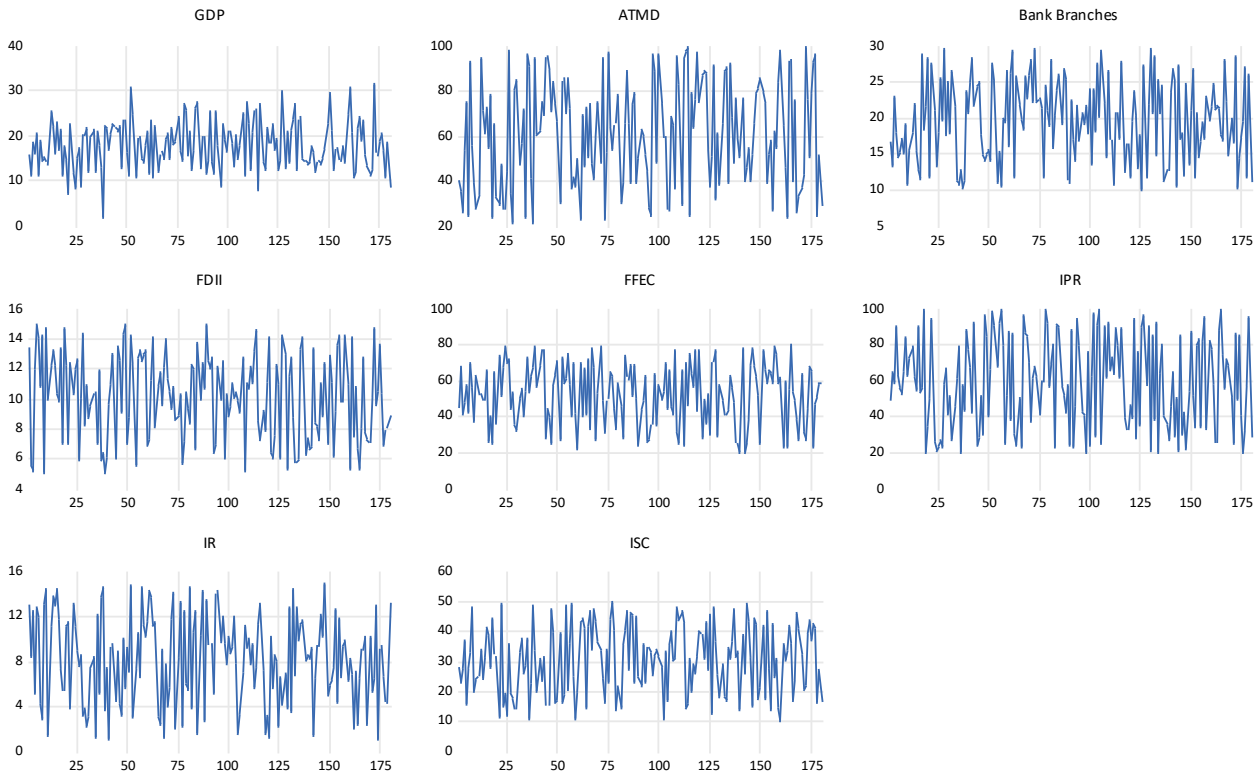

Figure 1. ASEAN (GDP, CO_2, ATMD, DC, FDII, FFEC, IPR, IR, ISC Data Source (WB-database, ASEAN stats database).

Table 8. DFI and CO_2 (OLS, 2SLS, GMM).

Variables	OLS		2SLS		GMM	
	Coefficient	p-value	Coefficient	p-value	Coefficient	p-value
ATMD	0.193	0.000***	0.19	0.000***	0.14	0.135
DC	0.229	0.000***	0.363	0.175	0.368	0.004***
FDII	0.189	0.000***	0.169	0.020**	0.178	0.020**
FFEC	0.106	0.000***	0.102	0.000***	0.101	0.000***
IPR	0.092	0.000***	0.091	0.000***	0.092	0.000***
IR	0.115	0.003***	0.114	0.037**	0.079	0.321
ISC	0.046	0.001***	0.042	0.037**	0.048	0.052*
Observations	180		180		180	
R-squared	0.903					
Sargen Test			0.29			
AR (2)					1.906	
Instrument rank			8		8	

Source: Compiled by author Note: *** indicates $p < 0.01$; ** indicates $p < 0.05$; and * indicates $p < 0.1$.

Table 8 shows the relationship between the DFI and CO_2 emissions. At last, for the regression results of ATM, it has a positive effect on CO_2 emissions significantly in both the POLS and 2SLS analysis, meaning that with the density of ATM rising by 1%, CO_2 emissions will increase by 0.193% and 0.190%, respectively. In contrast, the GMM model reveals a contrary effect. Similarly, DC significantly impacts CO_2 emissions, with a 1% rise in DC associated with increases of 0.229% in POLS, 0.363% in 2SLS, and 0.368% in GMM. These results contradict Hypothesis 2—underscoring the ambivalent effects of DFI. This study posits that digital financial inclusion (DFI) may reduce CO_2

emissions by enhancing resource efficiency and enabling the adoption of environmentally friendly technologies. Nonetheless, the empirical findings demonstrated an unexpected outcome, indicating a positive link between DFI and CO_2 emissions. Multiple factors may elucidate this outcome. A plausible reason is that the expansion of DFI has resulted in heightened industrial activity and energy consumption in the region. While DFI fosters economic progress, it may inadvertently lead to the proliferation of energy-intensive industries and elevated consumption, both of which augment CO_2 emissions. Moreover, DFI promotes economic expansion by broadening financial networks and advancing digitalization, which is crucial for economic progress, it also negatively affects the environment due to heightened energy use, increased e-waste, resource depletion, and the carbon footprint associated with digital services. The expansion of Internet penetration facilitates greater economic activity, often resulting in higher industrial production and energy consumption. As digital services proliferate, they create a demand for more goods and services, contributing to increased industrial output, which in turn leads to higher CO_2 emissions. Additionally, the rapid integration of digital financial services often coincides with the continued reliance of traditional industries on fossil fuels, particularly in developing ASEAN economies. The findings indicate that DFI can stimulate economic growth but may also intensify environmental issues unless paired with regulations that encourage sustainable activities. Policymakers must contemplate the incorporation of green technology in the proliferation of digital financial services, including the promotion of renewable energy use in digital infrastructures and the provision of incentives for eco-friendly financial transactions.

The study corroborates previous research indicating DFI's impact on CO_2 emissions (Khan et al., 2023; Wang et al., 2024; Wang et al., 2022), yet it contrasts with findings from J. Wang et al. (2023) and Zheng and Li (2022) who argue that DFI reduces CO_2 emissions. Furthermore, control variables like FDI also positively affect CO_2 emissions, suggesting that an upsurge in FDI intensifies CO_2 emissions due to heightened EG and consumption and infrastructure development. Similarly, increases in the Inflation Rate (IR) and Internet penetration rate (IPR) are linked to higher CO_2 emissions, as elevated inflation leads consumers to prioritize short-term economic activities over long-term energy investments, which increases energy consumption and impedes investments in green or eco-friendly projects. Likewise, a rise in Internet penetration escalates CO_2 emissions due to changes in consumption behaviors and the expansion of economic and industrial activities alongside digital economic growth. Finally, fossil fuel energy consumption (FFEC) and Industrialization (ISC) also exhibit positive and significant relationships with CO_2 emissions, indicating that increases in these factors contribute to higher CO_2 emissions. However, Huang et al. (2022) demonstrated a U-shaped relationship between DFI and environmental performance in China. Initially, increases in DFI contribute to heightened industrial activities and elevated pollution emissions. However, after reaching a specific threshold, further advancement in green innovation and energy efficiency practices leads to improved environmental sustainability. Other studies have underscored the negative impact of DFI on CO_2 emissions in the central China region (Zheng & Li, 2022). In contrast, the research conducted by Wang et al. (2022) aligned with our findings but is limited to the borders in the China region. The study demonstrated that DFI increases CO_2 emissions due to economic growth and industrial development. DFI, specifically, enables promotion and mobilization of business, which leads to increased energy consumption and highest ever Carbon footprint.

5. Conclusion, Policy Recommendations, and Limitations

In this study, our purpose is to determine the relationship between DFI and GDP as economic growth and CO_2 emissions as an environmental sustainability measure. The data were collected from 2005 to 2022 using various sources, including WDI, IMF, and ASEAN statistics. We employed research techniques such as POLS, 2SLS, and GMM to analyze the outcomes. The findings revealed that DFI catalyzes financial growth in ASEAN countries by enhancing economic activities by integrating more consumers into the financial network and facilitating international interactions, making the payment systems more efficient and accessible. Concurrently, this digitalization, while stimulating economic activities, also amplifies the ecological footprint. This increase is attributed to the escalation in industrialization and energy consumption, leading to heightened pollution and environmental degradation within the ASEAN region.

The role of government entities in mitigating these environmental challenges is critical, as they must balance economic activities and stability, which are primary objectives for all nations. These goals are often achieved through international trade, industrial advancements, and digital financial integration. However, such developments pose significant environmental challenges, which require government intervention through targeted policies that encourage the adoption of renewable energy and support sustainable, eco-friendly initiatives. Additionally, governments should promote environmentally sustainable digitalization practices and invest in the development of energy-efficient infrastructure such as green data centers and blockchain solutions that minimize energy consumption. The government should support the integration of renewable energy sources into digital financial systems. They should also collaborate with financial institutions to promote practices, such as offering green financing products like green bonds, climate impact bonds, and carbon credits. Additionally, alternative digital financial services like Internet banking, e-statements, mobile banking, and e-commerce should be prioritized to reduce environmental impact. These projects mitigate environmental externalities while enhancing financial access and advancing sustainable economic growth. To balance economic growth and environmental sustainability, policymakers, and financial institutions should prioritize sustainable practices within the digital financial sectors. Regulatory measures should be implemented to oversee and mitigate the carbon footprint of digital financial operations, emphasizing e-waste management and energy consumption monitoring.

Although our analysis provides substantial insights into the association between DFI and CO_2 emissions, it is essential to recognize that the environmental impacts of digital financial inclusion may not be immediate. A lagged effect may manifest, in which the benefits of DFI on economic growth are initially recognized, but its environmental consequences gradually surface as sectors develop and energy consumption escalates. Researechers could investigate the long-run impacts of DFI on CO_2 emissions, including the time lags between the influence of digitalization on economic growth and environmental sustainability.

This study is limited by its focus on a single region. Future research should expand to include a variety of global regions, such as the GCC countries, Europe, and North America. Additionally, the use of ATMs and debit cards as proxies for DFI, while useful, may not fully capture the impact of newer digital financial tools like mobile banking, digital wallets, and fintech solutions, which are becoming increasingly important in fostering financial inclusion. Incorporating these newer tools, along with an expanded dataset, would provide a more comprehensive and robust analysis of DFI's effects on economic development and CO_2 emissions.

Author contributions

Farooq Ahmad Bajwa: Conceptualization, methodology, data analysis, and original draft writing. Jingtao FU: Supervision, project administration, and critical review of the manuscript. Ishtiaq Ahmad Bajwa: Data collection, literature review, and contributing to the analysis. Manzar Rehman: Assisting in data interpretation and providing feedback on the manuscript. Karim Abbas: Contributing to the data analysis and review of the manuscript.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

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