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How does digital financial inclusion affect households' CO_2? Micro-evidence from an emerging country

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ABSTRACT

This paper examines, at the micro-level, the relationship between digital financial inclusion and households' CO_2 emissions, aiming to investigate the connection between financial inclusion and the environment. Exploiting a unique survey panel dataset of 13,624 Chinese households, I find that digital financial inclusion can increase households' CO_2 emissions, and this result is applicable to other emerging countries. Further analysis based on the mediation model sheds light on how digital financial inclusion influences direct and indirect households' CO_2 emissions, respectively. Specifically, digital financial inclusion encourages non-renewable energy consumption, thereby increasing households' direct CO_2 emissions. Simultaneously, it promotes subsistence and development consumption upgrades, contributing to increased households' indirect CO_2 emissions. Moreover, the study reveals that the impact of digital financial inclusion is heterogeneous. The environmental deterioration effect of digital financial inclusion is mainly driven by the actual uses of different services. As digital financial inclusion develops, its environmental detriment intensifies. Also, in cities where the Carbon Trade Policy (CTP) is implemented, digital financial inclusion can significantly reduce CO_2 emissions. Overall, the findings have several implications for addressing environmental problems in developing countries.

1. Introduction

Access to finance is recognized as a fundamental pillar in the global development landscape. According to a World Bank report, recent estimations indicate a substantial increase in worldwide financial activity, with the finance sector's contribution to global GDP surging, growing more than 1.8 times to 116.41 % over the past decade (Ozturk & Ullah, 2022). However, it's worth noting that the growth rate in financial sector in emerging countries has experienced a decline between 1980 and 2016. This decline underscores the urgent need for these countries to receive financial enhancement and investment support. Such support is vital for stimulating economic growth in these regions, thereby infusing vitality into the world economy.

Economic disparities, often characterized by a large portion of the population lacking access to essential financial services, contribute to economic stagnation (Allen et al., 2016). Factors such as inadequate infrastructure, low-income levels, and a scarcity of formal financial institutions in remote or marginalized areas play a role in financial exclusion (Li et al., 2022). Financial inclusion has emerged as a critical agenda in the context of economic growth in developing countries where access to formal financial services

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remains limited. Extending financial services to unbanked and underbanked populations is important as it fosters economic growth, reduces income inequality, and enhances overall welfare.

However, existing literature suggests that digital financial inclusion could affect the environmental quality either positively or negatively. Digital financial inclusion can help reallocate financial resources required to develop green technologies for sustainable industries, which can help reducing households' CO_2 emissions (Chhabra et al., 2021). Conversely, rapid financial development[2] may result in increased energy consumption, particularly in countries heavily reliant on non-renewable sources (Ozturk & Ullah, 2022). As an important dimension of financial development (Barajas, et al., 2020),[3] financial inclusion might also lead to environmental deterioration. Also, more access to goods and services always leads to more household consumption and increase related CO_2 emissions. As digital financial inclusion develops, disadvantaged people, in particular, can afford energy-intensive goods, such as cars, air conditioners, and refrigerators. As a result, they can emit CO_2 in the production, consumption and usage process (Sadorsky, 2010).

Emerging countries, collectively representing nearly two-thirds of the global population, account for more than 50 % of the total energy consumed in 2018 (Murshed, et al., 2023). Moreover, these economies were responsible for approximately 58 % of the total global CO_2 equivalent emissions during the same year (World Bank, 2018). Among these nations, China is one of the significant contributors to global carbon emissions, making this country an ideal emerging economy to study relationship between carbon emissions and financial inclusion. In 2006, China replaced the United States as the largest CO_2 emitter worldwide (International Energy Agency, I. E, 2009; Zheng et al., 2021). In 2021, China emitted more than 11.9 million tons of CO_2, accounting for 33 % of global emissions (Word Bank, 2021). China has also made substantial efforts to enhance financial inclusiveness, particularly through the rapid expansion of digital financial inclusion services (Wang, et al., 2022).

Additionally, the recently released digital financial inclusion index (*DFII*) and China Family Panel Studies (CFPS) provide rich micro-data for this study. Therefore, understanding the extent to which digital financial inclusion affects households' CO_2 emissions in China can provide valuable insights into this critical issue of emerging countries.

In this context, I investigate the impact of digital financial inclusion on CO_2 emissions of households, based on a unique survey panel dataset of 13,624 Chinese households in 2012, 2014, 2016, and 2018. Given that indirect CO_2 emissions significantly surpass direct CO_2 emissions (Ravallion et al., 2000), I analyze the mechanisms of how digital financial inclusion affects households' direct and indirect CO_2 emissions, respectively. I also investigate the heterogeneous impacts of digital financial inclusion. The results suggest that digital financial inclusion can increase households' CO_2 emissions, and this effect exacerbates as digital financial inclusion develops. It leads to the increase in the consumption of non-renewable energy sources, which results in increased direct CO_2 emissions. Additionally, digital financial inclusion promotes subsistence and development consumption upgrades, contributing to more indirect CO_2 emissions of households. Furthermore, the environmental deterioration effect of digital financial inclusion is mainly driven by the actual uses of different services. It is found that well-designed environmental policy can mitigate the adverse environmental effects.

The main contributions of this study are as follows: Firstly, I find that digital financial inclusion can lead to environmental deterioration, and this effect exacerbates as digital financial inclusion develops. Based on the data from 29 emerging countries, I find that the result is applicable to emerging countries, contrary to previous studies that suggested it benefits the environment in emerging counties (Cai & Song, 2022; Li et al., 2022; Lu et al., 2023; Qin et al., 2022; Song et al., 2023; Sun et al., 2023; Wang & Guo, 2022). Secondly, I contribute to the existing literature by empirically verifying that digital financial inclusion contributes to increased CO_2 emissions by changing households' consumption patterns (energy consumption, total consumption and consumption structure), providing a consumption-related and micro-level perspective. By contrast, existing research has mainly interpreted the mechanisms from production-related and macro aspects, such as industrial upgrades, technological progress, trade, and economic growth (Fareed, et al., 2022; Renzhi & Baek, 2020; Shahbaz et al., 2022; Wang et al., 2022). Thirdly, by dividing the sample into provinces that have implemented environmental policies and those that have not, I find that environmental policies can mitigate adverse environmental effects, providing valuable insights for policymakers seeking to balance financial development with environmental sustainability. Fourthly, due to the availability of data, micro-level empirical research and studies bridging CO_2 emissions to digital financial inclusion within household context are limited. This study provides microscopic evidence of the nexus between digital financial inclusion and households' CO_2 emissions using household data from a nationwide large-scale household survey. Fifthly, none of the previous studies have decomposed CO_2 emissions into direct and indirect CO_2 emissions while exploring the mechanisms. Nevertheless, indirect CO_2 emissions constitute the majority of total emissions, and the underlying mechanisms influencing these two emissions differ significantly (Ravallion et al., 2000). To assure the validity of the analysis, I distinguish direct and indirect CO_2 emissions while exploring the mechanisms. Lastly, the calculation of CO_2 emissions in this study is accurate and innovative. None of the previous studies have differentiated between emissions conversion coefficients (*ECC*) of rural and urban residents when calculating

[2] Financial development refers to the improvement in the ability of a financial system to perform its core function. As Levine (2005) articulates, these functions include: (i) information ex ante about possible investments and allocate capital; (ii) monitoring investments and exerting corporate control; (iv) mobilizing and pooling savings; (v) facilitating the trading, diversification, and management of risk; and (vi) easing the exchange of goods and services.

[3] A well-functioning financial system should not only have sufficient size of financial institutions and markets, but also overcome market frictions and inclusively provide financial services, including savings, payment, credit, and risk management, to a broad range of firms and households (World Bank Group, 2013). By ensuring financial inclusion, the critical financial functions may be carried out more effectively. In this regard, financial inclusion constitutes an essential dimension of financial development (Barajas, et al., 2020). This relationship is further clarified by the World Bank's Global Financial Development Database (Čihák et al., 2012), which identified four key characteristics of financial systems: (a) depth, (b) access/inclusion, (c) efficiency, and (d) stability. Together, these four dimensions provide a more comprehensive view of financial development.

households' indirect CO_2 emissions based on their consumption. By employing environmental input-output analysis (EIOA), I derive *ECC* for consumption of rural and urban households, respectively, accounting for the differences in production process and efficiency.

The paper is organized as follows. Section 2 provides the literature review and research hypotheses. Section 3 describes the methodology and data. Section 4 presents empirical analysis, including baseline regressions, robustness checks, mechanism analysis, and heterogeneity analysis. Section 5 concludes the paper and offers policy implications.

2. Literature review and research hypotheses

2.1. Key definitions

Financial inclusion is the process of ensuring the access to and usage of financial services for all members of society, including savings, credit, payment, and risk management (Allen et al., 2016). These services should be provided at an affordable cost in a fair and transparent manner for customers, while being sustainable for the providers (Demirgüç-Kunt et al., 2015; Kabakova & Plaksenkov, 2018; Rangarajan, 2008). While traditionally dominated by commercial banks, the providers have expanded to include sound private, non-profit, and public providers (Chakrabarty, 2012; United Nations Capital Development Fund, 2006). The concept of financial inclusion is multidimensional, emphasizing four key aspects: accessibility, usage, cost and quality of financial service (Pesqué-Cela et al., 2021).

Emergent digital technologies provide more opportunities to achieve financial inclusion because they are able to overcome existing structural and infrastructural problems to reach people who are excluded from traditional finance services (Ouma et al., 2017). Digital financial inclusion is thus defined as the usage of digital technologies to provide digital products and services, advancing financial inclusion (Liu et al., 2021).

Based on the definition above, I formulate hypotheses about the relationship between digital financial inclusion and households' CO_2 emissions, and the potential mechanisms.

As for the effect of digital financial inclusion on households' CO_2 emissions, I propose that the relationship between digital financial inclusion and households' CO_2 emissions can be either negative or positive.

As for the mechanisms, I propose that digital financial inclusion can influence households' direct CO_2 emissions by altering their non-renewable energy consumption, while it can impact households' indirect CO_2 emissions by affecting their total consumption and consumption structure. These hypotheses offer a micro and consumption-related perspective. Households' CO_2 emissions can be divided into direct and indirect CO_2 emissions. Direct CO_2 emissions come from households' energy requirements, including cooking, heating, driving and so on (Zhu, Peng, & Wu, 2012). These requirements are related to certain energy commodities, such as coal, natural gas and petrol. Indirect CO_2 emissions are embedded in the products that households use or consume. They are related to the manufacturing of products and services, including food, cloth, household maintenance, daily necessities and durables, transportation and communication, medicine and health care, education and recreation, and miscellaneous commodities and services. It's important to note that compared with direct CO_2 emissions, indirect CO_2 emissions are much higher (Wang & Yang, 2014; Zhang et al., 2017). Due to this difference, I analyze how digital financial inclusion affects direct and indirect CO_2 emissions separately.

The detailed discussions of the hypotheses are outlined as follows:

2.2. Environmentally-friendly effect

Digital financial inclusion plays a pivotal role in promoting eco-friendly household production and consumption by facilitating the transition towards cleaner industrial and energy systems (Li et al., 2022).

First, digital financial inclusion enables residents to buy and access available financial services online without leaving home. Examples such as M-Pesa in Kenya, the Pradhan Mantri Jan Dhan Yojana (PMJDY) program in India, and the Grameen Bank in Bangladesh have demonstrated the efficacy of these initiatives. This approach can not only directly reduce non-renewable energy consumption but also minimize the need for physical product transportation, thereby decreasing associated households' CO_2 emissions (Rosqvist & Hiselius, 2016; Song et al., 2023).

Second, advanced digital financial inclusion can improve innovation and technological progress in the production process Feng et al., 2022; Zhang & Ling, 2022), which accelerates the green transformation of production and indirectly reduces households' CO_2 emissions. By broadening financing channels and reducing financial costs, digital financial inclusion can reallocate financial resources required for innovative enterprises that are usually economically marginalized (Gomber et al., 2017; Lu et al., 2022; Tamazian et al., 2009). The majority of the companies engaged in innovation and green industries are small and medium enterprises (SMEs) (Zhang, Li, et al., 2023). However, owing to the profit-seeking behavior of traditional financial institutions and the information asymmetry in financial markets, SMEs face serious financial constraints (Stiglitz & Weiss, 1981). The widespread use of digital financial products can foster investment in SMEs, which can accelerate scientific progress and result in more energy-saving production (Lu et al., 2022). Moreover, digital financial inclusion can support industrial restructuring. It can also help finance the adoption of energy-efficient technologies, making these technologies more accessible (Cai & Song, 2022; Ye et al., 2020). Taking conventional industries for example, these technologies can restructure and replace traditional technologies and production practices with energy-efficient options through financing from digital financial inclusion (Yao & Tang, 2021).

Based on the above reasoning, the following hypothesis is proposed:

Hypothesis 1a. : *The development of digital financial inclusion can reduce CO_2 emissions of households.*

2.3. Environmental-deteriorating effect

Financial development allocates financial resources to economic activities, potentially resulting in the expansion of production scales and the intensification of consumption. This, in turn, can lead to increased energy demand and CO_2 emissions (Shahbaz & Lean, 2012). As a subset of financial development, digital financial inclusion also exhibits similar characteristics (Lu et al., 2023).

From the demand aspect, products become cheaper. Online payment overcomes geographical restrictions to offer consumers different products from around the world. As brick-and-mortar stores are not needed, the price of online products is lower because businesses' costs are lower (Huang et al., 2022). In this regard, by providing diverse and low-price products online, digital financial inclusion may increase household consumption, as well as CO_2 emissions. Also, by granting more investment in clean technologies, digital financial inclusion reduces production and industrial efforts (Khan & Ozturk, 2021), which may result in goods with lower prices. As such, residents may consume more, resulting in more CO_2 emissions (Zhang, Wu, et al., 2023).

From the supply aspect, more goods are produced to meet the increased household demand (Huang et al., 2022). Increased production can lead to excessive emissions that harm the environment. Even if penalties exist for excessive carbon emissions, the profits gained from increased revenues may still encourage companies to pay fines for increased production, resulting in increased CO_2 emissions, and a diminished energy-environmental performance (Wang et al., 2022).

Accordingly, the following contradictory hypothesis is proposed:

Hypothesis 1b. : *The expansion of digital financial inclusion can increase CO2 emissions of households.*

2.4. The mechanism of impact of digital financial inclusion on direct CO_2 emissions - a micro perspective

Digital financial inclusion comprises a variety of online services that may reduce non-renewable energy consumption (Lu et al., 2023), which may cultivate eco-friendly habits in the society. For example, digital financial inclusion can have a positive impact on enhancing access to clean energy, making it more affordable and accessible. In the case of Kenya's M-Pesa, the digital platform has facilitated the purchase of solar-powered products, reducing residents' consumption of non-renewable energy. What's more, digital financial inclusion can motivate the environmental consciousness of residents and encourage their participation in protecting environment by digitizing personal environment-protection achievements (Zhao et al., 2021). Take, "EcoCash Save the Environment" initiative in Zimbabwe, for example, for every electronic transaction or digital savings made through the platform, a portion goes toward tree planting and other environmental conservation efforts. Users can track their environmental contributions through the app, fostering a sense of responsibility for environmental sustainability. By this way, residents can become more aware of the need for and possible ways to reduce household non-renewable energy usage. They become motivated to conserve energy and adopt relevant behaviors, which are effective for household non-renewable energy savings (Steg, 2008).

While the impact of microfinance on household income remains a subject of debate in the literature, with studies based on Random Control Trial (RCT) data being subject to contention (Dahal & Fiala, 2020),[4] most studies based on observational data suggest potential positive effects of digital financial inclusion on households' income. (Li et al., 2022) and (Song, Li, Wu, & Yin, 2020) found digital financial inclusion may potentially increase households' expected income in several ways by providing access to different kinds of services. By collecting daily data of residents, for example, online credit can help mitigate information asymmetry, possibly relieving households from credit constraints. Online insurance could broaden access to insurance services, thus reducing households' uncertainty losses and improving their sense of security about future income. Online financing could diversify the channels for residents, possibly raising returns on investment. With increased income, households naturally tend to consume more non-renewable energy, resulting in more direct CO_2 emissions. Accordingly, the following hypotheses are proposed:

Hypothesis 2a. : *Digital financial inclusion can affect households' direct CO2 emissions by changing households' non-renewable energy consumption.*

2.5. The mechanism of impact of digital financial inclusion on indirect CO_2 emissions - a micro perspective

(1) Households' total consumption

By promoting technological innovation and providing approachable products online, digital financial inclusion can lower overall price levels and help access to more diversified categories of consumer goods, thus transforming total household consumption (D'Acunto et al., 2020; Hikida & Perry, 2020). This, in turn, can lead to changes in consumption-related emissions.

(2) Households' consumption structure

Digital financial inclusion has the potential to increase household income and thus make more goods and services accessible, including energy-saving and energy-intensive ones (Li et al., 2022). In this regard, digital financial inclusion may potentially improve households' consumption structure. The extent of the consumption upgrades depends on residents' current living standards.

Human consumption can be divided into different categories, which are often represented as a hierarchical pyramid (Liu & Hu, 2021; Zhang, et al., 2023). As shown in Fig. 1, from bottom to top, the needs are broadly classified as subsistence needs, development needs and enjoyment needs. Subsistence needs refer to basic necessities or essential requirements that an individual or a population

[4] It is mainly because existing research based on randomized control trials (RCT) is underpowered to detect reasonable effect sizes (Dahal & Fiala, 2020).

require to maintain a minimal standard of living. This typically includes food. Development needs go beyond subsistence or basic survival needs and are associated with the growth, improvement, and advancement of an individual, community, or society. Development needs can vary widely depending on the context. Enjoyment needs refer to experiences of pleasure, satisfaction, and enjoyment in life. This last category is always associated with intangible services.

People must meet lower needs before they meet higher ones. The people at economic disadvantage through digital financial inclusion, may have to spend more money on energy-intensive electric appliances following satisfaction of their needs pertinent to survival. This kind of consumption upgrade is defined as a development consumption upgrade and is related to more indirect CO_2 emissions. As for the middle class households, their requirement for development has already been met. They are more likely to meet higher needs of self-actualization when their financial constraints are released by digital financial inclusion. For example, they may spend more on education, entertainment, and other intangible services. This kind of consumption upgrade is defined as the enjoyment consumption upgrade and is linked to less indirect CO_2 emissions.

Overall, digital financial inclusion may lead to either development or enjoyment consumption upgrade, which can impact household's indirect CO_2 emissions.

Accordingly, the following hypotheses are proposed:

Hypothesis 2b. : *Digital financial inclusion can affect households' indirect CO_2 emissions by changing households' total consumption.*

Hypothesis 2c. : *Digital financial inclusion can affect households' indirect CO_2 emissions by improving households' consumption structure.*

Fig. 2 presents the research model of this study.

3. Methodology and data

3.1. Sample and data resources

The data in this paper are mainly obtained from four databases: Digital Financial Inclusion Index (*DFII*), China Family Panel Studies (CFPS), Carbon Emission Accounts and Datasets for emerging economies (CEADs) and China Statistical Database (CSD).

The measure of financial inclusion is always a key topic. As discussed before, financial inclusion is a multidimensional concept, an appropriate measure of financial inclusion has to be multidimensional (Pesqué-Cela et al., 2021). Beck et al. (2007) made the first attempt to measure financial inclusion. They defined it through two dimensions: (i) the access to (the possibility to use) and (ii) the use (the actual use) of financial services. Subsequent research has expanded upon these dimensions, incorporating cost (monetary and nonmonetary costs) and quality (usefulness of product matching with customers' needs) of financial services (Arora, 2018; Gupte et al.,

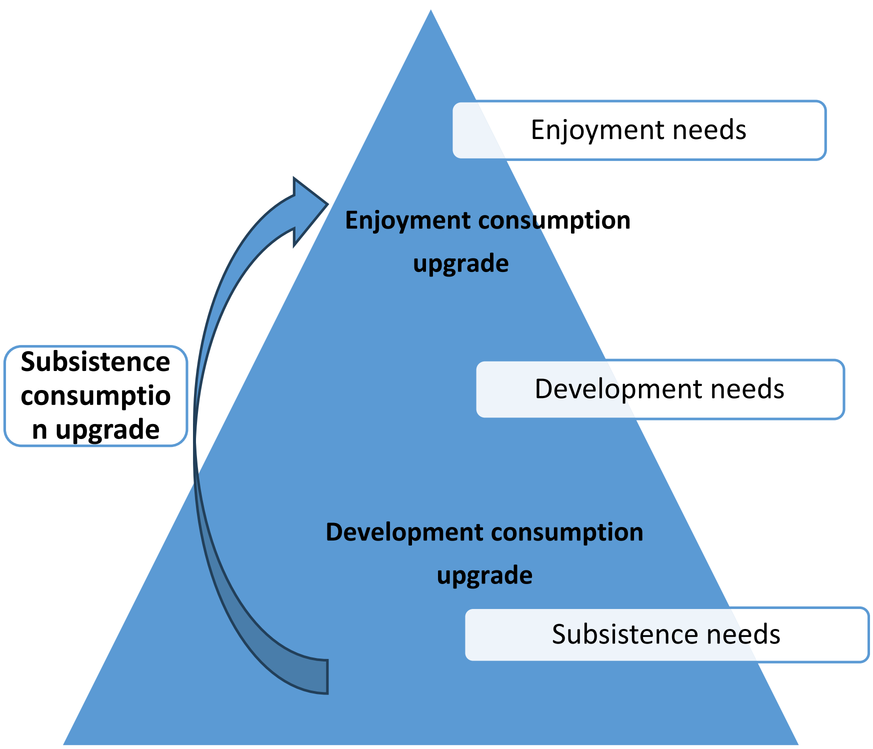

Fig. 1. Hierarchy of needs.

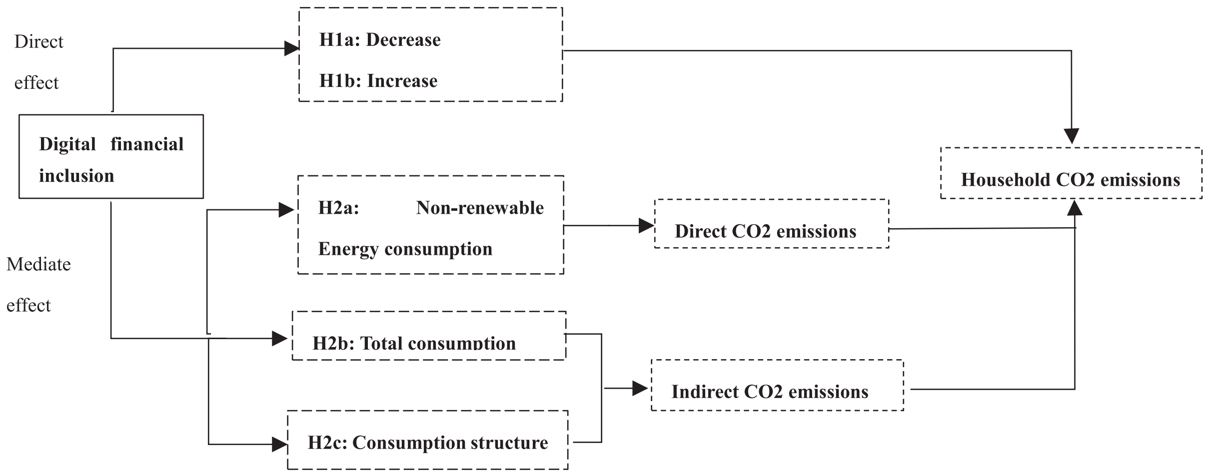

Fig. 2. Research model.

2012; Roa, 2015). Based on existing financial inclusion indexes and considering the new features of digital financial services, in combination with the availability and reliability of the data, the Institute of Digital Finance at Peking University and Ant Financial Services Group developed the *DFII*. The overall index encompasses three Level 1 dimensions: breadth of coverage, depth of usage and level of digitization. Each Level 1 dimension is further divided into Level 2 dimensions. For example, under the usage depth, the Level 2 dimensions include payment, money funds, credit, insurance, investment, and credit investigation. All level 2 dimensions are further broken down into 33 specific indicators (see Appendix Table A.1). The accessibility of traditional financial institutions is shown in the "number of outlets" and "number of service personnel". By contrast, under the model of Internet-based new finance, because the Internet has no location restrictions by nature, the reach of Internet financial services is reflected by the number of e-accounts, etc. (such as Internet payment accounts and the bank accounts they are bound to). The depth of usage measures the actual use of Internet financial services. Regarding the level of digitization, convenience and cost are the main features of digital financial services, which truly reflects their low cost and low threshold (Guo et al., 2016). The overall *DFII* is calculated using 33 indicators. After non-dimensionalizing these indicators, the coefficient of variation weighting method was used to assign weights to the indicators and form the Level 2 dimensions. Subsequently, the Analytic Hierarchy Process (AHP) was applied to assign weights to both Level 2 and Level 1 dimensions, which were combined to form the overall index. This index has been published at three geographical levels, namely, province, municipality, and county levels, to measure the development of digital financial inclusion from 2011 to 2021.

CFPS was launched by the Institute of Social Science Survey (ISSS) of Peking University in 2010 as a nationally representative annual longitudinal survey of Chinese communities, households, and individuals. The interview is conducted every two years. There have been five rounds of interviews so far, in 2010, 2012, 2014, 2016, and 2018. The data cover 162 counties of 25 provinces/municipalities and contain 16000 samples every time. They offer families' information on demographic characteristics, assets, and consumption to provide a comprehensive picture of households' economic situation, thus establishing a suitable database for this study. CEADs bring a group of professionals from the United Kingdom, the United States, and China to study emission accounting methodologies and applications for China and other developing countries. They provide reliable and up-to-date data about CO_2 emissions at the provincial level. CSD is compiled by the National Bureau of Statistics of China, and it provides data concerning the nation's economy, population, and other aspects of society.

I combine these databases and obtain a panel data sample from 13,624 households for years 2012, 2014, 2016, and 2018. The following data are excluded from the dataset: (1) data points with negative net income or negative net wealth, (2) data points with extreme net wealth, (3) data points whose householders are below 18 years old, and (4) data points with missing data.

3.1.1. Dependent variable

(1) Households' CO_2 Emissions (*HCE*)

Households' CO_2 emissions can be divided into direct and indirect CO_2 emissions. Direct CO_2 emissions come from household energy requirements, including cooking, heating, driving and so on. Indirect CO_2 emissions are embedded in the products that households use or consume. They are related to the manufacturing of products and services, including food, cloth, household maintenance, daily necessities and durables, transportation and communication, medicine and health care, education and recreation, and miscellaneous commodities and services. In Eq. (1), I obtain $HCE_{i,r}$ by summing up the $HDE_{i,r}$ and $HIE_{i,r}$.

$$HCE_{i,r} = HDE_{i,r} + HIE_{i,r} \tag{1}$$

Where $HDE_{i,r}$ is direct CO_2 emissions of *i*th household; $HIE_{i,r}$ is indirect CO_2 emissions of *i*th household in *r* area; $HCE_{i,r}$ is the total CO_2 emissions of *i*th household in *r* area.

(2) Households' Direct CO_2 Emissions (*HDE*)

Households' direct CO_2 emissions can be calculated by multiplying the physical unit of direct energy consumption within households by the corresponding emissions factors as follows:

$$HDE_i = \sum_m EF_m * Energy_{i,m} \tag{2}$$

Where HDE_i is households' direct CO_2 emission; EF_m is the emissions factors of the mth type of energy; $Energy_{i,m}$ is the consumption of mth type of energy within the ith household. Based on the emission factors provided by Liu et al. (2015) and calculation outlined by Qin et al. (2022), I calculate direct CO_2 emissions at the household level.

(3) Households' Indirect CO_2 Emissions (*HIE*)

According to the research of Li et al. (2019); Wei et al. (2007) and He et al. (2023), I calculate *HIE* by multiplying the spending in each consumption area with domestic emissions conversion coefficients (*ECC)*, which represents the amount of CO_2 emissions per RMB (Renminbi) spent in different consumption areas. It is worth noticing that *ECC* vary between rural and urban areas due to differences in production process and efficiency. As a result, I categorize *ECC* into rural and urban coefficients to correspond with households in different areas. Data on expenditures in each consumption area of each household are taken from CFPS. $HIE_{i,r}$ is calculated as follows:

$$HIE_{i,r,j} = ECC_{r,j} * y_{\exp,i,r,j} \tag{3}$$

and

$$HIE_{i,r} = \sum_j HIE_{i,r,j} \tag{4}$$

where $ECC_{r,j}$is the CO_2 emissions in the jth consumption in the r area, $y_{\exp,i,r,j}$ is the expenditure in the jth consumption of the ith household in the r area, $HIE_{i,r,j}$ refers to the indirect CO_2 emissions in the jth consumption of ith household in r area, and $HIE_{i,r}$ refers to the total indirect CO_2 emissions of the ith household in r area.

I apply the environmental input–output analysis to calculate indirect CO_2 emissions embedded in household consumption. The input–output analysis (Leontief, 1986) is widely used to demonstrate the interdependence between economic sectors. The framework was developed as an environmental input–output analysis (EIOA) for environmental studies by adding a column that shows the emission or resource intensity. The basic formula of EIOA is as follows:

$$\mathrm{X} = (\mathrm{I} - \mathrm{A})^{-1}\mathrm{F} \tag{5}$$

where $X = (x_i)$ is the vector of the total output, and x_i is the total output of sector i; I is the identity matrix, and $(I\text{-}A)^{-1}$ is the Leontief inverse matrix. $A = (a_{ij})$ is the technical coefficient matrix, and $a_{ij} = z_{ij}/ x_j$, where z_{ij} is the monetary input of sector j from sector i. $F= (f_i)$ is the final demand matrix, and f_i is the final demand for products of sector i.

$$\mathrm{ICE} = \mathrm{E}\,(\mathrm{I} - \mathrm{A})^{-1}\mathrm{F} \tag{6}$$

where *ICE* is the matrix delineating the total CO_2 emissions embedded in goods and services used for final consumption, and *E* is a vector representing the CO_2 emission intensity of all sectors, measured by CO_2 emissions per unit of economic output. Emissions induced by fossil fuel combustion and cement production are included in this study. CO_2 emissions of each sector in China's MRIO table are adopted from the CEADs database (Shan, et al., 2018; Shan et al., 2020). Eq. (7) shows the calculation of CO_2 emissions induced by the final demand, including rural and urban households, the government, capital and changes in inventory stock, and exports. Households' indirect CO_2 emissions can be calculated accordingly as follows:

$$\mathrm{HIE} = \mathrm{E}\,(\mathrm{I} - \mathrm{A})^{-1} y_{\exp} \tag{7}$$

where *HIE* is households' indirect CO_2 emissions, and y_{exp} is the rural and urban household consumption in each region. *ECC* and y_{exp} are then aggregated into eight categories of consumption in the household expenditure survey: food, clothing, residence, household facilities, transport, education, health care, and others. *ECC* is calculated according to the eight-category indirect CO_2 emissions and consumption as follows:

$$\mathrm{ECC} = HIE \Big/ y_{\exp} \tag{8}$$

Considering that the CO_2 intensity of China's domestic production is higher than the global average CO_2 intensity, I link Chinese MRIO tables with global tables to calculate the CO_2 emissions embedded in household imports. I establish the 2017 MRIO table for China's 42 sectors and 30 regions (26 provinces and four province-level municipalities). The 2007 and 2012 China input–output tables are from previously published work and describe economic linkages between 30 sectors in 30 regions (Mi, et al., 2018; Mi, et al., 2020). I adopt global input–output tables by EXIOBASE and connect China input–output tables with the global tables to calculate the CO_2 emissions embodied in imports. The EXIOBASE MRIO tables include 168 sectors, 44 major countries, and 5 regions in the world, describing international trade between them (Stadler, et al., 2018). The sectors in China and global input–output tables are matched for the connection. All MRIO tables are deflated to 2017 prices. Finally, the connected global MRIO tables delineate the interdependence between 30 sectors in 30 Chinese provinces as well as 48 countries/regions in the world. To calculate the household indirect

CO_2 emissions in the period 2011–2018 from the household expenditure surveys, I use linear interpolation to estimate the emission conversion coefficients in other years based on results in years 2007, 2012, and 2017.

Based on the equations above, I calculate the *ECC* and *HIE* of eight consumption areas in years 2012, 2014, 2016, and 2018. The average values of the *ECC* of 25 provinces are given in Table 1. House maintenance is the most carbon-intensive category in both 2012 and 2018, while the least intensive category in 2012 and 2018 is miscellaneous commodities and services. Only the *ECC* in medicine and health care shows an increase during this period. The highest rate of decrease is observed in the area of miscellaneous commodities and services, which is 50.95 %. Second comes transportation and communication, which shows a 47.74 % decrease. Households' indirect CO_2 emissions from 2012 to 2018 exhibit an increase of 17.62 %. Indirect CO_2 emissions come from house maintenance, while medicine and health care show the largest increase during this period.

3.1.2. Independent variable

The independent variable of interest is the digital financial inclusion index (*DFII*). I mainly use the data at the provincial level for empirical analysis because of the private and confidential clause of CFPS.

Fig. 3 shows the spatial distribution of the level of digital financial inclusion in mainland China in 2012 and 2021. Overall, the development of digital financial inclusion is unbalanced. A gradient change can be seen from Hangzhou to central China and then to western regions. The distribution suggests that geographic location still plays a role in the development of digital financial inclusion. In other words, the level of digital financial inclusion of a province is negatively correlated with its distance from Hangzhou, partially because the diffusion and promotion of digital finance are geographically dependent.

3.1.3. Mediating variables

(1) Non-renewable energy (*Nonrenew*)

As electricity is usually counted as indirect CO_2 emissions, I mainly calculate three types of non-renewable energy: natural gas, coal, and petroleum (Qin et al., 2022).

$$Energy\ consumption = Nature\ gas + Coal + Petrol \tag{9}$$

(2) Total household consumption (*Total*)

I use the total household consumption from the family economic database of CFPS. The calculation is defined as follows:

$$\begin{aligned} Total\ household\ consumption = {} & Food + Cloth + House\ maintenance + Daily\ necessities\ and\ durables \\ & + Transportation\ and\ communication + Medicine\ and\ health\ care + Education\ and\ recreation \\ & + Miscellaneous\ commodities\ and\ services \end{aligned} \tag{10}$$

(3) Household consumption structure

According to the research of Liu and Hu (2021), I divide the consumption structure into three hierarchies: subsistence consumption, development consumption, and enjoyment consumption.

a. Subsistence upgrade coefficient (*Subsistence*)

The decrease in this coefficient implies that the survival need is increasingly being met. The coefficient is defined as follows:

$$Subsistence = (Food + Cloth)/Total\ household\ consumption \tag{11}$$

b. Development upgrade coefficient (*Development*)

I use the development upgrade coefficient to represent the development consumption upgrade. The increase in this coefficient implies a higher upgrade of household consumption because people can only start to pay attention to their development needs after their needs for survival have been met. This coefficient is defined as follows:

Table 1
Emissions conversion coefficients (*ECC*) and CO_2 emissions of eight categories' consumption.

Categories	Average *ECC* of 25 provinces (kg CO_2/RMB)		Change (%)	Average emissions of 25 provinces (100 t CO_2)		Change (%)
	2012	2018		2012	2018	
Food	87,615.78	68,255.59	−22.10 %	13,100	11,910	−9.08 %
Cloth	110,748.20	85,767.68	−22.56 %	2063	2277	10.37 %
House maintenance	320,535.00	212,336.70	−33.76 %	7014	19,400	176.59 %
Daily necessities and durables	283,678.00	149,451.40	−47.32 %	15,400	11,430	−25.78 %
Transportation and communication	230,120.00	120,259.30	−47.74 %	6734	5780	−14.17 %
Medicine and health care	78,372.82	102,294.20	30.52 %	2546	5646	121.76 %
Education and recreation	86,154.41	65,006.27	−24.55 %	3343	4114	23.06 %
Miscellaneous commodities and services	76,795.08	37.667.27	−50.95 %	1588	358	−77.46 %
Total	-	-	-	51,788	60,915	17.62 %

(Source: Author calculation)

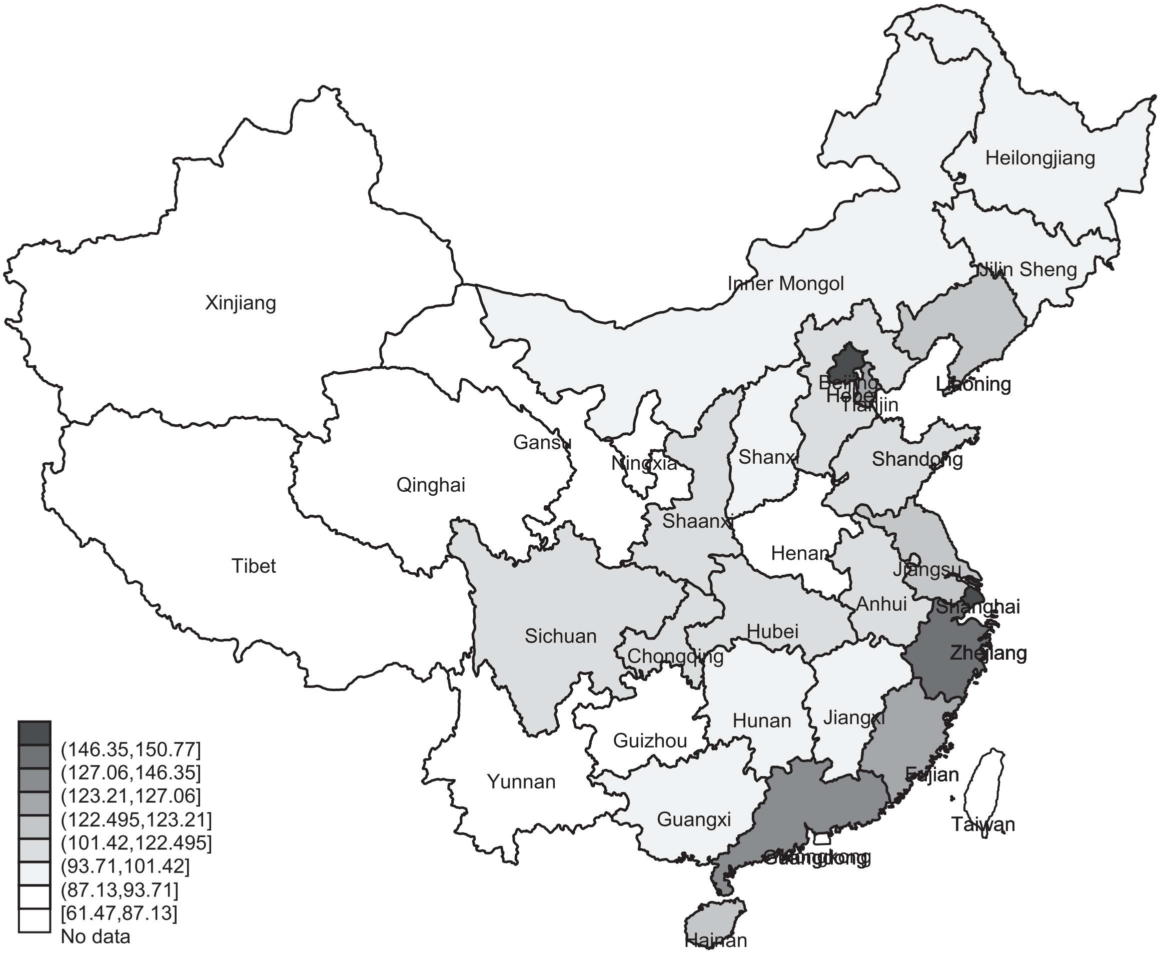

Fig. 3. Spatial distribution of the development of digital financial inclusion in 2012 (left) and 2021 (right). **(Source: Digital Financial Inclusion Index).**

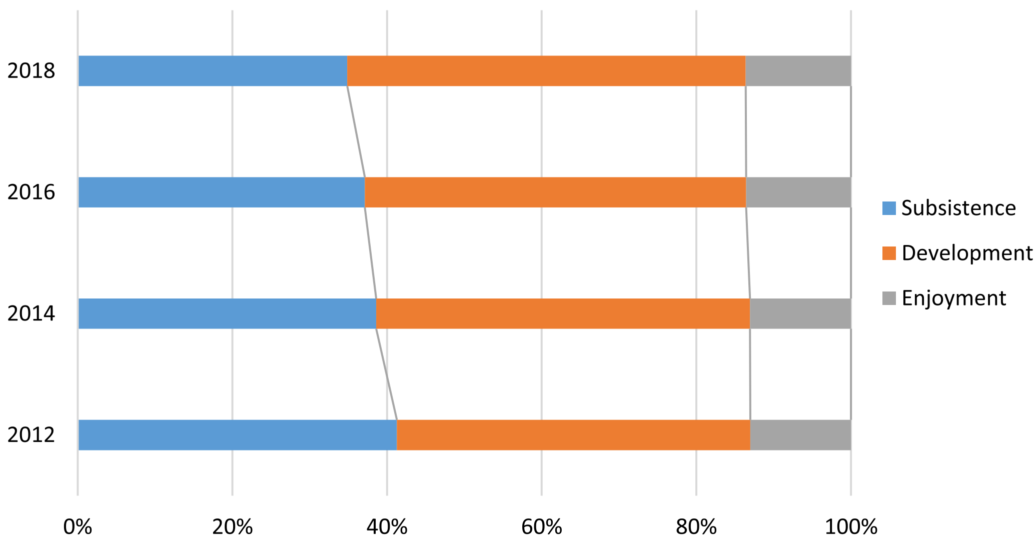

Fig. 4. Household consumption structure in China, **(Source: China Statistical Database).**

$$Development = (House\ maintenance + Daily\ necessities\ and\ durable + Transportation\ and\ communication + Medicine\ and\ health\ care)/(Total\ household\ consumption) \tag{12}$$

c. Enjoyment upgrade coefficient (*Enjoyment*)

I use the enjoyment upgrade coefficient to present the enjoyment consumption upgrade, which is people's highest demand. It only applies after the first two demands have been met. This coefficient is defined as follows:

$$Enjoyment = (Education\ and\ recreation + Miscellaneous\ commodities\ and\ services)/(Total\ household\ consumption) \tag{13}$$

Fig. 4 shows the fluctuation of different consumption areas in China in 2012, 2014, 2016, and 2018. The proportion of subsistence consumption shows a decline from 41.27 % in 2012 to 34.86 % in 2018. Marked by the decreasing proportion of food and cloth consumption, China's household consumption pattern shows a significant improvement during this period. Besides, the proportion of development consumption shows an increase during this period, from 45.71 % to 51.53 %, while the increase in the proportion of enjoyment consumption is relatively small (from 13.01 % to 13.62 %). These changes imply that residents' higher needs are starting to be met.

3.1.4. Control variables

Households vary in terms of lifestyle, size, and income, and in other aspects. Based on existing literature by Lenzen et al. (2004) and Qu et al. (2013), three categories of variables have essential influences on household consumption behaviors and are thus related to CO_2 emissions: (1) householder characteristics, namely householder's education years and householder's age; (2) household characteristics, including family income, family assets, family size, the child dependency ratio, the senior dependency ratio, and whether the family is engaged in agricultural production; (3) economic development, which includes the population density, per-capita GDP, urbanization rate, and financial development level. Table 2 shows the detailed variable descriptions. Householder and household characteristics data are taken from the CFPS. Data of the economic development of each province are taken from CSD.

All the variables are defined in Table 2.

Table 2
Variable definitions.

Types		Variables	Definition
Dependent variable		*HCE*	Households' CO_2 emissions (kg) =Households' direct CO_2 emissions + Households' indirect CO_2 emissions
		HDE	Households' direct CO_2 emissions(kg) = $\sum_{i=1}^{n}$ [Physical units of household energy comsumption*corresponding emission factors(*EF*)]
		HIE	Households' indirect CO_2 emissions(kg) = $\sum_{i=1}^{n}$ [Spending in each consumption area*corresponding emissions conversion coefficients(*ECC*)]
Independent variable		*DFII*	Digital financial inclusion index
		Coverage	Breadth of coverage: The accessibility of digital financial inclusion
		Usage	Depth of usage: The actual use of digital financial inclusion services
		Digital	Level of digitalization: Service convenience and cost.
Mediating variable	Non-renewable energy consumption	*Nonrenew*	Nature gas+Coal+Petrol (RMB)
	Total household consumption	*Total*	Family consumption (RMB)
	Household consumption structure	*Subsistence*	Subsistence upgrade (%) = (Food+Cloth) / Total consumption
		Development	Development upgrade (%): = (House maintenance + Daily necessities and durables + Transportation and communication + Medicine and health care) / Total consumption
		Enjoyment	Enjoyment upgrade (%): = (Education and recreation + Miscellaneous commodities and services) / Total consumption
Control variables	Householder characteristics	*Eduy*	Householder's years of education
		Age	Householder's age
	Household characteristics	*Fincome*	Family income (RMB)
		Fasset	Family asset (RMB)
		Fsize	Family size
		CDR	Child dependency ratio (%): The population under 18 years of age divided by the working-age population, aged 18–64
		SDR	Senior dependency ratio (%): The population aged 65 and older divided by the working-age population, aged 18–64
		Rural	Whether family is engaged in agricultural production: Yes: 1; No:0
	Economic development	*Per_GDP*	Per-capita GDP
		Urate	Urbanization rate (%): Urban population divided by total population
		Fdevelop	Financial development level: the outstanding loans in RMB of financial institutions divided by the GDP of the province

3.2. Descriptive statistics

The descriptive statistics of all variables are shown in Table 3. Households' CO_2 emissions are 6090,000 tons on average. Households' CO_2 emissions can reach a maximum of 243,000,000 tons and a minimum of 21,700 tons, indicating that the difference in CO_2 emissions between households is significant. The average level of the digital financial inclusion index (*DFII*) is 198.5081. Its maximum value is 377.73, which is almost five times the minimum value (75.87). There is a huge gap between different households when it comes to non-renewable energy consumption and total consumption. The average values of the subsistence coefficient, development coefficient, and enjoyment coefficient are 0.45, 0.33, and 0.22, respectively, which means that most Chinese households spend most of their income on subsistence products.

3.3. Model specification

Considering the possible non-normality of Household CO_2 emissions (*HCE*), Digital financial inclusion index (*DFII*), Total household consumption (*Total*), Family income (*Fincome*), Family asset (*Fasset*), Per-capita GDP (*Per_GDP*) and Financial development level (*Fdevelop*), they are transformed into logarithms in the regression.

To evaluate the impact of digital financial inclusion on households' CO_2 emissions, I implement the regression model as follows:

$$\ln HCE_{i,j,t} = \alpha_0 + \alpha_1 \ln DFII_{j,t} + \sum Controls_{i,j,t} + Province + Year + \varepsilon_{i,j,t} \tag{14}$$

where *i, j,*and *t* denote the household, province, and time, respectively; $HCE_{i,j,t}$ is households' CO_2 emissions; $DFII_{j,t}$ is the digital financial inclusion index; $\sum Province$ represents the province fixed effect; and $\sum Year$ is the time fixed effect. The employment of a two-way fixed effects model enables control for unobservable time-invariant (or slowly moving) factors and common time trends, thereby enhancing the validity of the estimation (Beck, 2001; Wooldridge, 2010). By specifying my models with a wide range of independent variables and, in particular, with both group-specific and period fixed effects, I control for potential sources of omitted variables bias.

4. Empirical results and discussion

The empirical research constitutes of four parts: (1) baseline regressions with fixed effects to examine the relationship between digital financial inclusion and households' CO_2 emissions; (2) robustness analyses to validate the stability and reliability of the baseline findings; (3) mechanism analysis to elucidate the channels through which digital financial inclusion influences households' CO_2 emissions; (4) heterogeneity analysis to uncover nuanced aspects of the relationship between digital financial inclusion and households' CO_2, revealing varying effects across different dimensions of digital financial inclusion, different levels of its development, and between cities with distinct environmental policy frameworks.

4.1. Baseline regressions

Based on Eq. (14), I conduct baseline regressions to test whether the relationship between digital financial inclusion and household CO_2 emissions is negative (H1a) or positive (H1b). The estimated results are shown in Table 4. In column (1), I only include the *lnDFII*. From columns (2) to (3), I add control variables and fixed effects in sequence. The coefficient of *lnDFII* in column (3) is statistically significant, which means that the development of digital financial inclusion increases households' CO_2 emissions, supporting H1b, not H1a.

As householders become more educated, their households release more CO_2. This point may suggest that more educated householders earn more and consume more. The householder's age has a significant negative influence on households' emissions. This may be because householders earn less after retirement, and as a result, the emissions drop. With the increase in family income and family assets, CO_2 emissions induced by household increase. As wealth increases, households can use more goods and services to meet their increasing demands, leading to an increase in energy consumption (Donglan et al., 2010; Feng et al., 2009). The proportion of children and the elderly has a positive impact on households' CO_2 emissions, which is consistent with the conclusion of Golley and Meng (2012). Households engaged in agricultural production release less CO_2 than those that are not.

4.2. Robustness analyses

This section presents an array of robustness analyses to ensure the reliability and validity of the results. First, to evaluate the applicability of the baseline regressions to emerging countries, I choose 29 emerging countries based on the data availability (See Appendix Table A.2). Second, to avoid the estimated deviation caused by the specialty of municipalities, I drop these samples. Thirdly, I perform 1 % winsorization on all variables to prevent the influence of extreme values. Fourthly, I replace *lnDFII* with its one-lagged form, $lnDFII_{t-1}$, to avoid estimation bias caused by reverse causality. At last, I use *mobile phone penetration* as an instrumental variable to solve other biases due to endogeneity. All the results are shown in Table 5.

4.2.1. Evidence from 29 emerging countries

The data for the *DFII* of emerging countries is from International Monetary Fund (IMF), and CO_2 emissions data is from CEADs. Additionally, I also include *GDP per capita*, *GDP per capita growth* and *urbanization rate* as control variables. The results, shown in

Table 3
Descriptive statistics.

Variables	N	Mean	Std. Dev.	Min	Max
HCE	13,624	6.09e+09	8.76e+09	2.17e+07	2.43e+11
HDE	13,624	518.34	674.50	0	13753.29
HID	13,624	6.09e+09	8.76e+09	2.17e+07	2.43e+11
DFII	13,624	198.51	75.50	75.87	377.73
Coverage	13,624	180.79	76.01	49.87	353.87
Usage	13,624	187.25	71.33	68.98	400.40
Digital	13,624	277.47	93.94	107.07	440.26
Nonrenew	13,624	3536.62	4166.38	0	104460.9
Total	13,624	47976.67	52256.69	132	923780
Subsistence	13,624	0.45	0.20	0	0.99
Development	13,624	0.33	0.21	0.01	1
Enjoyment	13,624	0.22	0.16	0	0.93
Eduy	13,624	7.00	4.12	0	19
Age	13,624	50.28	10.75	18	91
Fincome	13,624	47510.85	49178.74	0	1080000
Fasset	13,624	462262.9	1057706	100	50500000
Fsize	13,624	4.06	1.74	1	15
CDR	13,624	0.28	0.37	0	4
SDR	13,624	0.18	0.36	0	4
Rural	13,624	0.64	0.48	0	1
Per_GDP	13,624	47674.27	22112.31	19710	153095
Urate	13,624	0.55	0.12	0.36	0.90
Fdevelop	13,624	12969.22	4371.83	6767.54	25507.07

Table 4
Baseline regressions: The relationship between digital financial inclusion and household CO2 emissions.

Dependent variable Independent variables	(1) *lnHCE*	(2) *lnHCE*	(3) *lnHCE*
lnDFII	0.11***	0.08***	0.53***
	(8.18)	(3.14)	(2.65)
Eduy	-	0.02***	0.02***
		(11.17)	(2.02)
Age	-	−0.01***	−0.02***
		(−10.90)	(−10.83)
lnFincome	-	0.04***	0.04***
		(9.82)	(10.53)
lnFasset	-	0.18***	0.20***
		(28.60)	(31.30)
Fsize	-	0.10***	0.11***
		(19.52)	(22.62)
SDR	-	−0.05**	−0.05**
		(−2.33)	(−2.28)
CDR	-	−0.10***	−0.07***
		(−4.67)	(−3.19)
Rural	-	−0.3037***	−0.31***
		(−17.55)	(−18.18)
lnPer_GDP	-	−0.8530***	−0.81***
		(−14.06)	(−7.15)
Urate	-	2.2658***	−2.07***
		(11.45)	(−3.16)
lnFdevelop	-	0.1047***	−0.02
		(2.62)	(−0.18)
Year FE	NO	NO	YES
Province FE	NO	NO	YES
Observations	13,624	13,624	13,624
R^2	0.0033	0.2918	0.3467

Note: *, **, *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. z-statistics are given in parentheses.

column (1) of Table 5, imply that the development of digital financial inclusion in emerging countries can increase their households' CO_2 emissions. The findings from the baseline regression can be generalized to other emerging countries.

4.2.2. Dropping the samples from municipalities

Differently from other cities, municipalities are directly subordinate to the central government and hold greater autonomy in policy implementation, resource allocation, and economic decision-making. Therefore, the impact of digital financial inclusion on

Table 5
Robustness analyses.

Dependent Variables	Robustness check 1: 29 emerging countries	Robustness check 2: Dropping municipalities	Robustness check 3: Winsorization	Robustness check 4 : One-lagged *lnDFII*	Robustness check 5: Instrumental variable estimation	
	(1)*lnHCE*	(2)*lnHCE*	(3)*lnHCE*	(4)*lnHCE*	(5)*lnDFII*	(6)*lnHCE*
Independent Variables					First stage regression	Second stage regression
DFII	2.90* (1.74)	-	-	-	-	
lnDFII	-	0.55** (2.55)	0.44** (2.32)	-	-	0.44** (1.87)
$\overline{\ln DFII}$	-	-	-	-	27.00*** (541.50)	-
$lnDFII_{t-1}$	-	-	-	0.11*** (8.47)	-	-
Control variables	YES	YES	YES	YES	YES	YES
Year FE	-	YES	YES	YES	YES	YES
Province FE	-	YES	YES	YES	YES	YES
Observations	29	12,829	13,624	10,218	13,624	13,624
R^2	0.4993	0.3413	0.3571	0.2282	-	-
Weak identification test	-	-	-	-	-	2.9e+05
Overidentification test	-	-	-	-	-	0.000

Note: *, **, *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Z-statistics are given in parentheses.

households' CO_2 emissions in these municipalities may differ from those in other provinces due to factors such as more advanced infrastructure, higher average incomes, faster technology adoption rates, and distinct policy environments (Li et al., 2022; Wang et al., 2022; Yang et al., 2019). In order to avoid potential bias from the municipalities' unique characteristics, I drop the samples of municipalities, which excludes 795 household observations from the dataset. The results are shown in column (2) of Table 5. The results are consistent with the previous outcomes.

4.2.3. Winsorization

An extreme value can contribute to the invalidation of estimation. To minimize the effect and at the same time retain the authenticity of the data, I apply 1 % winsorization to all variables. The results are shown in column (3) of Table 5, and they are consistent with previous conclusions.

4.2.4. One-lagged form of lnDFII

The development of digital financial inclusion can affect households' CO_2 emissions, but in turn, households' CO_2 emissions can impact the level of digital financial inclusion. Household consumption may drive economic growth, which can promote the development of digital financial inclusion. To prevent reverse causality, I replace *lnDFII* with $lnDFII_{t-1}$ because households' CO_2 emissions in this period cannot affect the development of digital financial inclusion in the last period. The results are shown in column (4) of Table 5 and are align with previous conclusions.

4.2.5. Instrumental regression

The residual includes all unobserved idiosyncratic (i.e., individual-specific) factors that could have an impact on households' CO_2 emissions in addition to the *DFII*. It is difficult to ensure that the residual is not associated with the *DFII*. Potential endogeneity would lead to confounding of the causal relationship between the dependent variable and independent variable, thus leading to biased regression results. To address this, I use the average development of digital financial inclusion in provinces other than the one where the sample is located as an instrumental variable. The level of digital financial inclusion in one province is correlated with the average level of other provinces (Guo et al., 2016). At the same time, the households' CO_2 emissions of one province is not directly related to the average level of digital financial inclusion from other provinces. The results of instrumental regression are shown in columns (5) and (6) of Table 5. In the first stage of instrumental regression, $\overline{\ln DFII}$ is positively related to *lnDFII* at the 1 % level, meeting the requirement of correlation. As shown in column (6) of Table 5 the results are in line with the previous conclusion. The under-identification test and weak identification test also indicate that the selected instrument variables are influential.

4.3. Mechanism analysis

4.3.1. Mediation model

Based on the analyses above, I propose that digital financial inclusion can affect households' direct CO_2 emissions by altering their non-renewable energy consumption (H2a) and affect indirect CO_2 emissions by changing total consumption (H2b), and consumption structure (H2c). As such, I constructed following mediation models to test H2a, H2b and H2c:

$$\ln Y_{i,j,t} = \alpha_0 + \alpha_1 \ln DFII_{j,t} + \sum Controls_{i,j,t} + Province + Year + \varepsilon_{i,j,t} \tag{15}$$

$$\ln Mediator_{i,j,t} = \alpha_0 + \alpha_1 \ln DFII_{j,t} + \sum Controls_{i,j,t} + Province + Year + \varepsilon_{i,j,t} \tag{16}$$

$$\ln Y_{i,j,t} = \alpha_0 + \alpha_1 \ln DFII_{j,t} + \alpha_2 \ln Mediator_{i,j,t} + \sum Controls_{i,j,t} + Province + Year + \varepsilon_{i,j,t} \tag{17}$$

where *i, j,*and *t* denote the household, province, and time, respectively; $Y_{i,j,t}$ is dependent variables, including households' direct CO_2 emissions (*HDE*) and households' indirect CO_2 emissions (*HIE*); $DFII_{j,t}$ is the digital financial inclusion index; $Mediator_{i,j,t}$ is mediation variables, including non-renewable energy consumption (*Nonrenew*), household total consumption (*Total*) and household consumption structure (*Subsistence*, *Development* and *Enjoyment*); $\sum$ *Province* represents the province fixed effect; and $\sum$ *Year* is the time fixed effect.

4.3.2. Mechanism analysis

As existing literature suggest, compared with direct CO_2 emissions, indirect CO_2 emissions are much higher (Wang & Yang, 2014; Zhang et al., 2017). To ensure a comprehensive analysis, I examine the mechanism of how digital financial inclusion impacts direct and indirect CO_2 emissions, respectively. Tables 6, 7, and 8 show the results of the mediation models.

(1) Mechanism for households' direct CO_2 emissions (*HDE*)

Table 6 evaluates the mediating effect of non-renewable energy consumption on households' direct CO_2 emissions, testing H2a. In column (1), the coefficient of *lnDFII* on column (1) is 0.95 and is significant at 1 % level, indicating that the development of digital financial inclusion can increase households' direct CO_2 emissions. Column (2) of Table 6 shows that the coefficient of *lnDFII* is 0.8237 and is statistically significant, implying that digital financial inclusion encourages the consumption of non-renewable energy. The coefficients of column (3) are 0.1251 and 1.0274, respectively. Compared with the coefficient of *lnDFII* in column (1), that in column (3) is insignificant. This suggests that the effect of digital financial inclusion in promoting direct CO_2 emissions is entirely attributed to the increase in non-renewable energy consumption. The conclusion confirms H2a.

(2) Mechanism for households' indirect CO_2 emissions (*HID*)

Table 7 evaluates the mediating effect of total consumption on households' indirect CO_2 emissions, testing H2b. In Table 7 column (1), the coefficient of *lnDFII* on column (1) is significantly positive, indicating that the development of digital financial inclusion can increase households' indirect CO_2 emissions. Column (2) of Table 7 shows that the coefficient of *lnDFII* is 0.12, but it is statistically insignificant. The results mean that digital financial inclusion does not raise households' indirect CO_2 emissions by increasing their total consumption. The conclusion doesn't support H2b.

Table 8 evaluates the mediating effect of consumption structure on households' indirect CO_2 emissions, testing H2c. Column (2) of Table 8 shows that the coefficient of *lnDFII* is −0.26 and is significant at 1 % level, indicating that the development of digital financial inclusion can decrease subsistence consumption. The coefficients of *lnDFII* and *Subsistence* in column (3) are 0.29 and −1.39, respectively. Compared with the coefficient of *lnDFII* in column (1), that in column (3) is insignificant. The difference implies that the promotion effect of digital financial inclusion on indirect CO_2 emissions can be entirely attributed to the subsistence consumption upgrade.

As for column (4) of Table 8, the coefficient of *lnDFII* is significantly positive, implying that the development of digital financial inclusion can increase the ratio of development consumption. The coefficients of *lnDFII* and *Development* in column (5) are 0.39 and 1.34, respectively, which means that digital financial inclusion can increase households' indirect CO_2 emissions by increasing their ratio of development consumption.

Regarding column (6) of Table 8, the coefficient of *lnDFII* is positive but insignificant, which suggests that the development of digital financial inclusion has not promoted enjoyment consumption upgrade. The coefficients of *lnDFII* and *Enjoyment* in column (7) are 0.61 and −0.05, respectively, but the latter is insignificant. The results show that if digital financial inclusion can increase the ratio of enjoyment consumption, it may decrease indirect CO_2 emissions. The conclusion confirms H2c, particularly in relation to subsistence and development upgrade.

Table 6

Mediating effect of non-renewable energy consumption on households' direct CO_2 emissions.

Dependent Variables Independent Variables	(1) *lnHDE*	(2) *lnNonrenew*	(3) *lnHDE*
lnDFII	0.95*** (3.86)	0.82*** (3.86)	0.13 (1.14)
lnNonrenew	-	-	1.03*** (246.13)
Control variables	YES	YES	YES
Year FE	YES	YES	YES
Province FE	YES	YES	YES
Observations	13,624	13,624	13,624
R^2	0.2596	0.3277	0.8714

Note: *, **, *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. z-statistics are given in parentheses.

Table 7
Mediating effect of total consumption on households' indirect CO_2 emissions.

Dependent Variables Independent Variables	(1) *lnHIE*	(2) *lnTotal*	(3) *lnHIE*
lnDFII	0.53*** (2.65)	0.12 (0.63)	0.42*** (5.74)
lnTotal	-	-	1.02*** (348.92)
Control variables	YES	YES	YES
Year FE	YES	YES	YES
Province FE	YES	YES	YES
Observations	13,624	13,624	13,624
R^2	0.3467	0.3735	0.9364

Note: *, **, *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. z-statistics are given in parentheses.

Table 8
Mediating effect of consumption structure on households' indirect CO_2 emissions.

Dependent Variables Independent Variables		Subsistence Upgrade		Development Upgrade		Enjoyment Upgrade	
	(1) *lnHIE*	(2) *Subsistence*	(3) *lnHIE*	(4) *Development*	(5) *lnHIE*	(6) *Enjoyment*	(7) *lnHIE*
lnDFII	0.53*** (2.65)	−0.26*** (−4.70)	0.29 (1.46)	0.22*** (3.90)	0.39** (1.96)	0.03 (0.88)	0.61*** (2.86)
Subsistence	-	-	−1.39*** (−47.25)	-	-	-	-
Development	-	-	-	-	1.34*** (47.03)	-	-
Enjoyment	-	-	-	-	-	-	−0.05 (−1.20)
Control variables	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
Province FE	YES	YES	YES	YES	YES	YES	YES
Observations	13,624	13,624	13,624	13,624	13,624	13,624	13,624
R^2	0.3467	0.0812	0.4347	0.0969	0.4245	0.0435	0.3465

Note: *, **, *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. z-statistics are given in parentheses.

According to the analyses above, digital financial inclusion can increase households' direct and indirect CO_2 emissions. It encourages more consumption in non-renewable energy, and thus results in the increase in direct CO_2 emissions. Also, digital financial inclusion can promote subsistence and the development consumption upgrade but not the enjoyment consumption upgrade, and as a result, it can increase households' indirect CO_2 emissions. The results imply that most Chinese households still have difficulty making a living. Digital financial inclusion can increase households' income and decrease the prices of goods, which makes it possible for them to meet the requirement of survival (Wang & Yang, 2014). As a result, residents may afford goods and services that meet their needs above subsistence, such as the requirements of development and living a high-quality life. Products and services of these kinds are usually energy-intensive (e.g., houses, cars, and household appliances), so the development of digital financial inclusion can contribute to the increase in households' indirect CO_2 emissions. However, if digital financial inclusion continues to develop, households may be able to meet their enjoyment needs after their development needs have been met. In this regard, households' indirect CO_2 emissions may be reduced. The conclusion is widely applicable to other emerging countries, since they account for more than 50 % of the total energy consumed in 2018 (Murshed et al., 2023). Additionally, between 2016 and 2020, approximately 31.51 % of their population still lacked access to clean water and adequate food (Word Bank, 2021), emphasize the important of reducing energy use and upgrading consumption structure in similar contexts.

Overall, I can conclude that digital financial inclusion increases households' CO_2 emissions. It stimulates the consumption of non-renewable energy, thereby contributing to the rise in direct CO_2 emissions. Furthermore, digital financial inclusion promotes subsistence and development consumption upgrade, and thus leads to an increase in indirect CO_2 emissions. The conclusions confirm H2a and H2c, but do not support H2b (see Table 11 below).

4.4. Heterogeneity analysis

The heterogeneity analysis further extends the investigation by revealing how the impact of digital financial inclusion varies across its different dimensions, levels of its development and environmental policy contexts, providing a more nuanced understanding of the main findings.

Table 9
Heterogeneity analysis: Sub-dimensions of digital financial inclusion.

Dependent Variables Independent Variables	(1) *lnHCE*	(2) *lnHCE*	(3) *lnHCE*
Ln (Coverage)	0.19	-	-
	(1.57)		
Ln (Usage)	-	0.48***	-
		(3.77)	
Ln (Digital)	-	-	−0.07
			(−0.68)
Control variables	YES	YES	YES
Year FE	YES	YES	YES
Province FE	YES	YES	YES
Observations	13,624	13,624	13,624
R^2	0.3466	0.3470	0.3464

Note: *, **, *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. z-statistics are given in parentheses.

4.4.1. *Different dimensions of digital financial inclusion*

The digital financial inclusion index (*DFII*) consists of three sub-dimensions: breadth of coverage (*Coverage*), depth of usage (*Usage*) and level of digitalization (*Digital*). To analyze the heterogeneous impact of these dimensions on households' CO_2 emissions, they are regressed individually as independent variables, and the results are presented in Table 9. The coefficient of *Usage* is significantly positive, whereas those of *Coverage* and *Digital* are not statistically significant. The finding indicates that the environmental degradation associated with digital financial inclusion is primarily driven by the depth of usage. The potential explanations might be: (1) Depth of usage is an objective depiction of the actual use of digital financial inclusion services, which can affect consumption patterns and energy use (Li et al., 2020). In contrast, breadth of coverage and level of digitization, while representing accessibility, affordability and technical support of digital financial inclusion, do not necessarily translate into the actual usage of these services. Therefore, they have a weaker connection to changes in consumption behaviors that could impact household CO_2 emissions. (2) According to (Guo et al., 2016), breath of coverage and level of digitalization have already reached a certain level, and the depth of usage is now driving the development of digital financial inclusion. This suggests that further improvements in breath of coverage and level of digitalization may no longer lead to significant changes in household behavior.

Furthermore, I explore the heterogeneous impacts of different digital financial services (i.e. Payment, Money Funds, Credit, Insurance, Investment and Credit Investigation) on household CO_2 emissions. The coefficients are all significantly positive. While this consistency reinforces the environmental degradation influence of digital financial inclusions, it does not provide additional nuance beyond the primary findings.[5]

4.4.2. *The level of digital financial inclusion*

Fernandez et al. (2001) suggested that financial development has varying effects on the environment at different stages of growth. This study then uses threshold regression model (Hansen, 1999) to investigate the potential non-linear environmental effects of financial development.

$$\ln HCE_{i,j,t} = \alpha_0 + \alpha_1 \ln DFII_{j,t} {}^* I\left(\ln DFII_{j,t} \le q\right) + \alpha_2 \ln DFII_{j,t} {}^* I\left(\ln DFII_{j,t} > q\right) + \sum Controls_{i,j,t} + Province + Year + \varepsilon_{i,j,t} \tag{18}$$

where I () is the indicator function of 1 or 0.

The results show that there is a single threshold effect, significant at the 10 % level. Column (1) of Table 9 shows the results of the threshold regression. The results demonstrated a single statistically significant threshold value (5.77) for digital financial inclusion.[6] Below this threshold, the effect of digital financial inclusion is 0.42. However, as digital financial inclusion develops, the coefficient strengthens significantly to 0.44, indicating an amplified environmental impact. This result underscores the importance of acting. With the increase in levels of digital financial inclusion, there is a notable enhancement in environmental damage effects, highlighting the need for prompt measures to balance financial development with environmental conservation.

4.4.3. *Environmental regulation pilot cities*

The Chinese government has introduced the Carbon Trade Policy (CTP) in eight provinces/municipalities (Beijing, Shanghai, Tianjin, Chongqing, Hubei, Guangdong, Shenzhen, and Fujian). The policy aims to promote carbon trade and regulate trading prices. Well-designed environmental regulation programs have the potential to induce green innovation and affect household CO_2 emissions, thereby offsetting environmental degradation (Dou et al., 2022; Wen et al., 2020). To analyze the effects of the CTP, I divide the sample

[5] Since the results do not provide additional insights beyond the primary findings, the corresponding table is not displayed here. Please find Appendix Table A.3

[6] The number and values of the thresholds are determined using a bootstrap method. Through repeated sampling 300 times, p-values and confidence intervals are obtained to assess the statistical significance of the threshold effects. The analysis confirmed a single significant threshold, rejecting the possibility of two thresholds.

Table 10
Heterogeneity analysis: Different levels of digital financial inclusion and environmental policies.

Dependent Variable Independent Variables	(1) Non-linear Effect *lnHCE*	(2) CTP Provinces *lnHCE*	(3) Non-CTP Provinces ln*HCE*
*lnDFII** I (Th≤5.77)	0.42*** (8.73)	-	-
*lnDFII**I(Th > 5.77)	0.44*** (8.94)	-	-
lnDFII	-	−1.85** (−2.20)	0.82*** (3.23)
Control variables	YES	YES	YES
Year FE	YES	YES	YES
Province FE	YES	YES	YES
Observations	13,624	1874	11,750
R^2	0.0606	0.3918	0.3441

Note: *, **, *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. z-statistics are given in parentheses.

into provinces with implemented CTP policies and those without. The results, shown in column (2) and (3) of Table 10, reveal significant differences. The coefficient of *lnDFII* is significantly negative among provinces implemented CTP policies, while among non-CTP provinces, the coefficient is significantly positive. The finding has important policy implications. Well-designed environmental regulation programs, such as the CTP, can effectively influence household behavior towards greener practices. Therefore, policymakers should consider expanding and refining similar environmental regulation initiatives nationwide. By doing so, governments can encourage green innovation and strike a balance between financial development and environment protection.

5. Conclusions and policy implications

Emerging countries, accounting for more than one-third of the global gross value added, are currently experiencing economic stagnation. Unlike developed countries with well-established financial systems, less developed countries are facing higher levels of financial inequality. In this context, digital financial inclusion can enhance access to essential financial services and drive economic development in these countries. Nonetheless, concerns persist about the potential environmental consequences of increased consumption because of financial development. Despite this dichotomy, empirical research investigating the relationship between renewed financial development and households' CO_2 emissions remains scarce. Specifically, micro-level empirical research and studies bridging CO_2 emissions to digital financial inclusion within household context are limited.

This study investigates the connection between digital financial inclusion and households' CO_2 emissions. The empirical evidence from China is particularly important since China is a major carbon emitter and a rapidly growing economy. Based on a survey panel dataset of 13,624 Chinese households, I explore the relationship between digital financial inclusion and households' CO_2 emissions. Additionally, by employing a mediation model, I gain deeper insights into how digital financial inclusion influences direct and indirect CO_2 emissions of households, respectively. Table 11 summarizes all the hypotheses along with their corresponding test results and conclusions drawn from the empirical analysis. As shown in Table 11, the findings reveal that digital financial inclusion can lead to an increase in households' CO_2 emissions, and the finding is robust to the alternative model specifications and methods. Specifically, digital financial inclusion encourages non-renewable energy consumption, thereby increasing households' direct CO_2 emissions. Simultaneously, it promotes subsistence and development consumption upgrades, contributing to elevated household indirect CO_2 emissions. Beyond the results summarized in Table 11, the study further reveals that the environmental deterioration effect of digital financial inclusion is mainly driven by the actual uses of the services. Also, as digital financial inclusion develops, its detrimental impact on the environment intensifies. The environmental policy can mitigate the adverse environmental effects. Overall, the findings have several implications for addressing environmental problems in developing countries.

5.1. Practical implications

Based on the analyses, five main policy implications are drawn.

First, governments should establish an environmental benefit monitoring system for digital financial inclusion. By tracking the environmental performance of digital financial services, governments can develop a long-term mechanism to guide the sustainable development of digital financial inclusion, ensuring that financial inclusion inherently contributes to environmental goals. Addressing this issue is urgent, as the detrimental effects on the environment are expected to intensify with the continued development of digital financial inclusion.

Second, emphasize the active role of digital financial inclusion in promoting green financial services, which can encourage residents' green consumption. By integrating green finance, digital financial inclusion can provide green financial services that broaden consumer access to low-carbon lifestyle options. For example, digital financial platforms can rely on digital technology to track residents' consumption habits, offer preferential rates for green loans, and issue green digital coupons. Additionally, digital financial platforms could also incorporate sustainability metrics into their services, helping users understand the environmental impact of their transactions and promoting more environmentally conscious consumption.

Third, governments from developing countries should increase environmental awareness in residents and encourage consumption

Table 11
Hypothesis Testing and Conclusions.

Hypothesis	Test Result	Conclusions
H1a: The development of digital financial inclusion can reduce CO_2 emissions of households.	**Rejected** (Table 4 and Table 5)	Digital financial inclusion can increase household's CO_2 emissions.
H1b: The development of digital financial inclusion can increase CO_2 emissions of households.	**Non-rejected** (Table 4 and Table 5)	
H2a: Digital financial inclusion can affect households' direct CO_2 emissions by changing households' non-renewable energy consumption.	**Non-rejected** (Table 6)	Digital financial inclusion encourages non-renewable energy consumption, thereby increasing households' direct CO_2 emissions
H2b: Digital financial inclusion can affect households' indirect CO_2 emissions by changing households' total consumption.	**Rejected** (Table 7)	Digital financial inclusion doesn't change households' total consumption.
H2c: Digital financial inclusion can affect households' indirect CO_2 emissions by improving households' consumption structure.	**Subsistence upgrade: Non-rejected** (Table 8 column 1–3) **Development upgrade: Non-rejected** (Table 8 column 4–6) **Enjoyment upgrade: Rejected** (Table 8 column 7–9)	Digital financial inclusion promotes subsistence and development consumption upgrades, contributing to elevated household indirect CO_2 emissions.

upgrades. Given that these countries consume over half of global energy resources while a third of their population struggles with basic needs, promoting sustainable behavior is crucial. Governments can educate residents about the harmful effects of consuming non-renewable energy and energy-intensive products, as well as the irreversibility of global warming. Moreover, governments should improve the social welfare system and increase household income to upgrade the household consumption structure. In this regard, the environmentally friendly effect of digital financial inclusion can work.

Fourth, strengthen the ability of digital financial inclusion to allocate financial resources to achieve green transformation. Digital financial inclusion should be guided to play a more significant role in promoting green low-carbon innovations. Governments can encourage enterprises, especially those in energy-intensive industries, to replace their old-fashioned equipment with high-tech equipment through subsidies. Additionally, governments should also guide the flow of financial resources to enterprises with high added value, low pollution, and high efficiency, to mitigate financial constraints for environment-friendly and energy-saving enterprises. In this respect, the development of digital financial inclusion can benefit the environment by improving production efficiency and reducing energy intensity while producing products.

Lastly, given the global nature of environmental challenges, international cooperation and collaboration are essential. Governments of emerging countries should engage in international forums and partnerships to exchange best practices, mobilize resources, and address common environmental concerns related to economic development and digital financial inclusion.

5.2. Limitations and future research

This study has a few limitations, which provide important avenues for future research.

First, owing to the confidentiality agreement of CFPS, the index of digital financial inclusion have been used is provincial. Theoretically, it will be more academically precise and reliable if I can gain access to data from the household level.

Second, the data sample only covers China. Although the research is based on a representative emerging country and has significant policy implications, the impact of digital financial inclusion on households' CO_2 emissions may vary across countries. Further analysis is required to improve the generalizability of the results, including residents from emerging countries.

At last, I have only studied households' CO_2 emissions. Future studies can use different environmental variables, such as SO_2 emissions, so that can gain a comprehensive understanding of the effect of digital financial inclusion on all harmful gases.

CRediT authorship contribution statement

Yao Li: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The author declares that she has no competing interests.

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Appendix A

Table A.1
Digital Financial Inclusion Index System

Digital Financial Inclusion Index	Level 1 Dimension	Level 2 Dimension	Indicator
	Breadth of Coverage	Account coverage rate	Number of Alipay accounts owned by per 10,000 people
			Proportion of Alipay users who have bank cards bound to their Alipay accounts
			Average number of bank card bound to each Alipay account
	Depth of Usage	Payment	Number of payments per capita
			Amount of payments per capita
			Proportion of number of high frequency active users (50 times or more each year) to number of users with frequency of once or more each year
		Money Funds	Number of Yu'ebao purchases per capita
			Amount of Yu'ebao purchases per capita
			Number of people who have purchased Yu'ebao per 10,000 Alipay users
		Credit	Number of users with an Internet loan for consumption per 10,000 adult Alipay users
			Number of loans per capita
			Total Amount of loan per capita
			Number of users with an Internet loan for small & micro businesses per 10,000 adult Alipay users
			Number of loans per small & micro business
			Average amount of loan among small & micro businesses
		Insurance	Number of insured users per 10,000 Alipay users
			Number of insurance policies per capita
			Average insurance amount per capita
		Investment	Number of people engaged in Internet investment and money management Per 10,000 Alipay users
			Number of investments per capita
			Average investment amount per capita
		Credit Investigation	Number of credit investigation by natural persons per capita
			Number of users with access to credit-based livelihood services (including finance, accommodation, mobility, social contact, etc.) per 10,000 Alipay users
	Level of Digitalization	Mobility	Proportion of number of mobile payments
			Proportion of total amount of mobile payments
		Affordability	Average loan interest rate for small & micro businesses
			Average loan interest rate for individuals
		Credit	Proportion of number of Ant Check Later payments
			Proportion of total amount Ant Check Later payment
			Proportion of number of "Zhima Credit as deposit" cases (to number of full-deposit cases)
			Proportion of total amount of "Zhima Credit as deposit" (to amount of full-deposit)
		Convenience	Proportion of number of QR code payments by users
			Proportion of as above, please clarify with "Average amount" or "total amount" of QR code payment by users

(Source: Guo et al., 2016)

Table A.2
List of selected emerging countries

Argentina	Cote d'ivoire	Indonesia	Philippines	Vietnam
Bangladesh	Dominican Republic	Kenya	Romania	
Bolivia	El Salvador	Malaysia	South Africa	
Brazil	Ghana	Mexico	Sri Lanka	
Cambodia	Guatemala	Myanmar	Thailand	
Cameroon	Honduras	Pakistan	Tunisia	
China	India	Peru	Turkey	

Table A.3
Heterogeneity analysis: Usage of different digital financial inclusion services

Dependent Variables Independent Variables	(1) *lnHCE*	(2) *lnHCE*	(3) *lnHCE*	(4) *lnHCE*	(5) *lnHCE*	(6) *lnHCE*
Ln (Payment)	0.30*** (4.56)	-	-	-	-	-
Ln (Money Funds)	-	0.39* (1.78)	-	-	-	-
Ln (Credit)	-	-	0.14** (2.49)	-	-	-
Ln (Insurance)	-	-	-	0.14* (1.86)	-	-
Ln (Investment)	-	-	-	-	0.11*** (2.60)	-
Ln (Credit Investigation)	-	-	-	-	-	1.17** (2.48)
Control variables	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Province FE	YES	YES	YES	YES	YES	YES
Observations	13,624	10,218	13,624	13,624	10,218	6812
R^2	0.3472	0.3601	0.3467	0.3465	0.3603	0.3855

Note: *, **, *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. z-statistics are given in parentheses.

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