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The Impact of Financial Inclusion and Digitalization on CO_2 Emissions: A Cross-Country Empirical Analysis

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Abstract: This research investigates the influence of financial inclusion and digitalization on carbon dioxide (CO_2) emissions by analyzing a sample of 38 countries from 2006 to 2020. For our analysis, we use the SGMM method and fixed-effect panel threshold models. Financial inclusion and digitalization are measured using newly constructed indices derived from principal component analysis. Despite some variations in specific details, the overall trend in the relationship among CO_2 emissions, financial inclusion, and digitalization remains consistent across high-income and low- and middle-income countries. Our findings reveal that financial inclusion has a significant and non-linear impact on CO_2 emissions. Conversely, digitalization is found to reduce CO_2 emissions significantly. Furthermore, the threshold models indicate that the impact of financial inclusion on CO_2 emissions varies depending on the levels of financial inclusion and digitalization. The influence of financial inclusion on CO_2 emissions is lower at higher levels of financial inclusion and digital technology, and vice versa. Our findings have implications for policymakers who seek to develop economic policies for sustainable development. By adopting policies that promote digital technologies, policymakers can enhance financial inclusion and economic growth and reduce CO_2 emissions.

Keywords: financial inclusion; financial development; technology development; greenhouse gas emissions; climate

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1. Introduction

The increase in carbon dioxide (CO_2) emissions is a pressing issue due to its detrimental effects on the environment and the planet. These emissions are primarily generated from human activities such as burning fossil fuels for energy production, industrial processes, and deforestation. The continuous rise in CO_2 levels has led to the greenhouse effect, trapping heat and causing global temperatures to increase [1]. CO_2 emission trends are reported to vary between developed and developing countries [2]. CO_2 emissions have recently decreased in developed countries due to the shift towards renewable energy sources, energy-saving measures, and reduced industrial output (such as in Europe and the United States). Meanwhile, emissions in developing countries are rapidly increasing, driven by population growth, urbanization, and rapid industrialization (such as in China, India, and Southeast Asia) [3]. This poses significant challenges for mitigating climate change and achieving sustainability goals. As a result, academic researchers have focused their efforts on investigating the relationship between various factors and their impact on CO_2 emissions, such as trade openness [4], industrialization [5], foreign direct investment [6], and financial development [7]. Among the factors influencing CO_2 emissions, there has been a recent surge in interest in exploring the relationship between financial inclusion and the environment due to the recognition of financial inclusion's role in global policy discussions on sustainable development. Nevertheless, studies on this relationship have yielded inconclusive results [8].

In this context, the rapid advancement of digital technology has revolutionized various aspects of life, encompassing both the financial and environmental sectors. Because of significant interest in minimizing CO_2 emissions without sacrificing economic growth, and the financial inclusion of communities who have been marginalized thus far from the mainstream, digitalization may be a solution to achieve the dual objectives. Consequently, there is a pressing need to comprehend the intricate relationship between financial inclusion and CO_2 emissions within the framework of the digital age.

The existing literature acknowledges that this topic remains relatively unexplored and under-researched [9]. There have been a few studies that align closely with our research interest, examining the correlation between digital finance and CO_2 emissions. However, most of these studies have primarily focused on China, utilizing provincial-level data and relying on digital finance indices provided by Beijing University to measure the extent of digital finance [9,10]. While the economic structure of China is significantly different from that of other countries because of its centrally planned economy, results from a provincial-level study of such an economy cannot be generalized. Additionally, digital finance does not fully represent financial inclusion in the context of digital technology development, and using a combined index does not capture the complex interplay between financial inclusion, digital technology, and its impact on CO_2 emissions. Therefore, the lack of research on the interactive relationship between financial inclusion, digital technology, and CO_2 emissions on a broader scale is the driving force behind our study.

In summary, recent interest has surged in exploring how financial inclusion or digitalization separately affect CO_2 emissions, driven by their roles in sustainable development. However, existing studies offer inconclusive findings and rarely investigate the combined impact of financial inclusion and digitalization on CO_2 emissions. Hence, a significant research gap exists in understanding these interactions globally, motivating our study. The identified gaps are significant because they hinder our comprehensive understanding of the complex interplay between financial inclusion, digital technology, and CO_2 emissions on a global scale. Existing studies, primarily focused on China and relying on limited data sources or combined indices, fail to capture the nuances and variations across different regions and economic contexts. Consequently, there is a lack of robust evidence to inform policymakers and practitioners about effective strategies to promote sustainable development while addressing the challenges of climate change. In this study, we aim to provide evidence for a more comprehensive set of markets by investigating the complex relationship between financial inclusion, digital technology, and CO_2 emissions with a sample of 38 countries in 15 years, from 2006 to 2020. Our research questions are as follows:

1. How does financial inclusion affect CO_2 emissions?
2. How does digitalization affect CO_2 emissions?
3. How does digitalization influence the relationship between financial inclusion and CO_2 emissions?

This study is conducted within an international context, focusing on two main regions, Asia Pacific and Europe, due to the relevance of the research topic, which revolves around financial inclusion, digital technology, and CO_2 emissions. Asia Pacific is currently the most dynamic region globally, yet financial exclusion remains a pressing issue, attracting considerable attention from many countries [8]. In Europe, there are numerous high-income countries and several countries with high levels of financial inclusion. Nevertheless, financial exclusion still affects millions of people in developing countries within Europe, highlighting a significant imbalance in financial inclusion between high-income and low- and middle-income countries. In addition, digitalization has played a pivotal role in driving growth, expanding opportunities, and improving government services across the Asia Pacific and Europe. The fintech sector in Asia Pacific is experiencing remarkable growth and is leading in technology adoption [11–13]. Similarly, Europe is at the forefront of the research, development, and application of new technological advancements, with substantial support from respective governments. Regarding climate issues, both Asia Pacific and Europe rank among the regions with the highest CO_2 emissions globally, alongside North America. As the home to two-thirds of the world's poor population, the Asia Pacific region is considered one of the most vulnerable regions to the impacts of climate change [14]. It has been the largest emitter of CO_2 in the past decade, contributing to nearly one-third of global emissions. Similarly, Europe ranks third among the regions with the highest CO_2 emissions and actively promotes international climate change cooperation [15]. Therefore, the selection of European and Asian countries demonstrates our efforts to ensure the topic's relevance to the sample and the diversity within the sample, thereby enhancing the significance and generalizability of the findings. Additionally, this sample allows for examining the differences in the research topic between high-income and low- and middle-income country groups.

Our study contributes significantly to the existing literature in four key ways. Firstly, it offers fresh insights into the relationship between financial inclusion and CO_2 emissions by analyzing a broader range of economies and utilizing recent data. This expanded scope adds valuable evidence to the ongoing discourse, which has previously yielded conflicting findings [8]. Our study aims to provide conclusive evidence to better understand this complex relationship.

Secondly, we extend the analysis to include the impact of digital technology development on the interplay between financial inclusion and CO_2 emissions on a larger scale. Unlike prior research that often amalgamated financial inclusion and digital factors [9], our study examines the individual effects of each factor and their interactions with CO_2 emissions. This nuanced approach provides deeper insights into the subject and represents the first attempt, to our knowledge, to investigate the combined impact of digital technology adoption and financial inclusion on CO_2 emissions.

Thirdly, while previous studies have predominantly focused on China due to data availability constraints [9], our study overcomes this limitation by constructing indexes of financial inclusion and digitalization using principal component analysis (PCA). By doing so, we contribute to methodological advancements, making it easier for future studies to address similar topics more efficiently.

Lastly, our study examines whether the relationship between financial inclusion, digital technology, and CO_2 emissions varies between high-income and low- and middle-income countries. This comparative analysis provides critical implications for regional studies and the banking sector, particularly in offering financial services to communities previously excluded from credit and other financial opportunities.

In light of this, we contribute to sustainability and the United Nations' Sustainable Development Goals (SDGs) by highlighting the dual role of financial inclusion and digitalization in promoting environmental sustainability. Specifically, our findings support SDG 13 (Climate Action) by demonstrating the impact of digitalization on CO_2 emissions. Furthermore, by examining financial inclusion, our research aligns with SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation, and Infrastructure), while uncovering its nuanced effects on environmental outcomes. These insights provide valuable guidance for policymakers and the financial sector in leveraging emerging digital technologies to improve the accessibility, efficiency, and cost-effectiveness of financial services, thereby achieving a balance between economic growth and environmental preservation.

This study is structured into five sections. Following the introduction, Section 2 provides a literature review and hypothesis establishment. The research methodology, data collection, and variable descriptions are reported in Section 3. Section 4 discusses the research findings before concluding in Section 5.

2. Literature Review and Theoretical Analysis

2.1. Climate Change, CO_2 Emissions, and Their Drivers

Greenhouse gases, particularly CO_2 emissions, are recognized as one of the primary drivers of climate change and have become a critical environmental issue worldwide. Numerous studies have explored the factors influencing CO_2 emissions to propose strategies for reducing them. According to Grossman and Krueger [16], the scale of the economy, economic structure, and technological level are the three key factors that impact the environment. Economic growth requires more resources and energy consumption, so a larger economy is associated with higher pollution levels and increased CO_2 emissions. Transitioning from energy-intensive industries to service sectors can also help to reduce CO_2 emissions. Lastly, technological advancements facilitate more efficient energy use, lowering energy consumption and CO_2 emissions. Several studies have investigated and expanded these three factors to understand the broader influences on CO_2 emissions. The results of these studies, though, vary depending on the research sample, theoretical frameworks, and methods employed.

Currently, three main strands of the literature report on factors influencing CO_2 emissions. The first group focuses on the impact of economic growth and energy consumption on CO_2 emissions. Many studies have reported a non-linear relationship between economic growth and CO_2 emissions [17–21], while others have found a linear and positive relationship [22–24]. Some other authors have found no significant relationship between economic growth and CO_2 emissions [25,26]. Additionally, Acheampong [27] observed a negative impact of energy consumption on global economic growth, and economic growth was found to increase CO_2 emissions. Paramati et al. [28] reported the positive contribution of renewable energy consumption to economic output and its adverse effect on CO_2 emissions.

The second literature group focuses on the relationship between CO_2 emissions, industrial structure, and technological progress. Bernardini and Galli [29] found that energy intensity is lower in service-oriented economies compared to production-oriented economies. In addition, technological advancements contribute to improved energy efficiency and reduced energy intensity [30–32]. Foreign direct investment (FDI) and trade are also considered sources of technological progress. Wei et al. [33] demonstrated that industrialization and free trade positively impact CO_2 emissions. Ul-Haq J. et al. [34] also found evidence that industry value-added promotes environmental degradation. Elliott and Sun [35] found a negative relationship between FDI and energy intensity. The authors also noted that transitioning to renewable energy and enhancing environmentally related technological innovations can support long-term CO_2 emissions reduction [36,37]. Similarly, Shi J. et al. [38] reported that technical innovation could significantly reduce CO_2 emissions.

The third group of literature examines the relationship between urbanization and CO_2 emissions. Many studies have found a positive correlation between urbanization and CO_2 emissions [38–41]. This is attributed to increased demands for food, housing, transportation, land use, and energy consumption resulting from urbanization, leading to severe environmental degradation [42]. Meanwhile, Ul-Haq J. et al. [34] reported that urbanization could reduce environmental degradation in China. Some other studies still report uncertain or insignificant impacts of urbanization on CO_2 emissions [42,43].

Our study focuses on the first two strands. Building upon previous research, we select control variables to include alongside the main factors of interest in the model. These control variables, including income [44–46], population [8], urbanization [39,46,47], industry [48,49], economic openness [50], FDI [51], and renewable energy [37,52], have been selected based on their relevance and findings from previous studies.

Furthermore, according to Dong et al. [53], the level of CO_2 emission and its drivers vary significantly between countries with different income levels. Despite the identification of CO_2 emissions' drivers at various levels, such as national, regional, and global, the differences between countries with different income levels seem to have received inadequate attention. We found one study by Dong et al. [53] which reports that while countries with low and middle incomes have been contributing to global CO_2 emissions recently, primarily high-income or industrialized countries bear the main historical responsibility for the current concentration of CO_2 in the atmosphere. Therefore, high-income countries have the highest obligation to reduce their CO_2 emissions. At the same time, high- and middle-income countries also need to make efforts to limit the growth of their emissions in the future. Our study aims to examine the differences in the nexus between financial inclusion, digital technology, and CO_2 emissions between the high-income and low- and middle-income country groups.

2.2. Financial Inclusion and CO_2 Emissions

From the 2000s, inclusive finance emerged as a significant aspect of financial progress, assessing the availability of financial services and products to cater to the requirements of individuals and businesses in a fair, convenient, accountable, and enduring manner [54]. As a core component of financial development, financial inclusion contributes to the growth of financial sectors and institutions, facilitating sustainable economic development by identifying and investing in high-quality, innovative industries and enterprises while enhancing the efficiency of capital allocation and other factors. At an individual and household level, financial inclusion provides opportunities to individuals and households to equitably participate in economic growth and access to available opportunities [8].

The relationship between financial inclusion (FI) and environmental sustainability has yielded mixed results [55]. Many authors acknowledge the positive role of financial inclusion in contributing to environmental sustainability and climate mitigation by reducing CO_2 emissions. Indeed, one of the major barriers to the adoption of green energy is the high initial investment cost [48]. The role of finance lies in optimizing resource allocation. The development of finance can facilitate the flow of resources to green sectors with more rational and efficient allocation. Therefore, when financial resources are widely available, households are more likely to invest in and access green energy [56]. Similarly, for businesses, the development of financial inclusion helps to reduce the financial costs of upgrading environmentally friendly equipment and production technologies, thereby promoting the implementation of green projects [57]. Thus, energy-saving and environmentally friendly production activities can be facilitated by reducing financial costs and increasing financial access through widespread financial inclusion [58].

On the contrary, several studies suggest that enhancing financial inclusion can increase CO_2 emissions [8,59–61]. These authors argue that financial inclusion can expand the overall industrial production capacity by increasing access to capital for individuals and societies, exacerbating environmental degradation, and reducing environmental quality [16]. They contend that while financial inclusion can promote and improve production and industrial activities, it can also increase carbon emissions because expanding production levels often leads to a higher energy consumption and, consequently, higher CO_2 emissions. In addition, the availability of financial services can enhance consumer purchasing power, enabling consumers to buy energy-intensive products such as cars, refrigerators, and air conditioners, posing a significant environmental threat through increased CO_2 emissions [8].

Another group of scholars supports the non-linear relationship between financial inclusion and CO_2 emissions, linked to the Environmental Kuznets Curve (EKC) theory. They argue that environmental quality is associated with different stages of economic development, where early stages of development are characterized by environmental degradation and later stages are associated with sustainable environmental practices [62]. The non-linear shape of this relationship has also garnered attention in various studies, yet the results are inconsistent. Some studies report a U-shaped relationship between financial inclusion and CO_2 emissions [63], while others suggest an inverted N-shape [47,64]. Additionally, the non-linear nature of this relationship between comprehensive financial systems and CO_2 emissions varies depending on the level of economic development and the region.

Therefore, this study investigates the potential moderating effects of economic development and technological advancement on the relationship between financial inclusion and CO_2 emissions. By exploring both linear and non-linear relationships, a more nuanced understanding of the complex dynamics between these variables can be achieved. Accordingly, we propose the following hypotheses:

H1: *Financial inclusion can increase CO_2 emissions.*

H2: *The relationship between financial inclusion and CO_2 emissions is non-linear.*

2.3. Digitalization and CO_2 Emissions

Similar to studies on the relationship between FI and CO_2 emissions, research on the relationship between technology and climate change remains unclear and uncertain. Some studies suggest technological advancements can increase CO_2 emissions [9,65]. Other studies support the idea that the development of digital technology can facilitate sustainable environmental practices by reducing greenhouse gas emissions [66–69], whereas another group of authors has found a non-linear relationship between technology and environmental sustainability. For instance, Gu et al. [70] and Jiao et al. [71] have provided experimental evidence of an inverted U-shaped relationship between technology and CO_2 emissions.

Regarding the role of digitalization in the nexus of financial inclusion and CO_2 emissions, some recent studies suggest that the emergence of new products, such as digital finance, can impact carbon emissions. Digital finance has become a new trend in the financial development of certain countries, notably China. Current research primarily focuses on the Chinese context. Digital finance has been found to promote green total factor productivity in Chinese cities and enhance urban ecological efficiency through industrial upgrading [72]. In addition, with the development of new technologies, traditional finance has evolved into new financial services that are resource-efficient and environmentally friendly [73]. Digitization allows the finance industry to utilize information on digital platforms to direct funds toward green projects while promoting green financial products to the public more quickly and extensively. As a result, the issue of information asymmetry is addressed more rapidly and accurately, contributing to the efficient allocation of financial resources and improving environmental sustainability through the promotion of green projects [74]. Moreover, applying new technologies in finance helps to lower the threshold for financial services, making it easier for individuals and businesses to access financial services [72]. With lower costs and significantly faster speeds, digital finance creates favorable conditions for people to develop awareness of green consumption. Additionally, with the widespread coverage of technology, green public welfare activities are widely disseminated to various target audiences.

Furthermore, for businesses, with the assistance of new technologies, digital finance can expand lending channels, reduce borrowing costs, improve the efficiency of financial resource allocation, and alleviate financial constraints for some enterprises. These benefits create opportunities for businesses to enhance investment in research and development and drive technological innovation. These new technologies can enhance resource utilization efficiency and overall production productivity while gradually phasing out high-polluting and energy-intensive production models, thereby reducing CO_2 emissions [9].

Therefore, this study aims to provide insights into the specific effects of digitalization on CO_2 emissions and to examine how digitalization influences the connection between financial inclusion and CO_2 emissions. By exploring these aspects, a more comprehensive understanding of the potential contributions of digitalization in addressing environmental challenges can be gained. Accordingly, we propose the following hypotheses:

H3: *Digitalization can reduce CO_2 emissions.*

H4: *The relationship between digitalization and CO_2 emissions is non-linear.*

H5: *The impact of financial inclusion on CO_2 emissions is different across different levels of digital technology.*

3. Data and Methodology

3.1. Data

This study was conducted from 2006 to 2020 across 38 countries. The selection of the sample and time period was determined by data availability. The sample includes 24 high-income countries, namely Australia, Austria, Belgium, Croatia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, the Netherlands, Poland, Portugal, Singapore, the Slovak Republic, Slovenia, Spain, and Sweden. Additionally, the sample has 14 low- and middle-income countries, including Bangladesh, Bulgaria, Cambodia, Fiji, India, the Kyrgyz Republic, Malaysia, Mongolia, Nepal, Pakistan, the Philippines, the Russian Federation, the Solomon Islands, and Timor-Leste. The classification of countries is based on the World Bank Country Classification as of July 2022, utilizing the criteria of gross national income (GNI) per capita. All data used in the study were collected from the World Development Indicators (WDIs).

3.2. Research Models

This study examines the relationship between financial inclusion, greenhouse gas emissions, and the role of digitalization in this relationship. The study builds upon the STIRPAT model (Stochastic Impacts by Regression on Population, Affluence, and Technology) proposed by Dietz and Rosa [75]. This model has also been used in similar studies related to CO_2 emissions [8,67]. The model takes the following form:

$$I_{it} = \beta_0 + \beta_1 P_{it} + \beta_2 A_{it} + \beta_3 T_{it} + \varepsilon_{it}$$

I represents the environmental impact, P represents the population, A represents the affluence or economic activity per person, and T represents the environmental impact per unit of economic activity. The environmental impact is determined by the technology used for producing goods and services, as well as the social organization and culture that influence how the technology is utilized, for a specific country i, in a given year t. The coefficients β_1, β_2, and β_3 represent the elasticities of the environmental effects with respect to P, A, and T, respectively.

This study uses the CO_2 emissions variable (CO2) as our dependent variable. We focus on two primary variables of interest: the financial inclusion index (FI) and the digital technology index (DT). These variables were constructed using principal component analysis (PCA). The FI variable represents the level of financial inclusion and is based on three proxies: the number of bank branches per 100,000 adults (BRANCH), the percentage of financial system deposits to GDP (DEPO), and the percentage of domestic credit to the private sector as a proportion of GDP (CREDIT). The first proxy measures the extent of financial expansion and the ability to access finance, while the last two proxies represent the depth of financial institutions.

The DT variable reflects technological infrastructure and consists of three proxies: the number of secure internet servers (INTERNET), the number of mobile cellular subscriptions per 100 people (MOBILE), and the number of ATMs per 1000 adults (ATM). The first two proxies measure the basic infrastructure of digital technology, while the last proxy represents the application of technology in the financial sector. While previous literature has sometimes included ATMs as a proxy for financial inclusion, we have opted to retain ATMs in the digital technology (DT) index due to their significant role as technology-enabled tools that support modern banking services. ATMs now incorporate digital technology to enhance user experience, offering features such as automated transactions, fund transfers, and top-up services. This aligns with the purpose of the digital technology index, which aims to capture the extent of digital technology adoption within the financial system. To maintain a clear distinction between the two indices, the financial inclusion (FI) index is focused solely on traditional financial services, whereas the DT index emphasizes technological advancement. By categorizing ATMs within the DT index, we highlight the differentiation between traditional financial access (FI) and the growth of digital technology (DT), which is central to our study's conceptual framework.

Building on previous empirical studies on factors influencing CO_2 emissions (CO2), we added control variables, including the country's income (INC), population growth (POP), urbanization (URB), industry (IND), economic openness (OP), foreign direct investment (FDI), and renewable energy consumption (RE). By inheriting previous research [8,76], we took the natural logarithm of CO2, INC, URB, IND, OP, and RE before using them in the regression models. Taking a variable's natural logarithm can help to transform skewed or highly skewed data into a more symmetrical distribution. It also stabilizes the variance of a variable, which can make the data easier to analyze and interpret. We did not take the natural logarithm of FI and DT as they are indexes created by three standardized proxies with mean 0 and standard deviation 1. This technique was not applied for POP and FDI as they have negative values.

The following two models estimate the impact of financial inclusion on CO_2 emissions:

$$lnCO2_{it} = \propto_0 + \propto_1 FI_{it} + \propto_2 Control_{it} + \varepsilon_{it} \quad (1)$$

$$lnCO2_{it} = \beta_0 + \beta_1 FI_{it}^2 + \beta_2 FI_{it} + \beta_3 Control_{it} + \varepsilon_{it} \quad (2)$$

The following two models estimate the impact of digitalization on CO_2 emissions:

$$lnCO2_{it} = \gamma_0 + \gamma_1 DT_{it} + \gamma_2 Control_{it} + \varepsilon_{it} \quad (3)$$

$$lnCO2_{it} = \tau_0 + \tau_1 DT_{it}^2 + \tau_2 DT_{it} + \tau_3 Control_{it} + \varepsilon_{it} \quad (4)$$

The two following two models estimates the combined impact of financial inclusion and digitalization on CO_2 emissions:

$$lnCO2_{it} = \chi_0 + \chi_1 FI_{it} + \chi_2 DT_{it} + \chi_3 Control_{it} + \varepsilon_{it} \quad (5)$$

$$lnCO2_{it} = \mu_0 + \mu_1 FI_{it} + \mu_2 DT_{it} + \mu_1 FI_{it}.DT_{it} + \mu_3 Control_{it} + \varepsilon_{it} \quad (6)$$

This study utilizes the system generalized method of moments (SGMM), which is outlined by Arellano and Bover [77] and fully developed by Blundell and Bond [78] for panel regression analyses of the models. This method has the advantage of using instrumental variables to address the endogeneity issue of the explanatory variables.

To ensure the non-linear relationship between financial inclusion and CO_2 emissions robustness, we employ the fixed-effect panel threshold model proposed by Hansen [79], Petruška et al. [76], and Wang [80]. We expect to identify financial inclusion and digitalization thresholds while considering financial inclusion's impact on CO_2 emissions. We consider the following single-threshold model:

$$lnCO2_{it} = \omega_0 + \omega_1 FI_{it} I(FI_{it} \le \lambda) + \omega_2 FI_{it} I(FI_{it} > \lambda) + \omega_3 Control_{it} + \varepsilon_{it} \quad (7)$$

$$lnCO2_{it} = \nu_0 + \nu_1 FI_{it} I(DT_{it} \le \kappa) + \nu_2 FI_{it} I(DT_{it} > \kappa) + \nu_3 Control_{it} + \varepsilon_{it} \quad (8)$$

We also want to test the double-threshold model as follows:

$$lnCO2_{it} = \rho_0 + \rho_1 FI_{it} I(FI_{it} \le \lambda_1) + \rho_2 FI_{it} I(\lambda_1 < FI_{it} < \lambda_2) + \rho_3 FI_{it} I(FI_{it} \ge \lambda_2) + \rho_4 Control_{it} + \varepsilon_{it} \quad (9)$$

$$lnCO2_{it} = \eta_0 + \eta_1 FI_{it} I(DT_{it} \le \kappa_1) + \eta_2 FI_{it} I(\kappa_1 < DT_{it} < \kappa_2) + \eta_3 FI_{it} I(DT_{it} \ge \kappa_2) + \eta_4 Control_{it} + \varepsilon_{it} \quad (10)$$

In Models (7) and (9), FI is the threshold variable, while in Models (8) and (10), DT is the threshold variable. The function *I*() is a conditional function that takes a value of 1 if the proposition inside the parentheses is true and 0 otherwise. This implies that the impact of financial inclusion on CO_2 emissions will differ when the level of financial inclusion or digitalization exceeds or falls below a certain threshold. The variable notes are provided in Appendix A.

After performing the regression for all countries in the sample, we also estimate separate regression for high-income and low- and middle-income countries to examine the differences between the overall and individual results for each country group.

3.3. Creation of Financial Inclusion Index and Digital Technology Index by PCA

This study's two key independent variables are financial inclusion (FI) and digitalization (DT). The researchers employed PCA to construct these variables to create composite indices. The PCA method was used to reduce the multidimensionality of the data and construct composite indicators, helping to eliminate redundant information and extract underlying relationships and features [72].

Since the proxies of FI and DT have different units, scales, and significant variance differences, we standardized these variables using the z-score method before applying PCA to generate the FI and DT indices [6]. The z-score standardization will be measured as follows, where $\overline{X}$ is the average value of the variable, and δ is the standard deviation:

$$z - \text{score} = \frac{X_i - \overline{X}}{\delta}$$

In this research, the mean value of these standardized variables is 0, and their standard deviation is 1.

PCA is conducted in two steps. Firstly, different components are estimated to determine the lowest pairwise correlation and variations in the original variables. Then, only the retained components with eigenvalues greater than 1 are used to construct the index [73]. Table 1 presents the eigenvalues of Component 1 and the pattern matrix of PCA for the financial inclusion index (FI) and digital technology index (DT) for all countries in the sample. It can be observed that the eigenvalue of Component 1 is higher than 1. Thus, we select the pattern matrix of Component 1 to calculate the FI and DT variables.

Table 1. Pattern matrix of PCA for the financial inclusion index (FI) and digital technology index (DT).

Index	Symbol		Component 1
Financial inclusion index	FI	Eigenvalue	1.5482
		BRANCH	0.4459
		DEPO	0.5896
		CREDIT	0.6734
Digital technology index	DT	Eigenvalue	1.32681
		INTERNET	0.8632
		MOBILE	0.4706
		ATM	0.1825

Note: BRANCH: the number of bank branches per 100,000 adults; DEPO: the percentage of financial system deposits to GDP; CREDIT: the percentage of domestic credit to the private sector as a proportion of GDP; INTERNET: the number of secure internet servers; MOBILE: the number of mobile cellular subscriptions per 100 people; and ATM: the number of ATMs per 1000 adults.

4. Research Results Analysis

4.1. Trends of CO_2 Emissions, Financial Inclusion, and Digital Technology

Figure 1 depicts the average trend of CO_2 emissions, financial inclusion, and digitalization in 38 countries across the Asia Pacific and Europe regions from 2006 to 2020. In general, there is a slight decline in CO_2 emissions over the years. On the other hand, the development of digital technology infrastructure has been rapidly and continuously increasing, particularly since 2016, when the concept of the "Fourth Industrial Revolution" was first introduced at the World Economic Forum, marking a significant milestone in the awareness and discussion of the Fourth Industrial Revolution and initiating the global trend of digital transformation, leading to the growth of digital technology infrastructure in many countries [81]. This observation suggests a potential inverse relationship between lnCO2 and DT. Furthermore, the financial inclusion index shows fluctuations around the mean level (0) throughout the years. From 2006, the FI index steadily rose and reached its peak in 2009. However, it consistently declined for the following decade before experiencing a substantial increase in 2020.

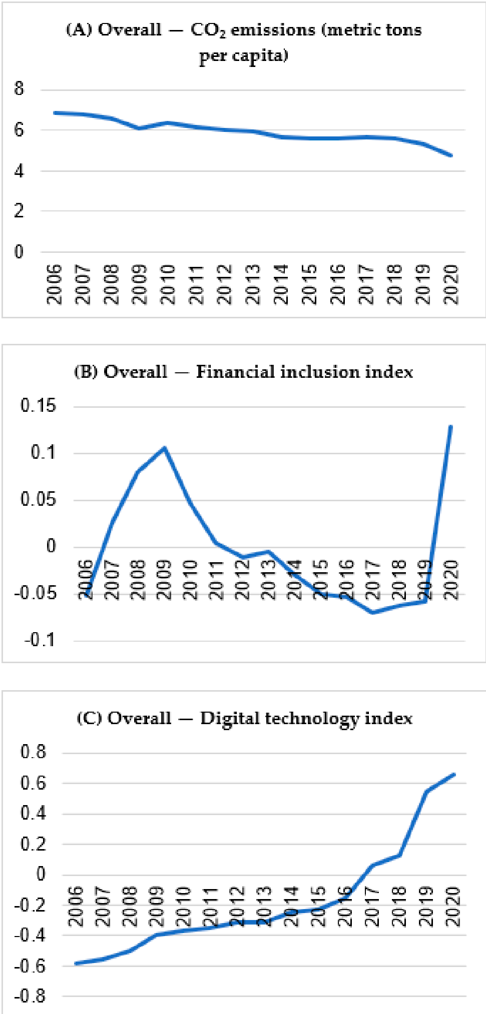

Figure 1. Trends of CO_2 emissions, financial inclusion, and digitalization in the complete sample. Note: The values used in Figure 1 represent the average values across the 38 countries in the study sample for CO_2 emissions (metric tons per capita) (**A**); financial inclusion index—FI (**B**); and digitalization index—DT (**C**).

Figure 2 illustrates the trends of CO_2 emissions, financial inclusion, and digitalization in the 24 high-income countries included in our sample. Overall, the trends in these high-income countries are similar to those observed in the complete sample. Initially, the high-income group exhibits a very high level of CO_2 emissions per capita, estimated at around 10 metric tons. However, their environmental efforts have led to a decreasing trend, gradually reducing emissions to approximately 6 metric tons per capita. In addition, the FI index in high-income countries witnessed an initial increase from 2006 to 2008. Then, it experienced a consistent decline over the subsequent 11 years before reversing its trajectory and commencing an upward trend from 2019 onwards. The drop in financial inclusion in developed countries from 2008 to 2019 was due to the lingering effects of the global financial crisis, resulting in tighter lending standards, reduced credit availability, and increased unemployment rates. Since 2019, there has been a shift toward promoting financial inclusion through initiatives such as technological advancements, regulatory reforms, and a renewed focus on expanding access to financial services. Despite fluctuations, the financial inclusion index for these countries consistently remains above the average (>0), indicating a relatively high level of financial inclusion in high-income countries. In terms of the DT variable, the level of digitalization in these countries exhibited a continuous increase from 2006 to 2020. Particularly, from 2016, the development of digital technology surpassed the average level and experienced significant growth. Notably, countries such as Germany, Japan, and the Netherlands have emerged as leaders in technological advancements.

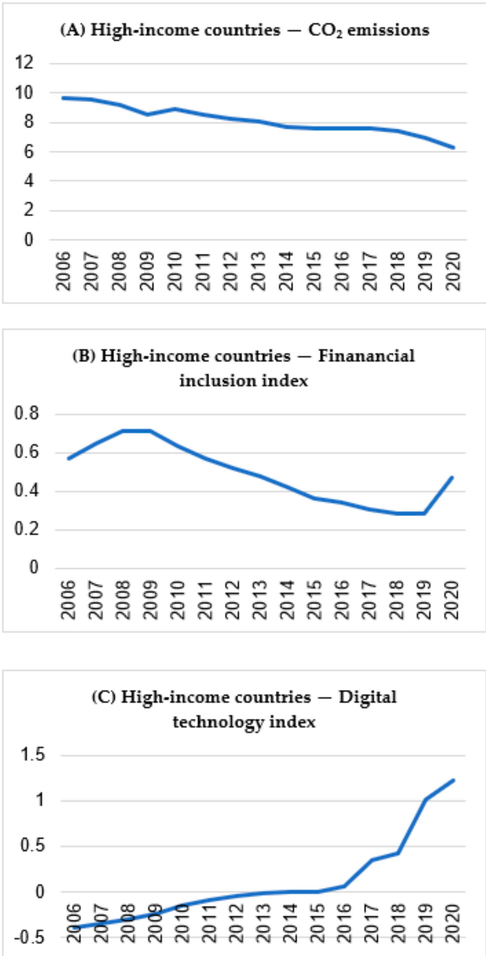

Figure 2. Trends of CO_2 emissions, financial inclusion, and digital technology in high-income countries. Note: The values used in Figure 2 represent the average values across 24 high-income countries in the study sample for CO_2 emissions (metric tons per capita) (**A**); financial inclusion index—FI (**B**); and digital technology index—DT (**C**).

Figure 3 illustrates the trends of CO_2 emissions, financial inclusion, and digitalization in low- and middle-income countries within the study sample from 2006 to 2020. Notably, these countries exhibit distinct patterns compared to the complete sample and high-income countries. Firstly, the amount of CO_2 emissions in low- and middle-income countries is significantly lower than in high-income countries, averaging around 2 metric tons per capita. Over the 14 years, there was a slight increase before a decline in 2020, reaching approximately the same level as in previous years. This suggests that low- and middle-income countries are also facing the responsibility of addressing the rise in greenhouse gas emissions. Regarding financial inclusion, the FI index steadily increases in low- and middle-income countries, indicating continuous improvement in financial access capabilities. However, the index remains below the average, implying that financial access is still limited and faces various challenges. Regarding digital technology infrastructure, low- and middle-income countries have also witnessed rapid development. Nevertheless, the infrastructure still lags significantly behind the average level. In 2020, there was a slight decrease, primarily driven by a decline in mobile cellular subscriptions (per 100 people) in some countries due to the impact of the COVID-19 pandemic.

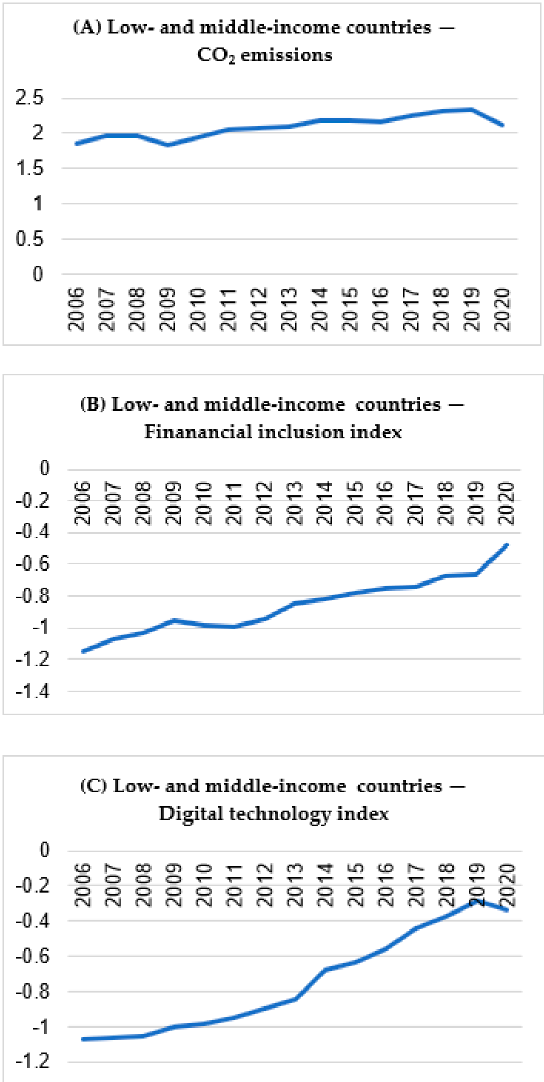

Figure 3. Trends of CO_2 emissions, financial inclusion, and digital technology in low- and middle-income countries. Note: The values used in the chart represent the average values across the 14 low- and middle-income countries in the study sample for CO_2 emissions (metric tons per capita) (**A**); financial inclusion index—FI (**B**); and digital technology index—DT (**C**).

4.2. Descriptive Statistics, Correlations Matrix, and Unit Root Tests

Table 2 presents the descriptive statistics of the variables in this study. It can be observed that the variable lnCO2 has a mean of 1.4, ranging from −0.5362 to 3.1422. The variable FI has a mean of 0.2828, with a relatively large range [−1.4038, 4.1301], indicating significant differences among countries. The variable DT has a mean of 0.7459 and ranges from −0.3783 to 9.4663, highlighting substantial variations in the digital technology index across the countries in the sample.

Table 2. Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
lnCO2	570	1.4632	0.8017	−0.5362	3.1422
FI	570	0.2828	1.0651	−1.4038	5.1301
DT	570	0.7459	1.1716	−0.3783	9.4663
lnINC	570	10.6358	1.6165	7.6772	17.3932
POP	570	0.1968	0.7567	−2.2585	2.6960
lnURB	570	4.0906	0.4111	2.9012	4.5858
lnIND	570	3.1354	0.4291	1.1475	4.2173
lnOP	570	4.5169	0.5830	3.2069	6.0927
FDI	570	2.9478	10.4221	−57.5323	106.5942
lnRE	570	2.7284	1.3183	−4.6058	4.5259

Note. lnCO2: natural logarithm of CO_2 emissions; FI: financial inclusion index; DT: digital technology index; lnINC: natural logarithm of GDP per capita; POP: population growth; lnURB: natural logarithm of urban population; lnIND: natural logarithm of industry's added value; lnOP: natural logarithm of economic openness; FDI: Foreign direct investment; and lnRE: natural logarithm of renewable energy consumption.

Table 3 displays the correlation matrix among the variables. The matrix reveals a strong correlation between the variable FI and lnCO2, with a relatively high correlation coefficient of 0.8906, which predicts a significant relationship between FI and CO_2 emissions. In addition, the independent variables exhibit correlation coefficients ranging from −0.4862 to 0.6173, indicating no strong correlations.

Table 3. Correlation matrix.

	lnCO2	FI	DIT	lnINC	POP	lnURB	lnIND	lnOP	FDI	lnRE
lnCO2	1									
FI	0.8906 ***	1								
DT	0.1661 ***	0.4142 ***	1							
lnINC	0.579 ***	0.5822 ***	0.1563 ***	1						
POP	0.175 ***	0.274 ***	0.1531 ***	0.1139 **	1					
lnURB	0.7767 ***	0.6173 ***	0.0698	0.5209 ***	0.0829 *	1				
lnIND	0.2704 ***	0.3018 ***	0.1396 ***	0.2211 ***	0.2733 ***	0.2706 ***	1			
lnOP	0.0517	0.0579	0.0322	0.0437	0.041	−0.0067	−0.0137	1		
FDI	−0.0641	−0.0925 *	−0.1996 ***	−0.1292 **	−0.1144 **	−0.0237	0.0858 *	−0.0314	1	
lnRE	−0.2747 ***	−0.4397 ***	−0.4862 ***	−0.3244 ***	−0.0799	−0.0692	0.1153 **	−0.0529	0.0027	1

Note: *, **, and *** represent significance at the 10%, 5%, and 1% levels, respectively.

Table 4 presents the results of the variance inflation factor (VIF) analysis, providing valuable insights into the multicollinearity within the regression model. With an average VIF value of 1.64, the findings suggest that multicollinearity among the predictor variables is relatively low. Each variable exhibits a VIF below the commonly accepted threshold of 5, indicating a minimal correlation with other predictors. These results bolster the reliability of the regression model, indicating that the independent variables contribute unique information to the prediction of the dependent variable.

Table 5 presents the results of the unit root test. We tested the variables' cross-sectional independence and found that all variables are cross-sectional dependent. Therefore, we employed the Pesaran panel unit root test to examine the stationarity of the variables. The results indicate that the absolute value of the CIPS value is greater than the absolute values of the critical values at 10%, 5%, and 1%. Therefore, all variables are stationary and suitable for the SGMM model.

Table 4. Variance inflation factor (VIF) test.

Variable	VIF	1/VIF
FI	2.8600	0.3496
lnURB	2.0000	0.5001
lnRE	1.8200	0.5482
lnINC	1.7700	0.5658
DT	1.6000	0.6239
lnIND	1.3600	0.7351
POP	1.1700	0.8518
FDI	1.1400	0.8779
lnOP	1.0100	0.9912
Mean VIF	1.6400	

Table 5. Panel unit root test results.

	Pesaran's Test of Cross-Sectional Independence		Pesaran Panel Unit Root Test				
	p-Value	Cross-Sectional Independence?	CIPS	Critical Value at 10%	Critical Value at 5%	Critical Value at 1%	Stationary?
lnCO2	0.0000	No	−4.31	−2.55	−2.64	−2.80	Yes
FI	0.0000	No	−4.68	−2.55	−2.64	−2.80	Yes
DT	0.0000	No	−3.57	−2.55	−2.64	−2.80	Yes
lnINC	0.0000	No	−3.57	−2.55	−2.64	−2.80	Yes
POP	0.0000	No	−3.95	−2.55	−2.64	−2.80	Yes
lnURB	0.0000	No	−3.93	−2.55	−2.64	−2.80	Yes
lnIND	0.0000	No	−3.22	−2.55	−2.64	−2.80	Yes
lnOP	0.0000	No	−4.10	−2.55	−2.64	−2.80	Yes
FDI	0.0002	No	−3.78	−2.55	−2.64	−2.80	Yes
lnRE	0.0000	No	−3.03	−2.55	−2.64	−2.80	Yes

Note: The panel unit root test is conducted in two steps: (1) checking for cross-sectional independence to determine the appropriate type of unit root test and (2) performing the unit root test. In this study, we utilized the Pesaran panel unit root test because all variables are cross-sectionally dependent.

4.3. Results and Discussion

Table 6 presents the results of the SGMM regression model for Models (1) to (6) for three panels: (A) complete sample, (B) high-income countries, and (C) low- and middle-income countries. Overall, the results for the variables of interest in the three panels are similar. The post-estimation tests' results shed light on how the GMM model operates. Firstly, the AR(1) test result with a *p*-value below 0.05 indicates the presence of first-order autocorrelation, which is expected in SGMM models, suggesting that past values strongly influence current observations. The AR(2) test result with a *p*-value greater than 0.05 suggests no second-order autocorrelation, implying a steadier relationship between consecutive data points. The absence of AR(2) autocorrelation is also necessary to validate the instruments used in SGMM models. The Sargan test shows a *p*-value greater than 0.05, indicating that the instruments are not over-identified and are well specified. This result suggests there is no strong evidence of overidentification violations. This means that the instruments and variables are well-balanced, validating the model's reliability. The Sargan tests excluding groups with *p*-values greater than 0.05 provide further support for the validity of the instruments when excluding specific groups. These results are favorable, showing that the instruments remain well specified across groups, with no serious issues of overidentification. Additionally, the Difference-in-Sargan tests reinforce this by showing no major differences among subsets of instruments, confirming the stability of the model. These findings support the use of the GMM model and indicate that the assumption of consistent slopes holds true. Overall, the AR and Sargan test results indicate that instrument-related issues in the SGMM model are well managed. The results meet key assumptions, confirming the validity of the instruments and effectively addressing concerns around instrument proliferation and overidentification.

Table 6. SGMM results.

lnCO2	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Panel A: All countries						
FI	1.1825 ***	1.1837 ***			1.0738 ***	0.8613 ***
FI^2		−0.1983 ***				
DT			−0.2705 **	−0.6352 *	−0.2027 ***	−0.1950 ***
DT^2				0.0727		
FI.DT						−0.0082
lnINC	−0.1533 **	−0.0929 *	−0.0084	0.1542 *	−0.1627 ***	−0.0529
POP	−0.2024	−0.1182	0.0727	0.1557	−0.1886	−0.1850 *
lnURB	0.1661	0.1194	1.4373 ***	0.9790 ***	0.2881	0.3197 *
lnIND	−0.3652 **	0.0027	0.1443	−0.1269	−0.1594	−0.0423
lnOP	0.3128	−0.0396	−0.1208	−0.3434 *	0.2333	0.3232 ***
FDI	0.0168	−0.0159	−0.0317 *	0.0014	0.0007	0.0062
lnRE	0.2230 ***	0.0051	−0.2550 ***	−0.1577 *	0.0518	0.0194
_cons	1.4873	1.7134 *	−3.4792 **	−1.4822	1.0086	−0.6450
AR(1)	0.0000	0.0040	0.0000	0.0000	0.0000	0.0000
AR(2)	0.4640	0.9670	0.7200	0.9680	0.7880	0.7940
Sargan tests of overid. restrictions (*p*-value)	0.9530	0.9000	0.1000	0.3290	0.9860	0.8310
Sargan tests excluding group (*p*-value)	0.9420	0.7960	0.1580	0.1220	0.8300	0.5510
Difference (*p*-value)	0.6950	0.7890	0.0700	0.9300	0.9980	0.9540
Panel B: High-income countries						
FI	1.0970 ***	1.1127 ***			1.1210 ***	1.0558 ***
FI^2		−0.1678 ***				
DT			−0.2624 *	−0.3612 *	−0.2250 ***	−0.2082 ***
DT^2				0.0357		
FI.DT						−0.0056
lnINC	−0.0544	−0.0812 *	−0.0220	0.0820	−0.0991 **	−0.0720 *
POP	−0.2478	−0.0449	0.1617	0.2579 *	−0.2310 *	−0.2478 **
lnURB	0.1334	0.1138	1.4649 ***	1.1059 ***	0.1381	0.1340
lnIND	−0.2851 **	−0.0625	0.1238	−0.0050	−0.1526	−0.1168
lnOP	0.3083 *	0.0117	−0.1917	−0.3438	0.1957 *	0.2675 **
FDI	0.0216 *	−0.0010	−0.0405 **	−0.0102	0.0053	0.0067
lnRE	0.2251 ***	0.0310	−0.2595 ***	−0.2007 ***	0.0998 *	0.0885 *
_cons	0.0640	1.6801 **	−2.9931 *	−1.4882	0.9156	0.5113
AR(1)	0.0000	0.0040	0.0000	0.0000	0.0000	0.0000
AR(2)	0.8020	0.5720	0.4630	0.7560	0.6550	0.9490
Sargan tests of overid. restrictions (*p*-value)	0.2740	0.1790	0.1510	0.3810	0.7100	0.9490
Sargan tests excluding group (*p*-value)	0.3370	0.4670	0.5510	0.2070	0.4430	0.3010
Difference (*p*-value)	0.2640	0.0950	0.0530	0.7890	0.8800	0.8860

Table 6. *Cont.*

lnCO2	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Panel C: Non-high-income countries						
FI	0.9654 ***	1.0597 ***			0.7003 ***	0.6476 ***
FI^2		−0.1134 *				
DT			−0.3417 **	−0.3774	−0.1340 *	−0.1633 **
DT^2				0.0243		
FI.DT						−0.0180 ***
lnINC	−0.1397 *	−0.1360 *	0.0217	0.1307 *	−0.1002 **	−0.0190
POP	−0.0845	−0.0872	−0.0150	0.0996	−0.0401	−0.0969
lnURB	0.4460	0.3013	1.2948 ***	1.1839 ***	0.7127 ***	0.6754 ***
lnIND	−0.2421	−0.0720	0.3576	−0.0203	−0.1499	−0.1019
lnOP	−0.0293	−0.0631	−0.0524	0.0179	−0.0094	−0.0496
FDI	−0.0201	−0.0123	−0.0169	0.0037	−0.0212 *	−0.0137
lnRE	0.1474 **	0.0051	−0.2916 ***	−0.1554 *	−0.0226	−0.0130
_cons	2.2533	1.9935 *	−4.0568 ***	−4.1744 ***	0.1708	0.0974
AR(1)	0.0150	0.0290	0.0000	0.0000	0.0000	0.0050
AR(2)	0.7400	0.7120	0.6150	0.1350	0.1970	0.6400
Sargan tests of overid. restrictions (*p*-value)	0.9980	0.9070	0.2030	0.2800	0.0790	0.0800
Sargan tests excluding group (*p*-value)	0.9620	0.8640	0.0870	0.4600	0.2400	0.1400
Difference (*p*-value)	0.9980	0.7240	0.6560	0.1360	0.7100	0.9150

Note: *, **, and *** represent significance at the 10%, 5%, and 1% levels, respectively. Models 1 and 2 examine the relationship between FI and CO_2. Models 3 and 4 investigate the relationship between DT and CO_2. Models 5 and 6 explore the combined effect of FI and DT on CO_2, as well as the interaction between DT and the relationship between FI and CO_2.

Models 1 and 2 results indicate the individual relationship between FI and CO_2 emissions. Across all three panels, both models consistently show that FI has a positive and statistically significant correlation with lnCO2 at a 1% significance level. Therefore, we accept the hypothesis H1, indicating that enhancing financial inclusion leads to higher CO_2 emissions among the countries in the sample, including both high-income and low- and middle-income countries. This finding aligns with studies conducted by Le et al. [8] and Gokmenoglu and Sadeghieh [59].

This relationship can be explained by the theory of the economy's scale proposed by Grossman and Krueger [16]. Financial inclusion aims to provide individuals and businesses previously excluded from the formal financial system access to financial services. This increased access often leads to greater economic activity, increasing energy consumption and carbon emissions. For example, as more people gain access to credit and loans, there may be a rise in production and consumption, leading to increased energy usage and emissions. Furthermore, financial inclusion can also lead to an expansion of transportation networks and infrastructure. As individuals and businesses gain access to financial services, they may be able to afford vehicles or invest in transportation-related businesses. Consequently, the number of vehicles on the road will increase, leading to higher fuel consumption and emissions. Additionally, limited access to sustainable finance options in some cases may result in a reliance on fossil fuels, contributing to higher CO_2 emissions.

Furthermore, the coefficient of the variable FI^2 in Model 2 is significant at the 1% level, except for low- and middle-income countries where it is only significant at the 10% level. This suggests a non-linear relationship between FI and CO_2, leading to the acceptance of the hypothesis H2. This result is consistent with Koshta et al.'s findings [62], providing grounds for implementing threshold models to examine changes in the FI-CO2 nexus across different levels of financial inclusion and digital technology.

Moving on to Models 3 and 4, they illustrate the impact of digitalization on CO_2 emissions. Across all three panels, the results consistently show that DT has a negative correlation with lnCO2, indicating that the development of digital technology helps to reduce CO_2 emissions. This finding is in line with Fan et al.'s research [74], leading to the acceptance of the hypothesis H3. Grossman and Krueger [16] also support this notion, explaining that new technologies enhance production and energy efficiency, thereby reducing energy consumption and CO_2 emissions.

Digitalization facilitates electronic transactions, reducing the need for paper-based processes and decreasing paper usage, which in turn mitigates deforestation and associated carbon emissions from paper production. Additionally, digital tools and automation optimize energy usage in manufacturing processes, leading to lower energy consumption and reduced CO_2 emissions [82]. The rise of digital technology also enables remote work and virtual meetings, reducing the need for commuting and business travel, thus lowering fuel consumption and emissions from vehicles and airplanes [83].

Moreover, digital solutions allow for better monitoring and control of energy consumption, leading to energy savings and reduced carbon emissions. They also facilitate the integration of renewable energy sources into the power grid, ensuring a more efficient and sustainable energy system with lower CO_2 emissions. Furthermore, digitalization enables the collection and analysis of vast amounts of data, which can be used to identify energy inefficiencies and develop more sustainable practices [84,85].

Despite these advancements, the positive impact of digitalization on CO_2 emissions in high-income countries is weak, reaching only the 10% significance level. Additionally, the variable DT^2 in Model 4 is insignificant, indicating no evidence of a non-linear relationship between digitalization and CO_2 emissions, thus rejecting the hypothesis H4. This finding contradicts the claims of Gu et al. [70] and Jiao et al. [71] regarding a non-linear relationship.

After analyzing the individual effects of financial inclusion and digitalization on CO_2 emissions, our study investigates their combined impact and interaction using Models 5 and 6. The results align with Models 1 to 4, showing that financial inclusion leads to higher CO_2 emissions, while digitalization reduces them. Additionally, Model 6 introduces the interaction term FI.DT to explore the role of digitalization in the FI–CO2 relationship. The findings reveal that DT does not affect this relationship in the complete sample or in high-income countries. However, in low- and middle-income countries, the interaction variable's parameter is -0.018, which is significant at the 1% level, indicating that the combination of financial inclusion and digitalization in these countries can help to mitigate CO_2 emissions. This suggests that developing and adopting new technology can counteract the adverse effects of financial inclusion on CO_2 emissions in low- and middle-income countries. Thus, the hypothesis H5 is accepted in Panel C (low- and middle-income countries) but rejected in Panels A (complete sample) and B (high-income countries). These findings echo previous studies conducted in China on the role of digital finance. For example, Wang et al. [9] found that digital finance facilitates CO_2 emission reduction by facilitating the restructuring of energy industrial sectors. Similarly, Chang et al. [86] proposed that digital finance influences CO_2 emissions by fostering entrepreneurship and technological innovation. As technology advances, traditional financial products are transitioning into resource-efficient and environmentally friendly ones [73]. Integrating digital technology into financial services promotes energy efficiency and resource conservation. By reducing paper and cash usage, digital technology enables electronic financial transactions, diminishing the need for paper production and deforestation, ultimately leading to lower CO_2 emissions [87]. Moreover, digital solutions encourage energy-saving practices through smart home devices, energy management systems, and smart transport systems [84]. Digitization empowers the finance industry to leverage digital platforms to direct funds toward green projects while promoting green financial products to the public more swiftly and extensively [88]. The divergent results observed between low- and middle-income countries and high-income countries suggest a notable insight: the advancement of digital technology has a more significant effect on environmental issues in low- and middle-income countries.

Regarding control variables, the results indicate a positive association between URB and lnCO2, suggesting that higher levels of urbanization correspond to higher CO_2 emissions, consistent with prior studies by Behera and Dash [39], York et al. [40], and Zhang and Lin [41]. Urbanization often leads to heightened energy consumption and transportation demand, thereby contributing to environmental degradation [89]. Moreover, lnINC exhibits a negative correlation with lnCO2, implying that higher income per capita is associated with lower greenhouse gas emissions, which is in line with findings from Le et al. [8]. This relationship can be attributed to the fact that individuals with higher incomes are more likely to adopt cleaner technologies, invest in sustainable infrastructure, transition towards service-oriented economic models, and cultivate greater environmental consciousness. However, it is essential to note that this relationship is not universally consistent and necessitates the implementation of policy interventions and clean technologies to achieve concurrent economic growth and greenhouse gas emission reduction.

To explore the potential non-linear relationship between financial inclusion and CO_2 emissions further, we employed the fixed-effect panel threshold model proposed by Hansen [79] and Wang [80]. Table 7 provides a summary of the threshold estimation results.

Table 7. Threshold estimations.

	FI as Threshold Variable			DT as Threshold Variable		
	Threshold	**Lower**	**Upper**	**Threshold**	**Lower**	**Upper**
Panel A: Complete sample						
Th-1	−0.0040	−0.0429	0.0005	0.3609	0.3599	0.3625
Th-21	−0.3825	−0.4233	−0.3668	0.3598	0.3595	0.3604
Th-22	2.0662	1.9663	2.1757	0.6870	0.6148	0.7189
Th-3	1.1628	1.0956	1.1675	1.6978	1.4326	1.7190
Single (Prob)	0.0000			0.0000		
Double (Prob)	0.0000			0.0000		
Triple (Prob)	0.1333			0.2700		
Panel B: High-income countries						
Th-1	−0.3825	−0.4065	−0.3668	0.5317	0.5076	0.5430
Th-21	−0.3897	−0.4233	−0.3825	0.3660	0.3602	0.3665
Th-22	1.4725	1.3876	1.4762	1.7319	1.7084	1.8062
Th-3	0.7726	0.7432	0.8331	0.5317	0.5282	0.5430
Single (Prob)	0.0000			0.0000		
Double (Prob)	0.0000			0.0000		
Triple (Prob)	0.8433			0.3967		
Panel C: Low- and middle-income countries						
Th-1	−0.4388	−0.4417	−0.2442	0.3578	0.3564	0.3585
Th-21	−0.4388	−0.4417	−0.4006	0.3578	0.3564	0.3585
Th-22	1.1964	1.1801	1.2159	0.6268	0.5590	0.6836
Th-3	2.2568	1.9001	2.3767	0.2767	0.2482	0.2897
Single (Prob)	0.0000			0.0000		
Double (Prob)	0.0000			0.0000		
Triple (Prob)	0.8333			0.7100		

Note: The threshold estimator is at a 95% confidence level. The threshold effect test was conducted using a bootstrap method with 300 iterations. Th-1, Th-21, Th-22, and Th-3 represent different threshold levels in the analysis, indicating points at which the relationship between variables changes.

Table 7 provides threshold estimations for models where FI and DT serve as the threshold variables across different country samples. FI thresholds are identified at values of Th-1, Th-21, Th-22, and Th-3. These thresholds represent critical points where the relationship between the variables shifts. The threshold estimates, along with the lower and upper bounds, give confidence intervals showing the potential range within which the threshold points are valid. Similarly, DT thresholds are found at values of Th-1, Th-21, Th-22, and Th-3 across the complete and segmented samples. These DT thresholds allow us to observe changes in the relationships tied specifically to the levels of digital technology within the samples. Each panel includes the *p*-values for single-, double-, and triple-threshold models, indicating whether a single, double, or triple threshold is statistically significant.

In Panel A (complete sample), the results show that the single- and double-threshold models are statistically significant (*p*-value = 0.0000), while the triple-threshold model is not significant for either FI or DT (*p*-values of 0.1333 and 0.2700). This suggests that a double-threshold model provides the most robust choice, capturing significant shifts in relationships without overcomplicating the model. In Panels B (high-income countries) and C (low- and middle-income countries), single and double thresholds remain significant (*p*-value = 0.0000), with the triple-threshold model being statistically insignificant for both FI and DT. This consistency across groups supports the selection of a double-threshold model for both FI and DT.

The results in Table 7 reveal that the relationship between FI and CO_2 emissions exhibits double thresholds across all three panels. In the complete sample, the thresholds for the FI variable are −0.3825 and 2.0662, while those for the DT variable are 0.3598 and 0.6870. Conversely, in high-income countries, the thresholds for the FI variable are −0.3897 and 1.4725, with corresponding thresholds for the DT variable at 0.3660 and 1.7319. Similarly, in low- and middle-income countries, the thresholds for the FI variable are −0.4388 and 1.1964, while those for the DT variable are 0.3578 and 0.6268. Notably, the second threshold of the FI variable in the high-income and low- and middle-income country groups is approximately the same, while the second threshold of the DT variable in high-income countries is twice as high as in low- and middle-income countries.

Table 8 provides a detailed overview of the results obtained from fixed-effect panel threshold models, offering distinct parameter estimates for the FI variable within various threshold ranges. The analysis reveals that the level of financial inclusion development significantly influences the impact of FI on CO_2 emissions. Particularly in countries with lower levels of FI, the effect of FI on CO_2 emissions is more pronounced. This observation holds true for both the high-income and low- and middle-income country groups at a significance level of 1%. In countries with lower financial inclusion, enhancing access to finance leads to a more substantial increase in CO_2 emissions compared to countries with higher financial inclusion. This phenomenon can be attributed to the prioritization of financial resources for expanding industrial production and consuming energy-intensive products, such as transportation, refrigeration, and air conditioning, in countries with lower financial inclusion levels. Conversely, countries with relatively higher levels of financial inclusion have partially satisfied the demand for finance in expanding production and consuming primary products. Further enhancing financial inclusion in these countries may facilitate the implementation of green projects and access to environmentally friendly products, thereby mitigating the impact of financial inclusion on CO_2 emissions.

When comparing the low- and middle-income group with the high-income group, it becomes evident that financial inclusion exerts a more pronounced impact on CO_2 emissions in low- and middle-income countries. Additionally, it is noteworthy that this impact diminishes more substantially as financial inclusion levels increase. Specifically, in the low- and middle-income group, when FI surpasses or equals the threshold value of 1.1964, the parameter of the FI variable decreases markedly to 0.4605. Conversely, in high-income countries, when FI reaches or exceeds 1.4725, the FI variable's parameter also decreases, albeit to a lesser extent, settling at 0.5470.

Table 8. Results of fixed-effect panel threshold models.

	Threshold Variable	
Variables	**FI**	**DT**
Panel A: Complete sample		
FI (DT ≤ 0.3598)		1.0736 ***
FI (0.3598 < DT < 0.687)		0.7066 ***
FI (DT ≥ 0.687)		0.5681 ***
FI (FI ≤ −0.3825)	1.4811 ***	
FI (−0.3825 < FI < 2.0662)	0.6593 ***	
FI (FI ≥ 2.0662)	0.4819 ***	
DT	−0.0147 ***	−0.0870 ***
lnINC	0.0000	−0.0170 **
POP	0.0061	−0.0410 ***
lnURB	−0.0168	0.3273 ***
lnIND	−0.0412 ***	0.0226
lnOP	0.0008	−0.0017
FDI	0.0002	−0.0019 **
lnRE	−0.0008	−0.0058
_cons	1.7640 ***	0.2044
Panel B: High-income countries		
FI (DT ≤ 0.3660)		1.0813 ***
FI (0.3660 < DT < 1.7319)		0.8228 ***
FI (DT ≥ 1.7319)		0.6340 ***
FI (FI ≤ −0.3897)	1.4549 ***	
FI (−0.3897 < FI < 1.4725)	0.7046 ***	
FI (FI ≥ 1.4725)	0.5470 ***	
DT	−0.0182 ***	−0.0737 ***
lnINC	0.0058	−0.0265 ***
POP	0.0143 **	−0.0665 ***
lnURB	0.0067	0.3092 ***
lnIND	−0.0467 ***	0.0359
lnOP	0.0070	−0.0098
FDI	0.0008 *	−0.0028 **
lnRE	−0.0005	−0.0002
_cons	1.5942 ***	0.3448 ***
Panel C: Low- and middle-income countries		
FI (DT ≤ 0.3578)		1.2692 ***
FI (0.3578 < DT < 0.6268)		1.0728 ***
FI (DT ≥ 0.6268)		0.6716 ***
FI (FI ≤ −0.4388)	1.4999 ***	
FI (−0.4388 < FI < 1.1964)	0.6532 ***	
FI (FI ≥ 1.1964)	0.4605 ***	
DT	−0.0158 *	−0.1110 ***
lnINC	0.0136 ***	−0.0068
POP	−0.0063	−0.0041
lnURB	−0.0297	0.3051 ***
lnIND	−0.0668 ***	0.0174
lnOP	−0.0079	0.0125
FDI	-7.4×10^{-5}	−0.0009
lnRE	0.0092	−0.0083
_cons	1.7644 ***	0.1876

Note: *, **, and *** represent significance at the 10%, 5%, and 1% levels, respectively.

When DT is chosen as the threshold variable, the results reveal that the level of technological advancement influences the impact of financial inclusion on CO_2 emissions Across all three panels, as technological development increases, the detrimental effect of FI on CO_2 emissions diminishes. While the SGMM model uncovered the role of digitalization in the nexus between financial inclusion and CO_2 emissions in low- and middle-income countries, the threshold models indicate that this role extends to the entire sample, suggesting that the development of digital technology can mitigate the adverse effects of financial inclusion on climate change, thereby supporting the hypothesis H5. These combined efforts contribute to a greener and more sustainable future by reducing paper and cash usage, promoting energy efficiency, conserving resources, fostering energy-saving practices, and facilitating smart transportation.

Moreover, high-income countries necessitate a higher level of digital technology development (with a threshold value of 1.7319) to alleviate the negative impact of financial inclusion on CO_2 emissions compared to low- and middle-income countries (with a threshold value of 0.6268). This disparity could be attributed to the elevated levels of CO_2 emissions in high-income countries, requiring more substantial efforts, including technological advancements, to address climate change concerns effectively. This finding underscores the significance of high-income countries prioritizing and investing in advanced digital technologies to effectively tackle climate change issues.

In summary, our study unveils several pivotal findings that offer valuable insights for researchers and policymakers alike. Firstly, by constructing financial inclusion and digital technology indexes, we delineate the evolving landscape of CO_2 emissions, financial inclusion, and digitalization across the sampled countries, notably distinguishing between the high-income and low- and middle-income groups. Our analysis reveals a notable ascent in CO_2 emissions within low- and middle-income countries, juxtaposed with relatively stable advancements in financial inclusion and digital technology, albeit at modest levels. Conversely, high-income countries exhibit a slight decline in CO_2 emissions, yet consistently high levels persist, paralleled by robust development in digital technology and financial inclusion. These trends underscore the shared responsibility of both high-income and low- and middle-income nations in curbing CO_2 emissions and addressing climate change.

Secondly, our study furnishes compelling evidence demonstrating that while financial inclusion may exacerbate CO_2 emissions, the advancement of digital technology can serve to mitigate them. Notably, our SGMM model uncovers the impact of digitalization on the nexus between financial inclusion and CO_2 emissions, particularly within the low- and middle-income country group. Specifically, digital technology development acts to counterbalance financial inclusion's influence on CO_2 emissions.

Lastly, our exploration of the non-linear relationship between financial inclusion and CO_2 emissions through SGMM and threshold models yields insightful revelations. Our findings suggest that the influence of financial inclusion on CO_2 emissions is contingent upon the levels of financial inclusion and digitalization within each country. Particularly noteworthy is the amplification of financial inclusion's impact on CO_2 emissions at lower levels of financial inclusion. Additionally, as digital technology advances, its mitigating effect on the impact of financial inclusion on CO_2 emissions becomes more pronounced. These nuanced insights underscore the imperative of tailoring interventions to account for varying levels of financial inclusion and technological advancement in pursuit of sustainable development.

By synthesizing these findings, our study not only advances scholarly understanding but also provides actionable insights for policymakers seeking to address climate change and foster sustainable development.

5. Conclusions

Our study illuminates the intricate relationship between financial inclusion, digital technology, and CO_2 emissions using an international sample of 38 countries in Asia Pacific and Europe from 2006 to 2020, offering crucial insights with practical implications for policymakers. We recognize the urgent need to reconcile economic growth with CO_2 emission reduction and emphasize the pivotal roles of financial inclusion and digitalization in achieving this balance. We investigate how financial inclusion and digitalization impact CO_2 emissions and whether digital technologies play an influencing role in the relationship between financial inclusion and CO_2 emissions. The SGMM method and fixed-effect threshold models are employed as the research methodology.

The results of our study indicate that while financial inclusion significantly increases CO_2 emissions, digitalization statistically significantly reduces CO_2 emissions. We also find that digitalization can help to mitigate the negative impact of financial inclusion on climate change. Additionally, the impact of financial inclusion on CO_2 emissions depends on the levels of financial inclusion and digitalization in each country.

Our study contributes significantly to the existing literature in several key ways. Firstly, we offer fresh insights into the impact of financial inclusion on CO_2 emissions, addressing the previous research's inconclusive nature. By utilizing a new sample and an updated period, our findings are robust, consistent across multiple models, and applicable to country groups with different income levels. Moreover, our international sample enhances the generalizability of our findings, providing more conclusive results. Secondly, we delve into the broader implications of digital technology development on the relationship between financial inclusion and CO_2 emissions. Instead of merging these factors into a single index, we analyze their individual impacts and interactions, offering deeper insights into their relationship. This approach enhances our understanding of the topic. Thirdly, by employing the PCA method to construct indexes, we overcome data limitations and contribute methodologically. This method also facilitates future research on the same topic, streamlining the process. Lastly, our study pioneers an investigation into whether the relationship between financial inclusion, digital technology, and CO_2 emissions varies between high-income and low- and middle-income countries. This novel inquiry offers implications for regional studies and suggests tailored approaches for different regions, enriching our understanding of this complex relationship. Our research findings have significant policy implications, particularly in addressing disparities among countries of varying income levels. Tailored strategies are essential, considering the unique challenges faced by low- and middle-income as well as high-income countries. For low- and middle-income nations, policies should prioritize enhancing financial inclusion through targeted interventions such as expanding access to affordable financial services, promoting financial literacy, and strengthening regulatory frameworks. Simultaneously, investments in digital infrastructure and technology adoption should be emphasized to facilitate sustainable development initiatives and drive economic growth. In high-income countries with advanced digital technology, policymakers should leverage these capabilities to drive sustainability efforts. Initiatives could include incentivizing the adoption of green technologies, promoting digital innovation in renewable energy and resource management, and investing in smart infrastructure to optimize energy efficiency and reduce carbon footprints.

To mitigate the negative impact of financial inclusion on CO_2 emissions, policies should focus on improving financial inclusion by providing appropriate financial services while ensuring the sustainability and safety of the financial system. Encouraging the development and application of digital technology, especially green technologies, can optimize energy and resource utilization and facilitate the transition to cashless payment methods. In addition, as a broader policy suggestion to complement the findings of our research, international collaboration is essential for addressing global challenges, particularly in the context of the complex relationships between financial inclusion, digital technology, and CO_2 emissions. Policymakers should prioritize fostering international partnerships, knowledge-sharing, and capacity-building programs, especially in low- and middle-income countries. Given that our study examines countries with varying income levels, we recognize that different income groups face distinct challenges in reducing CO_2 emissions and promoting sustainable development. Sharing experiences, resources, and best practices can support these efforts, particularly in low- and middle-income countries. Additionally, integrating sustainability into financial and technological policies—such as promoting renewable energy, advancing green technologies, and incentivizing sustainable practices—can be supported through financial incentives and regulations. These efforts are crucial for addressing the challenges identified in our study and ensuring sustainable development across countries at different income levels.

Our study proposes avenues for future research. Firstly, while our study provides valuable insights, the sample size of 38 countries may limit the generalizability of the findings. With this sample size, there is a risk of not fully capturing the diversity of countries globally, affecting the applicability of the results to countries not included in the sample. Additionally, the sample composition may introduce biases, and the smaller sample size could reduce the statistical power of the analysis, impacting the reliability of the results. Therefore, caution should be exercised when extrapolating the findings to broader populations, and future research could benefit from expanding the sample size to enhance the study's generalizability. In addition, another limitation of this study lies in the heterogeneity within the group of developing countries, which may impact the robustness of the findings related to CO_2 emissions. While we classified countries based on income levels per the World Bank's criteria, this approach may not fully account for the environmental and economic diversity within the developing group. Future research could explore alternative classification methods, such as grouping countries by CO_2 emission levels or environmental vulnerability, to provide a more nuanced understanding of the relationship between financial inclusion, digitalization, and environmental impact. Regarding the methodology, while the study proposes indexes for financial inclusion and digital technology using the PCA method, the explanatory power of these indexes is relatively low. Future research could explore alternative methods for constructing indexes that may offer higher effectiveness in capturing the multidimensional aspects of financial inclusion and digital technology. Additionally, findings recognize the heterogeneity across countries and emphasize the importance of considering contextual factors. Researchers could further explore country-specific characteristics such as institutional frameworks, policy environments, and cultural factors to understand better the variations in the relationship between financial inclusion, digital technology, and CO_2 emissions. Future research could also evaluate the implementation and outcomes of specific policies to promote sustainable financial inclusion and digital technology development and their implications for CO_2 emissions reduction. Sector-specific analyses could also be conducted to explore the potential of digitalization in reducing CO_2 emissions and promoting sustainability in different sectors. Conducting further research will contribute to a more comprehensive understanding of the topic and provide valuable insights for the formulation of effective policies for sustainable development and environmental protection.

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Appendix A. Variable Notes

Variables	Symbol	Description
CO_2 emissions	CO2	CO_2 emissions (metric tons per capita)
Financial inclusion index	FI	BRANCH—Bank branches per 100,000 adults DEPO—Financial system deposits to GDP (%) CREDIT—Domestic credit to private sector (% of GDP)
Digital technology index	DT	INTERNET–Secure internet servers (in natural log) (infrastructure) ATM—Number of ATMs per 1000 adults MOBILE—Mobile cellular subscriptions (per 100 people)
Income	INC	GDP per capita (constant 2010 US$)
Population	POP	Population growth (annual%)
Urbanization	URB	Urban population (% of total population)
Industry	IND	Industry (including construction), value added (%GDP)
Economic openness	OP	The total import and export in goods/GDP
FDI	FDI	Foreign direct investment, net inflows (%GDP)
Renewable energy	RE	Renewable energy consumption (% of total final energy consumption)

Note: The financial inclusion index (FI) is created with 3 proxies, BRANCH, DEPO, and CRE, by PCA. The digital technology index (DT) is created with 3 proxies, INTERNET, ATM, and MOBILE, by PCA.

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