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Digital financial inclusion in the context of financial development: Environmental destruction or the driving force for technological advancement

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ABSTRACT

This study employs the panel vector autoregression model to investigate how digital financial inclusion (DFI), technological advancement, environmental conditions, and economic growth are interconnected in 16 low financial development countries (LFDCs) and 29 high financial development countries (HFDCs) from 2015 to 2020. The results of the impulse response function reveal that in LFDCs, DFI enhances environmental quality while promoting technological progress. However, this improvement in environmental quality results in a decline in economic growth in these countries. In HFDCs, the promotion of DFI results in economic growth; however, it is accompanied by a decrease in environmental quality. Furthermore, the results of variance decomposition demonstrate that the interconnection among DFI, economic growth, environmental quality, and technological progress is more closely related in LFDCs than in HFDCs. Based on the findings, we recommend relevant policy implications for the respective country groups.

1. Introduction

The general development trend in most economies is focused on achieving stable and sustainable economic growth (Hammer & Pivo, 2017; Nogueira et al., 2022). To accomplish this goal, countries must address the fundamental issues of economic growth and environmental pollution. In 2023, the World Meteorological Organization reported that the global average temperature in 2022 was approximately 1.15 °C higher than the average during the preindustrial era (1850–1900). This increase in temperature is attributed to the greenhouse effect, with rising CO_2 concentrations due to human activities, including domestic and industrial production (Zheng et al., 2021). Moreover, poor air quality has led to over 6 million deaths annually, causing the total economic damage to exceed 6.1% of global gross domestic product (GDP) (World Bank, 2022). Therefore, the goal of reducing CO_2 emissions cannot be separated from economic development (Wang et al., 2022). However, it is challenging to achieve this simultaneously because economic growth is often accompanied by industrialization and increased production, resulting in higher levels of environmental pollution (Chen, Song, & Sun, 2022). According to Panayotou (1993), the correlation between economic growth and the environment can be elucidated using the environmental Kuznets curve theory, which takes the shape of an inverted U-curve. According to this theory, a country's environmental pollution tends to increase with economic development until it reaches a certain threshold, often referred to as the turning point, after which pollution begins to decrease. To limit the harsh trade-offs and accelerate progress toward the Kuznets curve's turning point, countries often use a combination of internal and external factors to their advantage as economic freedom promotes economic growth while reducing environmental pollution (Majeed et al., 2021; Ahmed et al., 2022). Government tax policies also have a positive correlation between economic growth and environmental quality (Xin et al., 2022), urbanization rate (UR) (Liang & Yang, 2019), institutional frameworks (Wawrzyniak & Doryń, 2020), and foreign direct investment (Abdouli & Hammami, 2020).

Since the early years of the 21st century, financial inclusion (FI), a traditional perspective, has been pursued by governments and central banks worldwide because of its contributions to economic growth (Ofori-Abebrese et al., 2020). According to Demirguc-Kunt et al. (2018), a 10% increase in FI leads to a 0.3% growth in per capita GDP. In addition, the experimental studies by Kim et al. (2018), Lenka and Sharma (2017), Erlando et al. (2020), and Dahiya and Kumar (2020) reinforced the positive role of FI in economic growth, instilling strong

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confidence in governments to enhance FI to drive economic growth. Recent findings by Liu et al. (2021), Qin et al. (2021), and Zaidi et al. (2021) revealed that FI can cause environmental pollution by encouraging small and medium-sized enterprises to expand their production. This raises the question of whether any factors can simultaneously promote economic growth and improve environmental quality to guide countries toward sustainable development.

Currently, the development of Technology 4.0 has transformed FI qualitatively and quantitatively, evolving it into digital financial inclusion (DFI). This transformation is expected to meet the requirements for sustainable development (P. Khera et al., 2021). Recent studies by Zhu and Li (2021) and Chen et al. (2023) demonstrated that DFI can promote total factor productivity (TFP), a vital element in Solow's growth model. Technological advancements can mitigate the risk of environmental pollution (Altinoz et al., 2021; Liang & Wang, 2023). An increase in DFI, through its transmission mechanism, stimulates TFP, which can simultaneously promote economic growth and improve environmental quality. Integrating DFI with technological progress allows for a more sustainable and balanced approach to economic development. By leveraging this synergy, countries can advance toward achieving both economic prosperity and environmental sustainability, creating a pathway for long-term sustainable growth. However, current research on this topic only examines the individual relationships between DFI and economic growth (Ahmad et al., 2021; Purva Khera et al., 2021; Shen et al., 2021), DFI and environmental quality (Huang et al., 2022; Wang et al., 2022), and technological progress and DFI (Li et al., 2022; Chen et al., 2023). No research has simultaneously examined the four relationships between DFI, economic growth, technological progress, and environmental conditions. Thus, exploring the role of DFI in all these aspects is a novel approach in this field. Additionally, according to Oanh et al. (2023), FI has varying degrees of impact depending on the level of FD. In this study, we analyzed two country groups—low financial development countries (LFDCs) and high financial development countries (HFDCs). This approach provides a more comprehensive insight into the contributions of DFI in different financial development (FD) contexts. A more nuanced understanding of the role of DFI can be obtained by comparing these two groups.

However, there is a lack of consistency when examining previous research methods used to study the relationship between DFI and economic growth, technological progress, and environmental quality. Different studies used various methodologies as follows: Ezzahid and Elouaourti (2017) used ordinary least squares and generalized least squares; Yang et al. (2022) used the generalized method of moments (GMM); Wang et al. (2022) employed spatial regression in their study; and Chen et al. (2023) and Huang et al. (2022) used the finite element method. No research has used panel vector autoregression (PVAR) to demonstrate the transmission mechanism in the changes of DFI to technological progress and examine whether this mechanism addresses economic growth while improving environmental quality. By adopting this approach, we can draw relevant policy implications for HFDCs and LFDCs that aim for sustainable development.

With the above approach, the present study addresses the following issues. First, building on prior research by Purva Khera et al. (2021) and Daud (2023), it employs the principal component analysis (PCA) method to construct the DFI variable based on digital financial components (internet, number of credit cards (NCC), number of debit cards (NCB), number of mobile money transactions (NMM), and mobile subscriptions (MS)). This measurement is applicable globally and allows for comparisons between different countries. Second, based on the studies by Le et al. (2021) and Oanh et al. (2023), we employ the PVAR method, in which there is no distinction between exogenous and endogenous variables, but all variables are common endogenous variables. Furthermore, each variable in the PVAR depends on its past data and all other variables, demonstrating simultaneousness and equal interdependence among the variables. This approach illustrates the transmission mechanism in the impact of DFI transformation on technological progress and subsequently examines whether this mechanism contributes to economic growth while improving environmental quality. Third, based on the study by Oanh et al. (2023), this study is conducted across two groups of countries—HFDCs and LFDCs. The study's overall results also reveal differences between the two groups of countries regarding the degree and direction of impact in these relationships—a categorization that allows for an objective assessment of the extent to which DFI contributes to the remaining variables.

The rest of the paper is structured as follows. Section 2 presents the literature review. Section 3 summarizes the data and research methodology. Section 4 explains the results and discussion. Finally, Section 5 presents the conclusion and some policy recommendations.

2. Literature review

2.1. Theories of DFI, environmental conditions, TFP, and economic growth

Research into FD has identified four distinct focal points that drive economic growth. The fundamental goal is to establish an affordable and dependable payment mechanism accessible to all, especially those with limited incomes. The second aspect is the role of financial intermediaries in amplifying transaction volume and redistributing resources from economic surplus to deficit units. This helps in improving resource allocation (Odeniran & Udeaja, 2010). The third aspect delves into the efficacy of risk management facilitated by the financial system. This is achieved by curtailing liquidity risks and promoting more streamlined investment financing and innovative economic risk-taking (Bencivenga & Smith, 1991; Greenwood & Jovanovic, 1990). Finally, the financial sector provides information regarding investment prospects and available capital in the system, thus amplifying the influence of asymmetric information (Ross, 2004).

From the aggregate production function perspective, the aforementioned financial influences play a significant role in effectively translating input savings and investments into amplified economic output. This transformation occurs through either capital accumulation (Hicks, 1969) or technological advancement (Schumpeter, 1912). Taking the capital accumulation pathway as an example, the well-known Solow growth model demonstrates that an escalation in savings rate (δ) results in heightened levels of both capital (k) and per capita output (y) in a steady state. This alteration in δ is depicted in Fig. 1. The transition from δ1 to δ2 elevates the stable state of k from $k1$ to $k2$, thus driving per capita output to increase from $y1$ to $y2$.

This analysis implies that the quality of investments can be enhanced

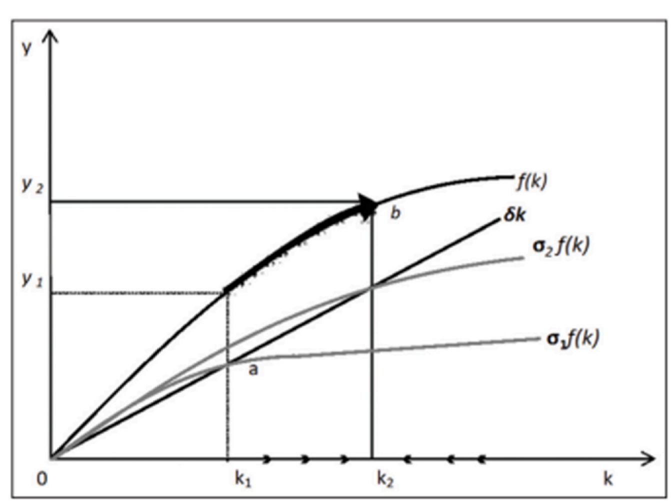

Fig. 1. Effects of savings on capital accumulation. Source: Odeniran and Udeaja (2010).

by removing financial constraints and mitigating failures in the financial market. This is because only projects yielding returns higher than the interest rate (IR) would receive financing. Thus, the entire production function experiences an upward shift, transitioning from $f(k)$ to $g(k)$. The augmented efficiency of the economy also stimulates savings as $\delta 2\, g(k) > \delta 2\, f(k)$ (Fig. 2). It is evident from Fig. 2 that the new steady state (*k3*) and the corresponding output per worker (*y3*) not only exceed the initial levels of *k1* and *y1* but also surpass even the elevated levels resulting from increased savings and investment, namely, *k2* and *y2*.

The financial sector contributes significantly to the enhancement of the production function by effectively overseeing and managing investment projects. In contrast to the Schumpeterian growth model, the Solow model primarily captures the short- and medium-term effects of enhancements in FD. However, it does not account for technological advancements or long-term economic growth. In recognition of this limitation, the Schumpeterian growth model was developed. Schumpeter emphasized the absolute necessity of a well-developed financial sector for entrepreneurs to successfully engage in innovative processes. As new projects often require financing that entrepreneurs may not be able to cover entirely on their own, a robust financial sector is indispensable. Innovation would be unattainable without this means of channeling funds, which severely hinders the potential for sustained economic growth. From this foundation, DFI plays a critical role in fostering economic growth. DFI introduces inventive financial products to encourage low-income individuals to save more, thus underscoring its vital role in this context (Odeniran & Udeaja, 2010).

Furthermore, according to the theory of new growth, knowledge accumulation (technology) is a crucial driver of growth. The first model introduced by Arrow (1962) maintains the classical premise of diminishing capital returns. In the second version proposed by Romer, the model demonstrates continuous endogenous growth. When a company invests in new equipment, it is essential to learn how to use that new technology and adjust its production processes to achieve higher profits. Technical knowledge increases as the workforce becomes more familiar with the latest technology. The assumption of knowledge spillover effects is crucial for a model that is consistent with perfect competition conditions. If knowledge is not leaked, a capital-accumulating firm will have higher productivity than its competitive rivals. Its profits will continue to rise and have the appropriate conditions to grow and dominate the market independently.

Later, Romer (1986, 1987) constructed the Arrow–Romer growth model. The knowledge spillover hypothesis suggests that knowledge leaks and all companies can access it freely. The knowledge that each company gains through its learning process will be freely disseminated to all other companies. Conversely, each company benefits from the knowledge that other companies generate in their learning process. The knowledge spillover process causes the return on capital to stop diminishing nationally.

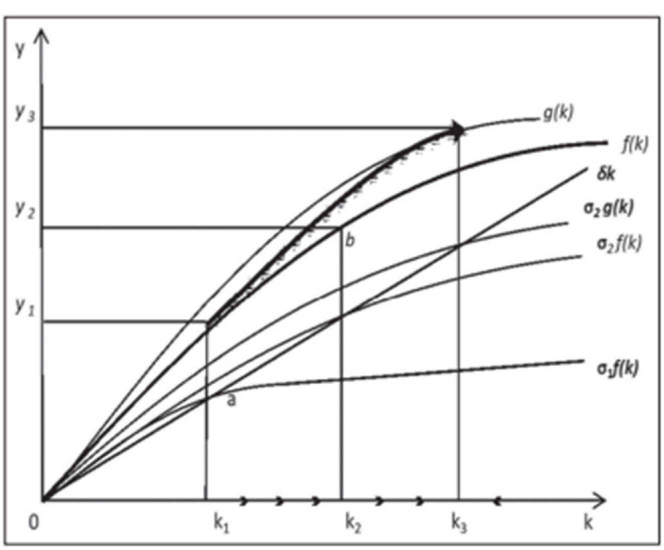

Fig. 2. Effects of savings on output. Source: Odeniran and Udeaja (2010).

FI is a system that ensures equal opportunities for individuals and businesses to conveniently access financial products and services at fair and affordable prices (World Bank, 2014). As technology, especially information technology, continues to advance, financial products and services have become more accessible and convenient in quantity and quality. According to Ozili (2018), DFI represents initiatives that grant accessible and affordable financial services to individuals and businesses underserved or excluded from the formal financial system. This objective is accomplished by using digital technologies, including mobile phones, the internet, and electronic payment systems, to widen access and enhance the efficiency of financial services. As defined previously, DFI directly influences the economy by stimulating the participation of various entities in economic activities as both providers and users of capital. This maximizes the available financial resources within the economy. The relationship between DFI, environmental quality, technological progress, and economic growth can be investigated using the following theories.

The financial intermediation theory proposed by Diamond (1984) suggests that banks function as financial intermediaries, facilitating the flow of funds between borrowers and savers and bridging the gap between customers with surplus and deficit funds in the market. Thus, financial intermediation plays a crucial role in determining the extent to which customers can access capital for investment and consumption during challenging times. Moreover, through George's theory of asymmetric information (1970), distinguishing between good and bad borrowers in financial activities poses a challenge due to asymmetric information (when one party possesses more knowledge or better information than the other), resulting in credit rationing, which affects the efficiency of financial operations and economic growth (Bofondi & Gobbi, 2003). Asymmetric information causes adverse selection and moral hazard issues, potentially leading to suboptimal allocation of capital and resources in the financial system. Effective management and mitigation of asymmetric information are crucial for promoting efficient financial intermediation and sustainable economic growth.

Based on the two theories mentioned above, DFI is a catalyst for promoting the participation of various entities in the economy as both providers and users of capital on a broad scale. This stimulates economic growth; however, this growth often comes with increased energy and gas consumption. When resource demand significantly increases, overexploitation and unsustainable practices may occur, resulting in the degradation and depletion of crucial natural resources and environmental pollution (Grossman & Krueger, 1995). Economic growth can harm the environment because of increased resource consumption and pollution. However, economic growth also creates an opportunity for technological advancements that can help counter these negative impacts (Porter & Linde, 1995). Additionally, the environmental Kuznets curve theory suggests a complex relationship between economic growth and the environment. According to this theory, environmental pollution in a country tends to increase with economic development until it reaches a certain level, known as the turning point. Beyond this turning point, additional economic growth causes a decline in pollution levels.

According to Solow's theory of economic growth (1956), TFP can stimulate economic growth. Technological advancements can help reduce environmental pollution, as confirmed by Liang and Wang (2023). To achieve technological advancements, the role of DFI cannot be overlooked (Zhu & Li, 2021; Li et al., 2022; Chen et al., 2023). Therefore, an increase in DFI through transmission mechanisms can promote TFP, causing both economic growth and improved environmental quality. In reality, not all countries have equal access to financial services, and this depends on various factors. For instance, in terms of internet access (Bayar et al., 2021), as of 2021, Pakistan had a population internet access rate of 21.04%; the Philippines had 52.68%; Nicaragua had 57.1%; but other countries had higher rates, such as Australia with 96.24%, Kuwait with 99.7%, and Qatar with 100%, implying that DFI also contributes differently to economic growth and technological advancement. This discrepancy is mainly due to differences in the FD level in each country. Such variations may lead countries to make trade-offs between environmental concerns and economic growth. In particular, in HFDCs, DFI allows companies and businesses easy access to loans from banks and financial institutions, contributing to economic growth. In addition, these countries can invest more in technological advancements, positively impacting environmental quality (Baulch et al., 2018). Baulch et al. (2018) found that companies in LFDCs have limitations in accessing finance to invest in technological advancements due to cost constraints. This difficulty in funding large projects indirectly results in increased energy consumption and CO_2 emissions (Le et al., 2020). In contrast, in HFDCs, DFI facilitates access to borrowing from banks and other financial institutions, enabling individuals to acquire energy-intensive products, including cars, freezers, microwaves, washing machines, and air conditioners. This heightened energy consumption from nonrenewable sources contributes to a remarkable increase in CO_2 and other greenhouse gas emissions. Furthermore, the increased level of DFI is linked to a higher reliance on fossil fuels for energy consumption, ultimately leading to high CO_2 emissions (Emara & El Said, 2021).

Inspired by the foundational theories of Arrow (1962) and Romer (1986, 1987), which argue that for sustained growth, an economy must continuously expand its knowledge base, the current study posits that to achieve uninterrupted growth, an economy must continually expand its knowledge base. This study utilizes DFI transmission in the context of FD. However, it acknowledges that different levels of FD result in varying degrees of DFI, as affirmed by Ezzahid and Elouaourti (2017) and Oanh et al. (2023). Therefore, this study extends its scope to HFDCs and LFDCs. This division enables the authors to compare the effects of comprehensive digital finance on technological progress in the two groups of countries. It investigates whether there is a trade-off between economic growth and environmental quality.

2.2. Empirical studies on the relationship between DFI, economic growth, TFP, and environmental conditions

DFI is a relatively new field that encompasses various interconnected aspects, such as technology, finance, regulatory frameworks, and societal implications. The complexity of this subject demands interdisciplinary research methods. In addition, the rapid pace of technological advancements and constantly evolving legal frameworks pose challenges to keeping up with the dynamic nature of DFI. In addition, as discussed below, there are several constraints. Therefore, there are limited studies on the relationship between DFI, environmental quality, TFP, and economic growth.

First, there is no unified method to measure DFI primarily because of difficulties in accessing data, especially in some LFDCs where internet services may be restricted. This limitation hinders the comparison and analysis of the impact of DFI on economic growth. Thaddeus et al. (2020) constructed a DFI index based on five indicators—the number of ATMs, the number of branches of commercial banks, outstanding loans from commercial banks (LCB), the proportion of mobile money transactions, and the number of mobile money agents. They assessed the effect of these five indicators on economic growth. Purva Khera et al. (2021) used the PCA method to build a measure of DFI based on the following indicators: MS per 100 people, the percentage of the population using the internet, the percentage of adults with a mobile money account, the percentage of people using the internet to pay bills, and the percentage of people using mobile phones for payments.

Ismael and Ali (2021) constructed a DFI variable based on cell phone numbers and mobile money transactions per 1000 adults. Shen et al. (2021) studied a DFI variable by considering different factors, such as the number of branches of commercial banks, the number of ATMs, and the percentage of individuals using the internet. Daud (2023) developed this variable based on the relationship between traditional DFI and digital variables. Moreover, Huang et al. (2022), Liu et al. (2021), and Zheng and Li (2022) studied DFI using 33 different criteria. However, these measurements were only used within the context of China. Furthermore, although some of the measurements incorporated DFI indicators, as demonstrated by Thaddeus et al. (2020), Shen et al. (2021), and Daud (2023), they may not fully assess the extent of DFI. In the current study, the PCA method is used to construct a DFI variable comprising seven components—internet usage index (IU), NCC, NCB, NMM, and MS as supply-side factors to assess the level of coverage, LCB, and deposits in commercial banks (DCB) as demand-side financial use factors. This measurement is applicable globally and allows for comparisons between different countries.

Second, studies on the relationship between DFI, technological advancements, environmental quality, and economic growth have been limited to individual relationships, such as the relationship between DFI and economic growth in studies by Shen et al. (2021), Purva Khera et al. (2021), Ahmad et al. (2021), Liu et al. (2021), Khera et al. (2022), and Chinoda and Kapingura (2023); the relationship between DFI and environmental quality in studies by Huang et al. (2022), Lee et al. (2022), Liu et al. (2022), Yang et al. (2022), Wang et al. (2022), and Zheng et al. (2023); and the relationship between DFI and technological advancements in studies by Zhu and Li (2021), Li et al. (2022), and Chen et al. (2023). To date, no study has simultaneously examined the relationship among DFI, economic growth, technological advancements, and environmental quality. Therefore, in this study, we address this gap and explore the role of DFI in these interrelated relationships.

Third, in terms of research scope, studies on the relationship between DFI and environmental quality or the relationship between DFI and technological innovation have mainly been conducted in various provinces or regions in China, such as studies conducted by Ahmad et al. (2021), Fu and Huang (2018), Huang et al. (2022), Liu et al. (2021), Zheng and Li (2022), Xue and Zhang (2022), Yang et al. (2022), Wang et al. (2022), Zhu and Li (2021), Li et al. (2022), and Chen et al. (2023). In addition, research on the relationship between DFI and economic growth has been conducted on a broader scale, with Shen et al. (2021) studying 105 countries, Purva Khera et al. (2021) studying 52 developing countries, Chinoda and Kapingura (2023) focusing on Sub-Saharan African countries, and Daud (2023) investigating 84 countries. Chen et al. (2021) investigated the influence of FinTech products on the operational efficiency of commercial banks in China. Chen, Song, and Sun (2022) also emphasized the role of digitization as a business-supporting factor that accelerates and expands the scale of innovation in many Chinese companies. No study has simultaneously examined the four relationships within the context of FD. As mentioned earlier, FI has varying degrees of impact depending on the level of FD, according to the findings of Oanh et al. (2023). In the current study, we investigate two groups of countries—HFDCs and LFDCs—to gain a more comprehensive understanding of the contribution of DFI to technological advancement and explore whether there is a trade-off between economic growth and environmental quality in these two groups of countries.

Fourth, concerning research methods, previous studies on the relationship between DFI and economic growth, technological advancements, and environmental quality have employed different methods, lacking uniformity. For instance, Ezzahid and Elouaourti (2017) used ordinary least squares and generalized least squares; Yang et al. (2022) used the GMM method; Wang et al. (2022) employed spatial regression; Chen et al. (2023) and Huang et al. (2022) applied the finite element method; Shen et al. (2021) used spatial regression; and Chinoda and Kapingura (2023) used the stochastic GMM (SGMM) method. However, no study has used PVAR to demonstrate the transmission mechanism of the impact of DFI on technological advancement and examine whether this mechanism addresses economic growth while improving environmental quality. Using this approach, we draw appropriate policy implications for the two groups of countries—HFDCs and LFDCs—focusing on sustainable development. This study addresses these issues and provides insights into potential policy implications.

3. Data and methodology

3.1. Research variables and research models

The DFI variable, as explored in Section 2, cannot be adequately measured by a single variable because it encompasses multiple dimensions that cannot be accurately represented by a single factor. Therefore, various indicators are used to measure DFI. To foster DFI, it is crucial to consider both the demand- and supply-side aspects. Based on the study by Purva Khera et al. (2021), we construct DFI based on seven components: IU, NCC, NCB, NMM, and MS as supply-side factors to assess the level of coverage, CB, and DCB as demand-side financial use factors.

Based on the study by Liu et al. (2022), the variable economic growth is measured by the natural logarithm of the annual average GDP per capita. Further, based on the economic growth theory of Solow (1956) and the study by Ezzahid and Elouaourti (2017), technological advancement is measured by TFP. Following Wang et al. (2022) and Liu et al. (2022), environmental quality is measured by the average per capita CO_2 emissions. In addition, the following control variables are introduced: UR, trade openness (OPEN), inflation rate (INF), economic integration (FDG), unemployment rate (UNE), population growth rate (PG), and IR. Table 1 lists the measurements and data sources of these variables.

3.2. Methodology and dataset

3.2.1. PCA

In the current study, the PCA technique is used to calculate DFI. The research model is as follows:

$$DFI_j = W_{j1}X_1 + W_{j2}X_2 + \ldots + W_{j7}X_7$$

where W_1, W_2, …, W_7 are the weights assigned to each component, and X_1, X_2, …, X_7 are the measured variables, representing the six components listed above. It is essential to conduct data normalization to prevent biases arising from varying measurement units of indicators. This procedure converts the data into a consistent range, typically within the interval of [0; 1]. Data normalization allows the presentation of standardized information across different criteria. Han et al. (2011) proposed various methods for data normalization, including the minimum–maximum normalization method. This technique prepares data for analysis and ensures comparison among variables. In this study, DFI is normalized using the following formula, with the DFI index having values within the range [0; 1]:

$$DFI_i = \frac{DFI_i - DFI_{min}}{DFI_{max} - DFI_{min}} \quad (*)$$

3.2.2. PVAR model

In this study, the PVAR model is employed, which considers all variables as collectively endogenous without distinguishing between exogenous and endogenous variables. Each variable in the PVAR depends on its past data and the past data of all other variables, implying simultaneous and equal relationships between the variables. This characteristic makes the PVAR model well-suited for this study. The research model is as follows:

$$Y_{i,t} = A_1 Y_{i,t-1} + A_2 Y_{i,t-2} + \ldots + A_k Y_{i,t-k} + \beta_x X_{i,t} + u_i + \varepsilon_{i,t}$$

where.

$Y_{i,t} = (GDP_{i,t}, TFP_{i,t}, DFI_{i,t}, CO2_{i,t})$ is a random vector of dimension (1 × 4) comprising endogenous variables;

$Y_{i,t-p}$ represents the vector of lagged endogenous variables of each dimension (1 × 4);

Table 1
Description of the variables.

Variable	Sign	Measurement	Studies	Data source
Main variable				
Economic growth	GDP	GDP per capita (Ln)	Liu et al. (2022)	WB
TFP	TFP	TFP	Ezzahid and Elouaourti (2017), Chen et al. (2023)	OUR WORLD IN DATA
Environmental Quality	CO_2	Amount of CO_2 emissions generated per individual in a particular region or country	Liu et al. (2021), Zheng et al. (2023)	WB
DFI	DFI	We used the PCA technique to calculate DFI. The research model is as follows: $DFI_j = W_{j1}X_1 + W_{j2}X_2 + \ldots + W_{j7}X_7$ where W1, W2, …, W7 are the weights assigned to each respective component, and X1, X2, …, X7 are the measured variables representing variables that denote the six components described below		
+Percentage of internet users	IU	Percentage of people in a specific country or region who have access to and use the internet (%)	Zheng et al. (2023), Liu et al. (2022), and Purva Khera et al. (2021)	WB; FAS
+MS	MS	Proportion of mobile phone subscriptions per 100 individuals (%)		
+NCC	NCC	Total NCC issued by financial institutions by the total number of adults multiplied by 1000		
+NCB	NCB	Total NCB issued by financial institutions by the total number of adults multiplied by 1000		
+NMM	NMM	Total NMM completed by financial institutions or mobile money service providers by the total number of adults multiplied by 1000		
+Outstanding LCB	LCB	Total value of loans extended by commercial banks in a specific country to the size of its GDP		
+Outstanding balance of DCB	DCB	Total value of deposits held in commercial banks in a specific country to the size of its GDP		
Control variable				
IR	IR	IR (%)	Ezzahid and Elouaourti (2017)	WB
PG	PG	Percentage change in a population's size in a year (%)	Liu et al. (2021) and Ezzahid and Elouaourti (2017)	
OPEN	OPEN	Combined value of a country's imports and exports of goods and services relative to its GDP (%)	Liu et al. (2021)	
FDG	FDG	Net amount of FDI received by a country as a percentage of its GDP (%)	Zheng et al. (2023)	
UR	UR	Percentage of a country's population residing in urban areas relative to its total population (%)	Nkalu et al. (2019)	
INF	INF	Percentage change in the consumer price index in a year (%)	Ezzahid and Elouaourti (2017)	
UNE	UNE	Percentage of unemployed individuals relative to the total labor force in a specific country or region (%)	Chinoda and Kapingura (2023)	

$A_1, A_2, \ldots, A_k$ is the vector of the estimated coefficients, with each coefficient being a matrix of dimension (kxk);

where k denotes the optimal lag order in the model;

$X_{i,t}$ represents the vector of exogenous variables of each dimension (1×7), including the following variables: PG, INF, OPEN, UNE, FDG, UR, and IR.

β_x is the matrix of the estimated coefficients, with each coefficient being a matrix of dimension (lxk);

u_i denotes the vector of fixed effects or the error term of the dependent variable;

$\varepsilon_{i,t}$ represents the vector of idiosyncratic errors or residuals.

3.2.3. *Data*

The research data cover 55 countries from 2015 to 2020, and the classification of countries into HFDCs and LFDCs is based on specific criteria. Following Oanh et al. (2023), we computed the average FD index for all countries, referred to as the average global FD. HFDCs are expected to have a higher average FD (2015–2020) than the global average FD, whereas LFDCs are expected to have a lower average FD (2015–2020) than the global average FD. Fig. 3 displays the classification results for 16 LFDCs and 29 HFDCs. However, due to the limited sample size and short period (2015–2020), we employed the frequency conversion method to transform the data from annual to quarterly observations, increasing the number of observations and thereby enhancing the reliability of the PVAR model results.

Fig. 3 depicts that Australia has the highest FD index, followed by Hong Kong and Singapore. However, the Kyrgyz Republic, Ecuador, and the Dominican Republic had the lowest FD indices.

4. Research results and discussion

4.1. *PCA result*

Table 2 presents the results of the PCA. According to the results, DFI is calculated as follows:

Table 2
PCA results.

DFI	LCB	DCB	MS	IU	NCC	NCB	NMM
	0.384	0.3964	0.287	0.387	0.214	0.121	0.165

DFI = 0.384*LCB+0.3964*DCB+0.287*MS+0.3874*IU+0.214*NCC+0.121*NCB+0.165*NMM

Then, Equation (*) is used to normalize DFI to calculate the DFI coefficient.

The results reveal that IU, LCB, and DCB significantly contribute to DFI with coefficients of 0.387, 0.384, and 0.396, respectively. This implies that both supply-side factors (LCB and DCB) and the proportion of internet users should be prioritized in promoting DFI.

4.2. *PVAR results*

4.2.1. *Descriptive statistics*

The results in Table 3 indicate that the average GDP, DFI, and CO_2 emissions of HFDCs are 9.45, 0.41, and 6.58, respectively, whereas the values of LFDCs are 8.23, 0.26, and 1.92, respectively. In contrast, the TFP in LFDCs is higher than that in HFDCs. An intriguing issue is that CO_2 emissions in HFDCs are more than three times higher than those in LFDCs, although the economic growth difference between the two groups is approximately 1.2%.

4.2.2. *Unit root test results*

The findings of Table 4 reveal that in the LFDCs model, variables such as DFI, UNE, FDG, UR, INF, and IR demonstrate stationarity at first differences I(0), while GDP, TFP, CO_2, PG, and OPEN are stationary at level I(1). In the HFDCs model, DFI, TFP, CO_2, PG, OPEN, FDG, INF, and IR are stationary at level I(0), whereas other variables have stationarity at first differences I(1). The variables in the research model for LFDCs and HFDCs exhibit different levels of stationarity. Given these findings, we estimate the PVAR model for further analysis.

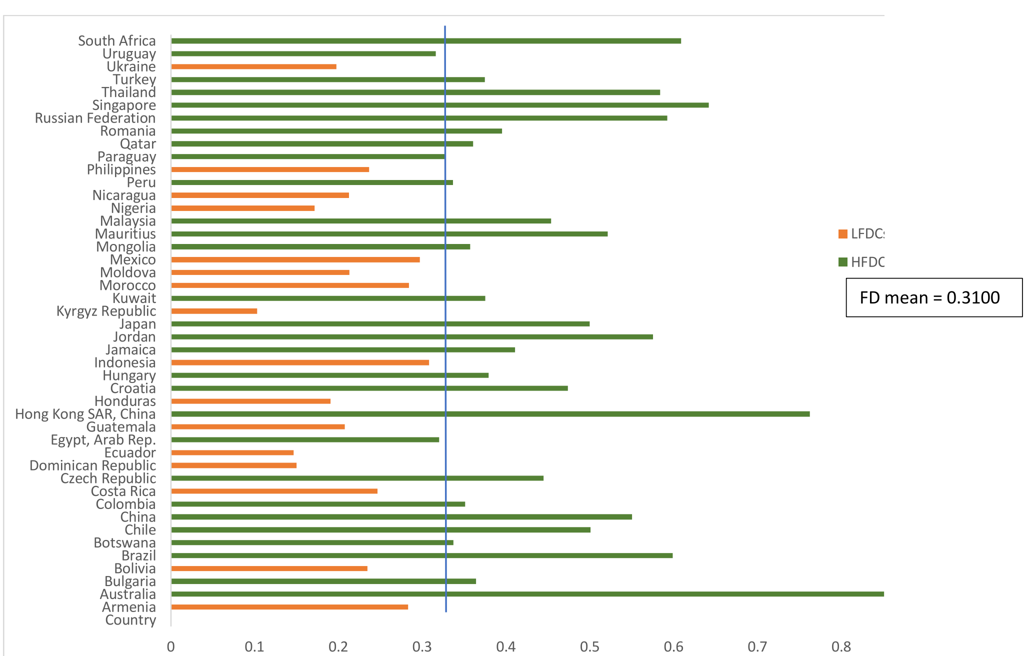

Fig. 3. Results of the division of LFDCs and HFDCs.

Table 3
Descriptive statistical results of the variables from 2015 to 2020.

	LFDCs				HFDCs			
	Mean	Std. dev.	Minimum	Maximum	Mean	Std. dev.	Minimum	Maximum
GDP	8.2308	0.5848	7.0217	9.4469	9.4503	0.8244	7.7997	11.1122
DFI	0.2598	0.0693	0.1191	0.3981	0.4118	0.1626	0.1974	1.0000
TFP	1.0121	0.0551	0.8865	1.2465	0.9981	0.0621	0.7268	1.1365
CO_2	1.9279	0.9763	0.5375	4.4808	6.5817	6.7255	0.8729	35.2904
PG	1.0593	0.9877	−1.7570	2.5412	0.9802	1.4733	−1.8328	9.2199
OPEN	68.5141	23.7513	16.3522	110.9616	96.5457	77.0107	24.3197	389.4059
UNE	6.3629	4.2719	1.2100	21.2100	7.3866	5.5837	0.1000	25.5400
FDG	2.6397	2.6189	−5.1603	17.1312	5.1486	13.4333	−40.0866	109.0253
UR	60.2434	12.9483	35.7770	82.5400	74.5864	17.1511	40.7600	100.0000
INF	4.3581	5.7937	−1.4036	48.6999	3.2934	3.8613	−2.5403	29.5066
IR	5.2455	3.2357	0.5892	14.1482	3.7873	4.1648	0.0100	25.4092

Table 4
Results of the unit root test.

Variables	LFDCs		HFDCs	
	Coefficient	Probability	Coefficient	Probability
GDP	60.1265	0.3318	70.1646	0.2161
DFI	115.31	0.0000***	141.42	0.0000***
TFP	55.1320	0.1357	45.0316	0.0515*
CO_2	67.1354	0.1114	53.3650	0.044**
PG	52.0467	0.5802	139.74	0.0000***
OPEN	35.1600	0.2147	62.1325	0.078*
UNE	63.8974	0.0062***	70.3161	0.2069
FDG	53.0341	0.0074***	99.1346	0.0000***
UR	124.135	0.0000***	55.1640	0.2871
INF	70.1642	0.0003***	99.1344	0.0035***
IR	86.4653	0.0016***	95.1643	0.0040***

4.2.3. *Optimal lag selection*

Before conducting the PVAR estimation, it is essential to establish the most appropriate lag length for the system of equations. The results of this determination are presented in Tables 5 and 6, providing insights into the optimal lag selection for the subsequent PVAR model estimation.

The results of the optimal lag (Table 5) demonstrate that the optimal lag for both groups of countries is lag 1, and Fig. 4 verifies the model stability of both country groups at lag 1, indicating that both models are stable.

4.2.4. *Testing the stability of the model*

Fig. 4 depicts that all the eigenvalues of the characteristic polynomial in the models are inside the unit circle. This observation implies that the PVAR models at various stages are stable and sustainable, indicating that the system is likely to converge to a steady state.

4.2.5. *Test for autocorrelation*

Table 7 displays the results of the autocorrelation test for both the LFDC and HFDC models at lag 1, indicating that neither model exhibits autocorrelation.

4.2.6. *Impulse response function (IRF) results*

The results of the IRF (Fig. 5) in LFDCs illustrate that when there is a shock that increases DFI by a standard deviation (SD), TFP increases by 0.0007 SD, CO_2 emissions decline by 0.021 SD, and GDP declines by 0.015 SD. When there is a shock in economic growth that increases by a SD, DFI declines by 0.0021 SD, whereas CO_2 emissions and TFP increase by 0.07 SD and 0.0063 SD, respectively. Similarly, in Fig. 6, the results of the IRF in HFDCs demonstrate that when there is a shock that increases DFI by a SD, CO_2 emissions and GDP increase by 0.008 SD and 0.8400 SD, respectively, while TFP decreases by 0.0009 SD. If a shock leads to a SD increase in GDP, the resulting consequences are as follows: TFP, CO_2 emissions, and DFI increase by 0.0018 SD, 0.004 SD, and 0.0002 SD, respectively.

Table 5
Optimal lag selection for the LFDCs.

Lags	LogL	LR	FPE	AIC	SC	HQ
0	−421.2000	NA	4.6337	12.8849	13.0176	12.9373
1	−195.9027	39.9782*	0.0219*	7.5122*	9.2374	8.1939*
2	−182.4075	20.0384	0.0243	7.5881	9.8441	8.4796

Note: * represents the optimal lag order according to this criterion; therefore, we choose lag 1 as the ideal lag length.

These results indicate that in LFDCs, DFI improves environmental quality while promoting technological progress, which is consistent with the findings of Huang et al. (2022), Lee et al. (2022), and Chen et al. (2023). However, this also reduces economic growth in these countries, which is inconsistent with the initial expectations of DFI. However, regarding FD, it can be argued that in LFDCs, there are certain inequalities as follows:

First, in terms of access, especially internet access (Bayar et al., 2021), as of 2021, Pakistan had a population internet access rate of 21.04%, the Philippines 52.68%, and Nicaragua 57.1%, while other countries had higher rates such as Australia with 96.24%, Kuwait 99.7%, and even Qatar 100%. This inequality in internet access limits accessibility to information, development, and digital infrastructure applications, resulting in growing disparities within countries, such as urban–rural divide, rich–poor divide, and disparities between cities and suburbs (Ji et al., 2019). Therefore, the contribution of DFI only enhances growth in large cities and urban areas but is not sufficient to uplift the national economy. Moreover, some people, especially those in rural areas or low-income groups, may lack knowledge of digital finance, hindering their ability to use these services effectively. A lack of understanding can lead to improper usage or unnecessary risks.

Second, the sustainable development goals (.) have made many countries adopt new development strategies focused on green growth (Dmuchowski et al., 2021). Consequently, countries are gradually prioritizing environmental quality. However, emphasis on using environmentally friendly devices and renewable energy sources is increasing business costs. Moreover, digital financial technologies may require the workforce to acquire new knowledge and technical skills to work with new systems. This may demand retraining or transitioning to other suitable industries for the workforce. As a result, economic growth may temporarily decline. However, the experimental evidence from IRF (Fig. 5) indicates that the decline only occurs in the short term and is transient.

Fig. 5 also illustrates that promoting technological progress increases DFI and GDP while reducing CO_2 emissions. Additionally, Table 8 presents the variance decomposition (VD) results for GDP, CO_2, and DFI, all of which had significant contributions from technological progress. Therefore, it is possible to achieve simultaneous economic growth and environmental quality through technological advancement.

Similarly, in Fig. 6, the IRF results in HFDCs indicate a positive two-way correlation between economic growth and DFI, which is consistent

Table 6
Optimal lag selection for the HFDCs.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	−4731.9460	NA	264,055.2000	20.9975	21.0249	21.0083
1	−3849.2900	1749.6560	5484.0960	17.1232*	17.23263*	17.1664
2	−3847.2360	4.0444	5655.6820	17.1540	17.3455	17.2295

Note: * represents the optimal lag order according to this criterion; therefore, we choose lag 1 as the ideal lag length.

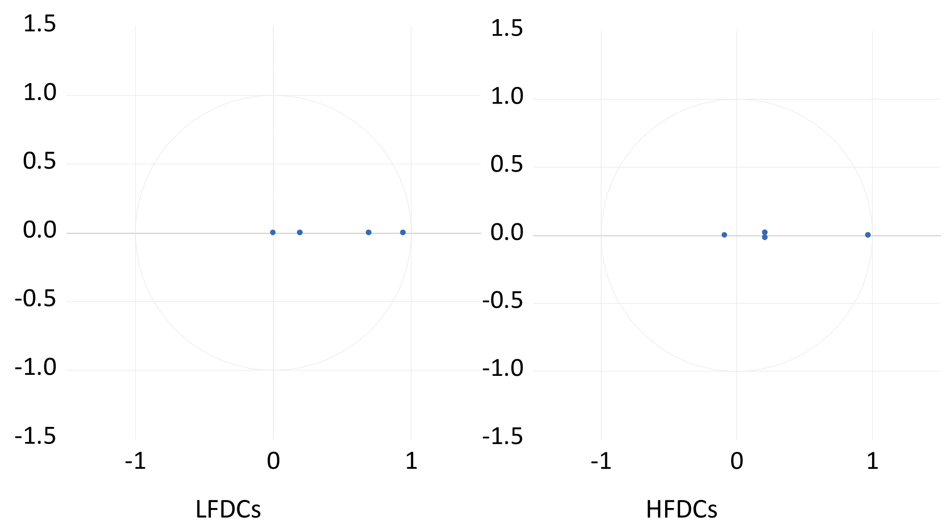

Fig. 4. Testing the stability of the model.

Table 7
Results of the autocorrelation test.

	Lags	LM stat	Prob
LFDCs	1	8.1346	0.5473
HDFCs	1	11.9467	0.1560

with the findings of Shen et al. (2021), Purva Khera et al. (2021), Ahmad et al. (2021), and Khera et al. (2022). A positive two-way correlation between CO_2 emissions and DFI is also found, which is consistent with the studies by Le et al. (2020), Liu et al. (2021), Qin et al. (2021), and Zaidi et al. (2021). This implies that DFI promotes economic growth by stimulating economic agents' participation as providers and users of capital on a broad scale. However, economic growth is often associated with the utilization and consumption of natural resources, including energy, water, and other materials, causing environmental pollution. This indicates a trade-off between economic growth and environmental quality in HFDCs. Fig. 6 also reveals a two-way negative correlation between technological progress and DFI in HFDCs. This implies that, in these countries, technological innovation is highly advanced, sometimes even excessively so, resulting in complex mechanisms and operational processes in DFI. Moreover, the high level of development in DFI creates interconnectedness among various economic systems. When macroeconomic shocks occur, HFDCs may suffer severe damage, causing instability in their financial systems (Oanh et al., 2023).

Table 8 displays the results of VD, indicating that GDP contributes 2.28% to changes in DFI in LFDCs; DFI itself contributes 95.51%; CO_2 contributes 1.18%; and TFP contributes 3.44% (average of four periods). On the contrary, GDP contributes 1.58% to changes in DFI in HFDCs; DFI itself contributes 93.76%; CO_2 contributes 1.56%; and TFP contributes 3.10%. Thus, GDP, TFP, and CO_2 changes in LFDCs have higher contributions from the other variables compared with those in HFDCs. This implies that the relationships among DFI, economic growth, CO_2 emissions, and technological progress in LFDCs are more tightly interconnected than those in HFDCs.

5. Conclusion and policy implications

5.1. Conclusion

The present study utilizes the PVAR model to investigate the relationship between DFI, technological advancement, environmental conditions, and economic growth in the context of FD from 2015 to 2020. We calculated the average FD index for all countries, known as the average global FD. HFDCs are expected to exhibit a higher average FD than the global average, whereas LFDCs are expected to have a lower average FD than the global average. The results of the optimal lag demonstrate that the optimal lag for both groups of countries is lag 1, and the results of the autocorrelation test for both LFDC and HFDC models are at lag 1, indicating that none of the models exhibits autocorrelation. The outcomes of the IRF illustrate that in LFDCs, DFI enhances environmental quality while promoting technological progress. However, this improvement in environmental quality leads to a decline in economic growth in these countries. In HFDCs, the promotion of DFI results in economic growth; however, a decrease in environmental quality accompanies it. Furthermore, the results of VD demonstrate that the interconnection among DFI, economic growth, environmental quality, and technological progress is more tightly linked in LFDCs than in HFDCs. We propose relevant policy implications for the studied countries based on the findings.

5.2. Policy implications

5.2.1. For LFDCs

First, research and technology development should be promoted. They should focus on supporting the research and development of new technologies with the potential to mitigate the negative effects of DFI on the environment. This will enhance the role of DFI in economic growth

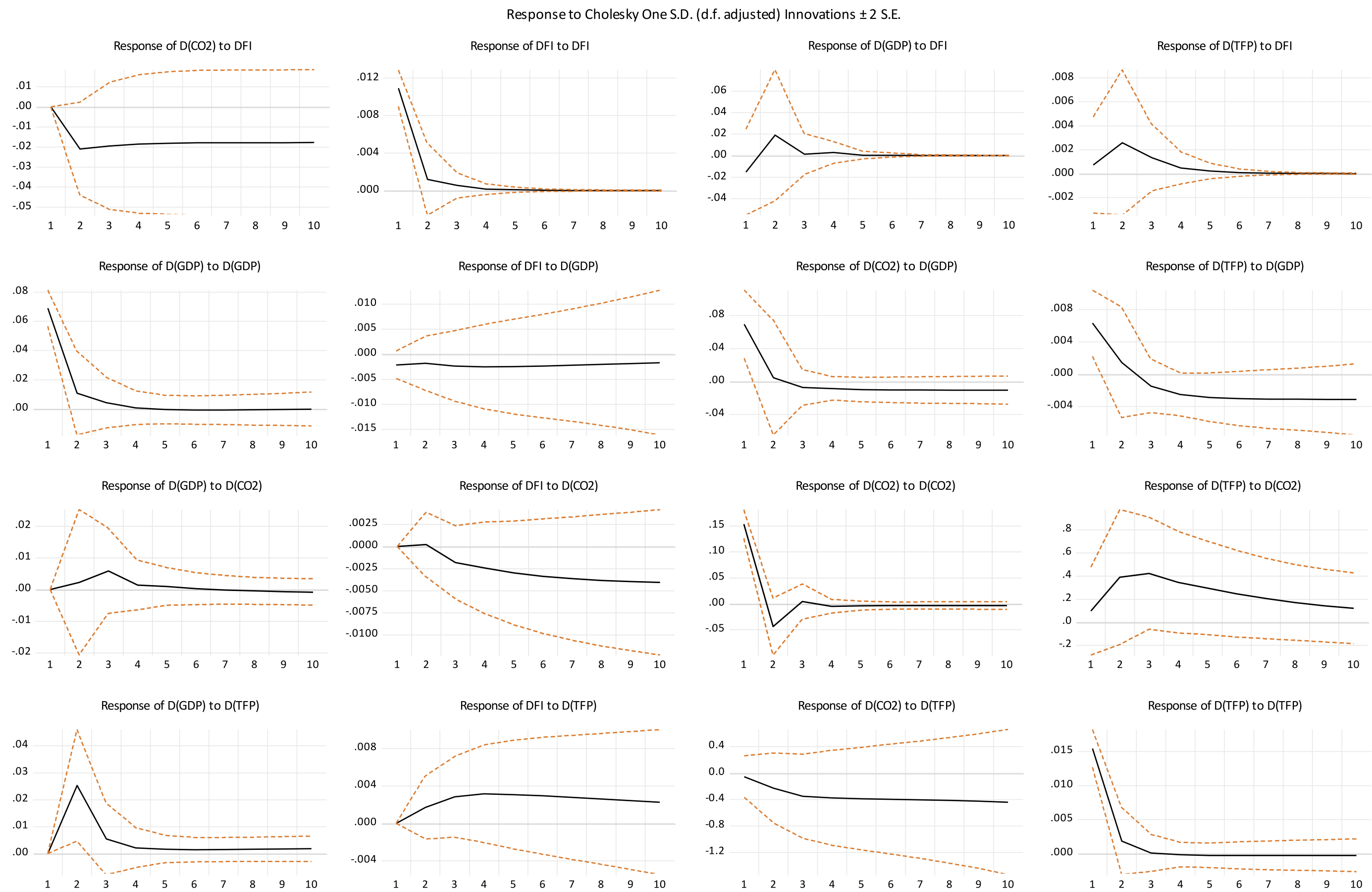

Fig. 5. IRF results for LFDCs.

and significantly reduce CO_2 emissions. Second, the internet network should be expanded. The internet provides favorable conditions for individuals and businesses to participate in online business activities, which is the most fundamental prerequisite for building a DFI.

5.2.2. For HLDs

First, there should be monitoring and environmental regulation compliance. This is essential to ensure that businesses and individuals implement environmental protection measures and minimize the negative effects of their business activities. Second, the understanding of DFI should be enhanced. Stringent criteria are to be established to limit excessive use of comprehensive digital finance. Policies that promote DFI growth such as investing in underserved communities should be implemented. In addition, investment in financial infrastructure, including banking networks, financial markets, payment systems, and continuous innovation in digital financial services, will enhance access to finance for businesses and citizens. This helps support business activity, investment, and consumption; enhances the spillover of economic resources; and promotes economic growth. However, the environmental quality in these countries must be closely monitored and controlled.

5.3. Further research suggestions

Although internet technology emerged in the 1970s, the widespread adoption of computer technology, particularly Industry 4.0 in the financial sector, was only heavily promoted by technologically advanced countries at the beginning of the 21st century. Its diffusion to developing nations has only occurred relatively recently. Due to limitations in data accessibility, the current study covers 2015 to 2020. Future research will continue to gather data to enhance the study quality. Furthermore, many countries are currently implementing sustainable development strategies to reduce greenhouse gas emissions, such as CO_2, a major contributor to the greenhouse effect. Although sustainable development encompasses three objectives—economic, social, and environmental—in the current study, two objectives, economic and environmental, were examined. The social sustainability objective was not addressed, which is a limitation and a future research direction for us.

Availability of data and material

Not applicable.

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Authors' contributions

Tran Thi Kim Oanh's tasks on the article development: Conceptualization, Validation, Resources, Investigation, Data curation, Software, Writing-Original draft preparation, Writing-Reviewing and Editing.

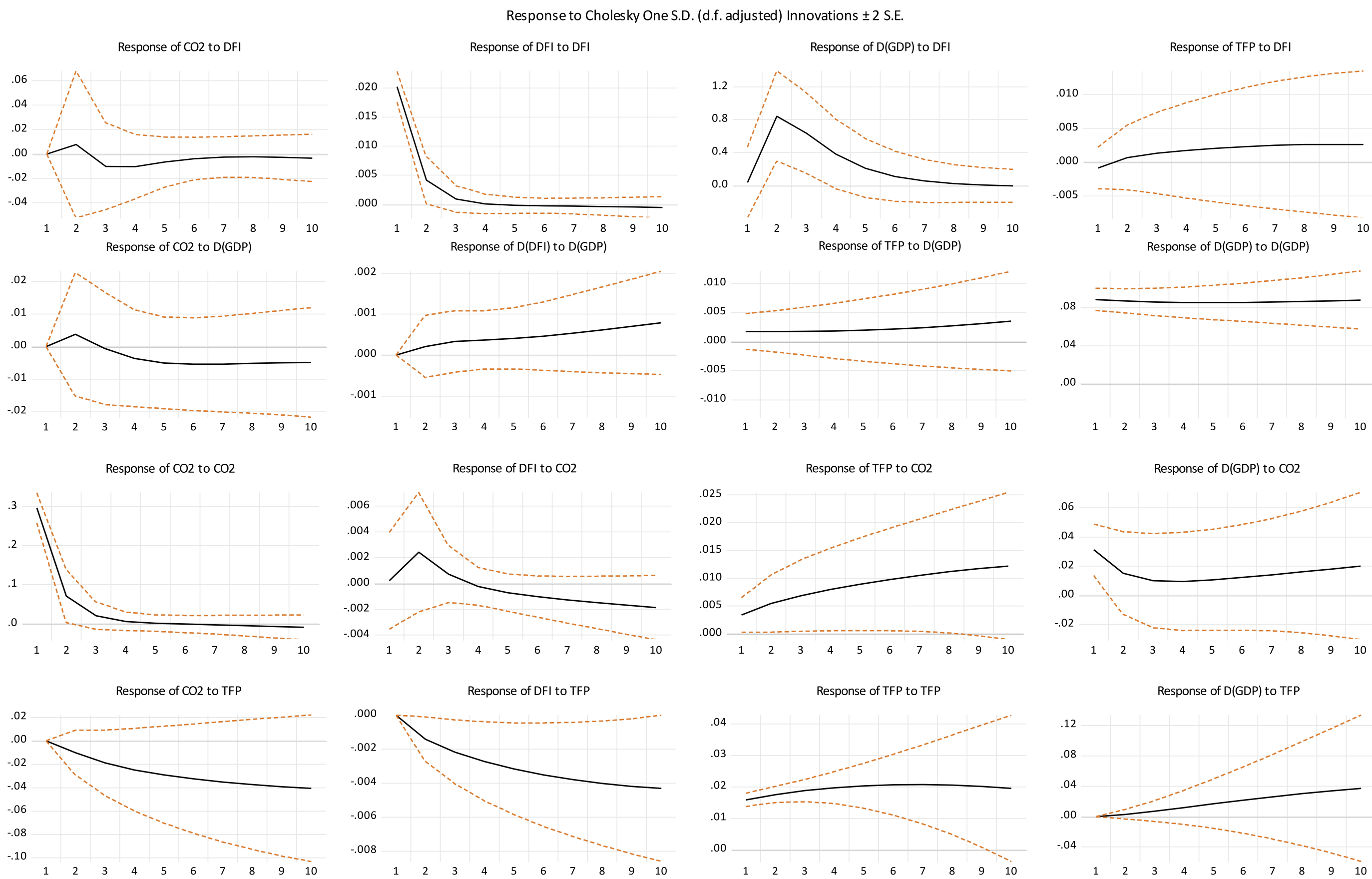

Fig. 6. IRF results for HFDCs.

Table 8
Results of the VD.

VD of GDP								
LFDCs					HFDCs			
Period	GDP	DFI	CO_2	TFP	GDP	DFI	CO_2	TFP
1	100	0	0	0	100	0	0	0
2	95.12	1.96	1.09	1.83	95.16	2.32	1.11	1.41
3	92.63	2.96	1.6	2.81	92.13	3.8	2.18	1.89
4	89.13	3.52	2.8	4.55	88.63	4.13	3.33	3.91
VD of DFI								
Period	GDP	DFI	CO_2	TFP	GDP	DFI	CO_2	TFP
1	1.32	95.36	0.96	2.36	0.96	95.76	1.32	1.96
2	1.98	93.6	1.32	3.1	1.32	94.81	1.48	2.39
3	2.64	91.25	2.31	3.8	1.84	93.11	1.64	3.41
4	3.17	89.83	2.51	4.49	2.21	91.36	1.8	4.63
VD of CO_2								
Period	GDP	DFI	CO_2	TFP	GDP	DFI	CO_2	TFP
1	2.36	1.01	96.58	0.05	0.19	0.89	97.8	1.12
2	3.48	1.21	92.36	2.95	0.38	1.32	96.2	2.1
3	4.31	1.64	89.62	4.43	0.8	1.86	94.84	2.5
4	5.2	1.9	86.39	6.51	1.1	2	94.14	2.76
VD of the TFP								
Period	GDP	DFI	CO_2	TFP	GDP	DFI	CO_2	TFP
1	0.13	0.21	0.05	99.61	0.14	0.22	0.07	99.57
2	0.38	0.54	2.95	96.13	0.38	0.8	2.95	95.87
3	0.73	1.01	4.43	93.83	0.83	1.31	4.43	93.43
4	1.02	1.31	6.51	91.16	1.12	1.84	6.51	90.53

Declaration of competing interests

The authors declare that they have no competing interests.

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