Mathematics

Research article

The impact of information and communication technology on financial inclusion—based on a global perspective

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Abstract: In order to test the effect of information and communication technology (ICT) level on financial inclusion, based on the sample data of countries around the world in 2011, 2014, and 2017, this paper firstly uses the coefficient of variation method and the Euclidean distance method to construct the ICT level index and the financial inclusion index, and then conducts empirical analysis through a linear regression model. Further, a mediating effect model is employed to explore the impact mechanism of the ICT level on financial inclusion. Finally, the impact heterogeneity is explored based on the internal and external characteristics of each country. The empirical results show that: first, the ICT level can effectively improve financial inclusion, but its effects on the width and the depth of financial inclusion are different; second, the ICT level improves a country's financial inclusion by promoting the improvement and development of the digital payment system; third, the impact of the ICT level on financial inclusion shows significant heterogeneity among different countries or regions with differences in banking structure, economic development level and international financial environment. Last but not least, the conclusions of this paper can help countries or regions to improve financial inclusion in a targeted manner through information and communication technology.

1. Introduction

Financial inclusion increases the availability of financial services and enables more groups to access financial services such as payments, loans, savings, and insurance provided by formal financial institutions. After the subprime mortgage crisis, financial inclusion has received increasing attention. The reason is that since the global financial crisis in 2008, financial exclusion has become more common among countries due to regional differences, economic levels, and policy factors [1]. Financial exclusion will have a certain negative impact on individuals, countries, and the world, such as persistent income inequality and slow economic growth [2], reducing the efficiency of financial resource allocation accumulating financial risks, and even becoming the shackles of economic growth and social development. As the opposite of financial exclusion, financial inclusion helps groups who were originally "excluded" from traditional financial services to obtain financial services provided by formal institutions effectively. This improves the availability of financial services for groups, such as residents and enterprises, alleviates financial exclusion, and thus reduces its negative effects.

Therefore, in recent years, many countries and regions have joined hands with the World Bank to carry out financial inclusion projects and set goals to improve financial inclusion to realize its positive effects. For example: in Argentina, the government actively promotes the development of formal financial credit, builds a favorable financial development environment, and optimizes the efficiency of Value-added Tax (VAT) collection in the financial system [3]. In the EU economies, financial inclusion helps individuals establish good savings and loan relationships with enterprises and the financial system, indirectly affecting economic development [4]. In the Middle East and North Africa, financial inclusion reduces poverty, income inequality, and unemployment, contributing to financial stability and development [5]. Evans [6] pointed out that financial inclusion can ensure the participation of different sectors of society in formal finance, thereby expanding the currency policy coverage, which in turn increases the effectiveness of monetary policy. Based on Asian-country samples, Malik et al. concluded that financial inclusion has a positive impact on financial stability [7], and it can mediate the relationship between governance quality and financial stability. It can be seen that financial inclusion not only helps to alleviate the negative effects of financial exclusion since the global financial crisis but also plays an essential role in maintaining financial market stability, promoting economic growth, and improving residents' living standards.

Since financial inclusion contributes so much to social development,it is particularly important to find a way to improve financial inclusion. Some scholars find that information technology plays an important role in this aspect. This is because the development of general information technology (ICT) has made the internet and mobile phones popular, making financial services break through the time and space constraints, and greatly reducing the cost of financial services.At the same time, it also reduces transaction costs and default risks caused by information asymmetry, which promotes the optimization of traditional financial services and products, thus improving financial inclusion [8]. From the perspective of banks, information technology improves the efficiency and stability of banking operations. It expands market capacity by improving financial innovation, thereby improving the efficiency of commercial banks in issuing loans and absorbing savings [9]. For example, Ouma et al. [10] studied sub-Saharan African countries and noted a positive relationship between the availability and use of mobile phones and the financial inclusion of households and businesses, with mobile phone use making households and businesses more motivated to receive or send remittances and accumulate savings. In terms of enterprise loans, the adoption of ICT has also reduced the information asymmetry

between small and medium-sized enterprises (SMEs) and banks. As a result, banks can better judge the likelihood of companies making repayments on time and provide credit funds for the projects and working capital needs of innovative SMEs [11]. As for other financial markets, Lechman and Marszk studied the Exchange Traded Fund (ETF) markets in Japan, Mexico, the United States, and South Korea and proved a significant positive correlation between increased ICT penetration and ETF market development [12].Garven also pointed out that the development of the Internet has dramatically facilitated the purchase of commercial insurance [13], reducing the cost of participating in the insurance market, lowering the market entry threshold, and indirectly improving the availability of commercial insurance.

To sum up, the improvement of the ICT level can help a country expand its financial inclusion and gradually restrain the adverse effects of financial exclusion. This process has transformed from financial exclusion to inclusion and then to deep integration. However, little literature analyzes explicitly the impact of the ICT level on financial inclusion, and many deficiencies exist in relevant literature; for example, the research scope is mainly limited to some countries and regions, and the comprehensive quantification of the ICT level is generally lacking. Therefore, in order to better explore the many subtle relationships between the ICT level and financial inclusion and supplement the gaps in the previous literature, this paper proposes and intends to solve the following three questions: (1) Does the ICT level have a significant impact on the degree of financial inclusion of countries? (2) What is the impact mechanism? (3) Is there heterogeneity among different countries? In order to solve the above problems, this paper first builds the indexes based on the Global Findex Database, Global Financial Development, and World Development Index (WDI) data; then, the OLS method is employed. After that, we test the impact mechanism and finally explore the heterogeneity. Based on a global perspective, this paper uses 281 samples in 2011, 2014, and 2017 for empirical analysis (The Financial inclusion index (IFI) constructed in this paper is based on data from the Global Findex and Global Financial Development. The global Findex database has so far only released data for 2011, 2014 and 2017.). A fixed-effect model is constructed to verify the impact of the ICT level on financial inclusion. Further, the impact path and the heterogeneity are explored.

The marginal contributions of this paper are reflected in the following aspects: First, this paper explores the impact of the ICT level on financial inclusion from a global perspective. Most of the existing literature studies the relationship between the two from the perspective of individual countries or regions. This means that strict comparisons of financial inclusion between countries are lacking. Therefore, this paper expands the sample to most countries worldwide and analyzes the relationship. Second, it analyzes the mediating effect of the ICT level on the degree of financial inclusion through digital payment. Third, from the perspectives of income level, bank concentration, and financial environment differences in various countries, this paper profoundly analyzes the heterogeneous impact of the ICT level on the degree of financial inclusion. The structure of the rest of this paper is arranged as follows: Section 2 elaborates the research scheme and hypotheses; Section 3 describes the research design and variable selection; Section 4 conducts the empirical analysis, the mediating effect, and the robustness tests; Section 5 performs the robustness test on the index construction; the last Section draws the research conclusions and puts forward some policy implications.

2.   Research scheme and hypotheses

2.1. The impact of ICT on financial inclusion

Due to the mutual penetration and deep integration of ICT and the traditional financial industry, the operational efficiency of financial markets and the accessibility of financial services are improved, promoting the development of financial inclusion through the following specific channels: (1) Improving the coverage of financial services. Traditional financial institutions need to increase the coverage by adding institutional outlets, but the high cost makes it difficult for traditional financial services to penetrate economically backward areas. Furthermore, due to the lack of physical collateral, SMEs and farmers generally have difficulty accessing financial services and products [14].The cross-border integration of information and communication technology and financial services has overcome this obstacle. In some areas without institutional outlets, customers can still obtain the financial services they need through information and communication equipment such as computers and mobile phones, thus increasing the coverage of the country's overall financial services and enhancing financial inclusion [15]. (2) Increasing risk-control abilities and reducing the loan threshold. with the support of information and communication technology, on the one hand, financial institutions can optimize the current risk management mode through big data analysis and blockchain technology, so as to more accurately control the risk status of customers, and accordingly a lower loan interest rate that is more in line with the customer's risk profile is given; on the other hand, the ICT provides customers with credit guarantee in the form of "digital guarantee", which enables the "long tail group" abandoned by traditional finance for a long time to be included in financial services, greatly alleviating the financing constraints of financial institutions on small and medium-sized enterprises [16]. (3) Data processing of information to reduce transaction costs. Relying on the development of information technology, financial institutions can efficiently complete the collection and analysis of customer information and better predict customer preferences and needs so that they can design and provide customers with more specialized financial products [17]. In this way, financial institutions can also attract many corporate and individual users, thus greatly reducing the cost of customer acquisition. In addition, Internet applications (such as blockchain and cloud computing) based on information and communication technology can process massive data with low cost and low risk, thereby reducing the cost of risk prevention and control for financial institutions. In addition, using information technology to develop a management system with data collection and performance evaluation functions can help enterprises improve their management capabilities, thus improving the feasibility of inclusive finance development [18]. (4) Promoting the development of financial technology (Fintech). General information technology is the cornerstone of fintech development and digital finance. In recent years, information and communication technology has promoted the application of artificial intelligence, big data, blockchain, and other emerging technologies in the finance-related fields, and Fintech has emerged and developed rapidly [19]. The rise of Fintech assists traditional financial institutions in mining information, reduces the information asymmetry between financial institutions and SMEs, and eases the financing constraints of SMEs [20,21], not only improving the operational efficiency of financial institutions but also expanding the scope of their financial services. Therefore, based on the above theoretical analysis, this paper presents the primary hypothesis H1.

H1: ICT has a significant positive impact on financial inclusion.

2.2. The mediating effect of ICT on financial inclusion

In recent year, ICT has promoted the development and popularization of digital payment. On the one hand, with the improvement of science and technology and the innovation of production technology, the production efficiency and scale of information and communication equipment have been rapidly improved. The increasing sales of mobile phones, computers, broadband facilities and other electronic equipments also witness the growing needs of the people. On the other hand, the development level of information technology has also been gradually improved, and its improvement also provided technical support for the transformation and upgrading of traditional financial services. Then, an online financial service, digital payment, is derived.The popularity and use of the Internet and mobile phones in the world have promoted the development of digital payment services (such as digital banking and digital financial payment) [22,23]. Digital payment is a financial service that gathers online remittance, transfer, savings, and other payment transfers. It is usually developed and designed by traditional financial institutions in collaboration with other non-financial institutions, such as various online applications developed by banks [24]. Digital payment is the product of the development of information and communication technology and traditional financial services to a certain stage. Only when both are relatively developed can a country's digital payment system emerge and be accepted by the public. Theoretically, on the one hand, the network is the premise and foundation of digital payment. Information and communication technology realizes the full coverage of urban and rural networks by building first-class 5G network services, which provides a good prerequisite for implementing digital payment. On the other hand, complex information and communication technologies such as blockchain and cloud computing provide high-speed, secure, and mobile "connection services" for payment systems, thereby enabling the construction of the value chain of "customer-merchant-third party payment system-financial institution".

Similarly, the development of digital payment has extensively promoted the development of financial inclusion in various countries. Generally speaking, digital payment promotes financial inclusion mainly through financial, wealth, cost efficiency channels and consumption channels. Through the financial channel, digital payment breaks through the limitation of time and space on the supply and demand of financial services, realizing the externality of network and economy. It also reduces transaction costs and the threshold of financial services, thus optimizing the operating efficiency of financial markets. In addition, digital payment improves the accuracy and profitability of financial services through the acquisition of structured data. For example, digital banks acquire accurate risk portraits of customers through information and communication technologies, thus developing digital products and services to meet the needs of digital customers and attract more customer groups [24]. Through the wealth channel, digital payment promotes public awareness of financial management. Based on its solid data foundation, digital payment platforms have designed many small, high-quality financial products so that more long-tail users can enjoy financial management services. For example, Prete points out that digital payment tools and financial literacy influence the choice of financial products [25]. Through the cost-efficiency channel, digital payment platforms help financial institutions reduce operating costs and improve service efficiency [26,27], while providing individuals and enterprises with faster, more convenient, lower-cost financial services. For instance, customers can easily complete operations like bill access, fund transfer, balance inquiry, and check payment through online banking [28]. It can be seen from the above that the development of digital payment can significantly improve a country's degree of financial inclusion, whether through

the channels of finance, wealth, entrepreneurship, or cost efficiency. In terms of consumption channels, digital payment agents, online shopping platforms and financial institutions cooperate with each other to better meet the needs of online shopping consumption. This fosters people's new consumption habits and further promotes the spread of online financial services, thus affecting the development of financial inclusion. Combined with the above analysis on the impact of ICT on digital payment, this paper puts forward the following hypothesis:

H2: ICT promotes the improvement of financial inclusion by driving the development of digital payment.

2.3. Heterogeneity analysis of the impact of ICT on financial inclusion

2.3.1.   Differences in the impact of banking structure on financial inclusion

When the degree of banking monopoly is high, there are a few large banks and most small and medium-sized banks in the market. Financial services are concentrated in a few large banks, the concentration of the banking industry is high, the intensity of market competition is low, and small and medium-sized banks have to survive in the cracks. Conversely, when the degree of banking monopoly is low, the size of banks in the market is comparable, and financial services are evenly distributed among the banks. The concentration of the banking industry is low, and the market competition is high. In order to maintain the current market share, banks must strive for innovation and breakthroughs.

Whether a country's banking structure has a significant difference in the effect of ICT on the degree of financial inclusion should be considered from capital scale, business structure, and risk prevention. First of all, in terms of the capital scale, with the strong capital, large banks can inject a steady stream of funds into the process of financial innovation, so that ICT can be better applied to financial services. ICT can reduce information asymmetry and agency costs, which can help banks and SMEs establish stable relationships and benefit both parties [29]. If banks and SMEs break through the original technical barriers and incorporate the "long-tail groups" previously abandoned by traditional financial services into financial services, the country's financial inclusion will be significantly improved. In contrast, small and medium-sized banks have limited capital, so their ability to apply ICT to financial services to improve financial inclusion is limited. To sum up, in terms of the capital scale, countries with high banking concentration are more conducive to developing financial inclusion [30].

Secondly, in terms of the business structure, large banks have a strong ability to provide credit and financial services to large enterprises for reasons such as asset size and information collection and transmission, while small banks have more advantages in financing small and medium-sized enterprises [31]. According to the market hypothesis, Han pointed out that in a market with a high concentration of banks, SMEs can obtain fewer credit opportunities from banks, lower credit lines, and higher default costs [32]. On the contrary, small and medium-sized banks also have more geographical and information advantages than large banks in relational loans to SMEs. Therefore, small and medium-sized banks have an important advantage in the establishment of an inclusive financial system, because their main target audience is precisely matched to the most financially excluded groups. From the business structure perspective, countries with low bank concentration should have a higher degree of financial inclusion.

Finally, in terms of risk prevention, the higher the concentration of banks, the more stable the

market and the stronger the risk prevention ability. The higher the concentration of banks, the large and medium-sized banks will pool more capital and have higher profits to obtain a higher capital buffer to withstand cyclical risks such as financial crises [2,33]. In addition, as mentioned above, big banks have more capital to apply ICTs to financial services. Thus, by promoting the use of ICTs, big banks are in a better position to obtain credit and supervise loans from lenders. It could also help banks provide financial services to individuals and businesses that are otherwise ill-informed. Therefore, in terms of risk prevention, countries with a high concentration of banks should have a higher degree of financial inclusion.

In conclusion, countries with different banking structures may have higher or lower levels of financial inclusion in different dimensions. Therefore, this paper proposes the following hypothesis:

H3a: Differences in banking structure will affect the effect of ICT on financial inclusion, but the specific direction is uncertain.

2.3.2. Differences in the impact of economic development on financial inclusion

Studies have shown a causal relationship between economic income and ICT. The first hypothesis holds that ICT is beneficial to economic income growth. On the one hand, investment in ICT as a sector will increase a country's labor opportunities and enterprise productivity, thus making a positive contribution to its economic growth and directly causing a significant increase in the level of economic development [34,35]. On the other hand, as a kind of social capital, ICT also has an indirect effect on economic growth [36]. Specifically, ICT can facilitate people to obtain information and make information sharing more convenient, which can effectively reduce the transaction cost in the market, forming spillover effects and positive externalities. The most significant is to increase arbitrage opportunities and reduce search costs for market traders. Therefore, ICT will ultimately increase the overall productivity, thereby significantly improving the level of economic development of a country. Another hypothesis is that economic growth drives the development of ICT infrastructure; that is, increased economic income will enable countries to have more funds and resources to improve existing ICT infrastructure. Meanwhile, high-income countries are more dependent on the digital economy to boost their economic competitiveness, thus strengthening more advanced information and communication technologies [37]. In addition, the development of ICT will also promote the adoption of digital payments and enable people to develop their digital payment habits earlier, which, according to previous assumptions, will also affect financial inclusion to some extent.

Moreover, much research also believes that increasing economic income is conducive to increasing financial inclusion [36]. On the one hand, the increase in economic income provides strong capital support for ICT investment, thereby increasing the access to the financial services required by information and communication equipment such as computers and mobile phones and ultimately enhancing the coverage of the country's overall financial services and financial inclusion. On the other hand, the level of economic development directly affects the development of the financial market. Capital is the core of the financial market operation, as well as the cornerstone and focus of the financial system of a modern, internationalized country. In countries with a high level of economic development, financial institutions often have high levels of operation and management and advanced financial service technology, which are conducive to promoting financial inclusion. Meanwhile, for developed markets with better economic development and emerging markets with weaker economic development, the impact of economic policies and financial cycle effects on the operating environment

of financial markets is also heterogeneous [38–41], which affects the development of financial inclusion to a certain extent. For example, Zawadzki studied and compared the performance of ETFs in developed markets and emerging markets and found that there were significant differences in the pricing of EFT [38]. To sum up, there is a positive causal relationship between a country's economic development level and its ICT level, and the improvement of economic development level itself contributes to the improvement of financial inclusion. Therefore, this paper puts forward the following hypothesis:

H3b: Countries with high levels of economic development have a higher degree of financial inclusion than countries with low levels of economic development

2.3.3. Differences in the impact of economic development on financial inclusion

In addition to the internal financial factors, the economic exchanges and financial operating environment among countries also have a heterogeneous influence on the degree of financial inclusion. In this paper, two regions with different financial operating environments such as OIC Allies (hereinafter referred to as OIC) and Latin American countries (LA) are selected to conduct empirical tests. The reason for choosing the former OIC is that muslims account for one quarter of the World's population, but a large part of them cannot access basic financial services [42]. At the same time, the Islamic financial system in OIC countries has its own unique operating rules and modes. The latter is chosen because LA includes many developing countries, most of which have serious financial exclusion and strict capital control. Specific analysis is as follows:

Islamic countries (OIC) specifically practice a special system called Islamic finance. Islamic finance is a unique form of finance that not only conforms to the provisions of relevant Sharia but also have the dual characteristics of finance and religion. Therefore, it is quite different from the traditional financial system in terms of the operating system, governance structure, and risk beliefs. In terms of the operating system, the overall operation of Islamic banks follows Islamic doctrine, prohibiting interest and regarding it as shameful and immoral to charge fixed interest before the benefit of the investment project is determined [43,44]. Although Islamic banks cannot compare with traditional banks in terms of income and profitability, their higher intermediary ratios, asset quality, and capitalization have reduced the damage caused by the 2008 global financial crisis [45]. The Islamic financial system also has a good performance in resisting other risks. Abedifar et al. [46] pointed out that in areas with a large Muslim population, small-scale, highly leveraged Islamic banks have lower credit default risks. Hosen et al. [47] studied the sample of Bangladesh banks and found that the non-performing loan ratio of Islamic banks was lower than that of traditional banks. Risk beliefs are primarily driven by religious beliefs, with devout Islamic believers or religious online borrowers having lower default rates. In terms of the governance structure, besides the board of directors, Islamic banks also have a Shariah Supervisory Committee. Therefore, in addition to being accountable to shareholders, management is also accountable to the Shariah Council for the legality of its operations.

In recent years, Islamic finance has developed a large market scale and mature operation mode, not only providing financial services for many Muslim groups but also breeding financial products, such as Islamic bonds, funds, and insurance, in line with Islamic doctrines. Credit trading instruments, such as the Mudarabah contract and the Musharakah contract, which share profits and losses, have contributed to solving financial inclusion problems and financing access [44]. In addition, since ICT can positively impact financial markets and financial institutions, if combined with Islamic financial

products to design new low-cost digital financial products, it will help expand the development space of Islamic banks and financial inclusion in Islamic countries [48]. To sum up, this paper proposes the following hypothesis, H3c:

H3c: The impact of ICT on financial inclusion differs significantly between Islamic and non-Islamic countries, but the specific direction is uncertain.

The financial systems of countries in Latin America and the Caribbean have a relatively high degree of opening to the outside world. But this liberalized financial system increases foreign exchange risks and the instability of international capital inflows, forcing most Latin American countries (LA) to maintain some capital control [49]. Besides, the region is dominated by developing countries with underdeveloped economies [50], resulting in its financial development level being at a medium-low position compared to the world average [50]. In the World Bank's 2019 Financial Development and Structure Data report, the proportion of private sector credit to GDP in countries such as Argentina, Mexico, and Brazil is well below the global average for middle- and high-income countries [51]. In addition to the problem of lagging financial development, social inequality in LA is also more prominent, especially in terms of spatial inequality Constrained by the geographical environment, social resources are gathered in some domestic cities. This leads to inadequate financial institutions and communication infrastructure in small cities and rural areas in LA, further exacerbating financial exclusion in these countries.

In order to alleviate the widespread financial exclusion in LA and achieve the goal of expanding financial inclusion, LA have also been improving their information and communication conditions in recent years to promote progress in financial technology and other aspects. At the same time, LA have successively introduced corresponding financial inclusion policies and strengthened financial supervision and investment by financial intermediaries. Although these measures have contributed to the development of fintech to a certain extent, their development is still at the periphery of the global fintech industry and financial system, and their role in promoting financial inclusion is very limited [50]. Considering the slow start of financial technology in Latin American countries [52] and its complex financial operating environment, we speculate that the improvement of the ICT level has a limited effect on the expansion of financial inclusion in LA. In summary, this paper proposes the following hypothesis H3d:

H3d: The impact of ICT on financial inclusion in Latin American countries is limited.

3. Research design and variable selection

3.1. Index construction

In this sub-section, this paper quantifies the core explanatory variable information communication technology (ICT) and the explained variable international financial inclusion (IFI).

First, we construct the index of financial inclusion (IFI). Although there is no unified standard method to measure the financial inclusiveness of a country, most scholars combine multiple dimensions when constructing the IFI. In previous studies, such as Sarma and Pais [53], Gupte et al. [54], financial inclusion is basically divided into three dimensions: access, use, and quality. However, considering that they are only available after the year after 2014 and there are so many missing datas in the sample countries, this paper to construct IFI index from availability and utilization dimensions, just like what is done in Amidžić et al. [55].The usage dimension refers to residents' use of financial products and

services, which is mainly reflected in the loans and savings obtained by residents and enterprises through financial institutions. In this paper, the IFI width is used to measure the outreach dimension, and the IFI depth is used to measure the usage dimension. Finally, the IFI width and the IFI depth are fitted into the comprehensive financial inclusion index (IFI).

In selecting data of the two dimensions, this paper adopts various financial service access data from databases like the Global Findex Database , International Monetary Fund (IMF) and the Global Financial Development. According to Sarma and Pais [53], Amidžić et al. [55], and Sharma and Changkakati [56], we measure the "use" from two aspects of saving and borrowing (i.e., financial inclusion depth). The detail indicators include the IFI width: credit card users, accounts of financial institutions, the number of ATMs, Debit card user, branches of commercial banks; the IFI depth: proportion of deposits in the financial system to GDP, number of depositors with financial institutions, Depositors with commercial banks (per 1,000 adults), the proportion of private credit provided by financial institutions to GDP, number of borrowers with financial institutions and Borrowers from commercial banks (per 1,000 adults).

In terms of the index calculation method, referring to the expansion of Chakravarty and Pal [57], we adopt the Euclidean distance method and coefficient of variation method to make the weight of each dimension explicit. The basic idea of determining the weight by the coefficient of variation method is to assign weights to the indicators according to the degree of variation (difference) of all sample values in an indicator. If the coefficient of variation of an indicator is large, it means that this indicator has great explanatory power in measuring the index difference, so this indicator should be given a large weight. The main idea of the Euclidean distance method is to judge the distance between each value and the optimal value. The shorter the distance, the better the value and the larger the comprehensive index value. The IFI construction process is as follows:

First of all, due to the large differences in the dimension of each indicator, the variation of the variable and the order of magnitude, it is necessary to perform dimensionless processing on the original data. This paper selects the extreme difference processing method, and the index is standardized within a reasonable range through the exponential logarithm method. $x_{i,j}$ is the indicator value after the extreme difference processing; $y_{i,j}$ is the ith original data of indicator j.

$$x_{i,j} = Ln(y_{i,j} + 1) \tag{3.1}$$

Then, the weight coefficient of each indicator is obtained by means of the coefficient of variation method. CV_{ij} is the coefficient of variation of the indicator j (where σ_j is the standard deviation, and n_j is the average of the indicator):

$$CV_j = \frac{\sigma_j}{n_j} \tag{3.2}$$

After that, the weight ω_{ij} of indicator j is obtained according to the coefficient of variation. Specifically:

$$\omega_j = \frac{CV_j}{\sum CV_j} \tag{3.3}$$

Further, according to the Euclidean distance method and the dimensionless indicators and weights calculated by Eqs (3.1) and (3.3), the single-dimension indicator $IFI_{k,i}$ is calculated (k refers to the dimension, including the IFI width and the IFI depth), and its calculation method is as follows:

$$IFI_{k,i} = 1 - \frac{\sqrt{\omega_1^2(1 - x_{k,i1})^2 + \omega_2^2(1 - x_{k,i2})^2 + \cdots \ldots + \omega_n^2(1 - x_{k,in})^2}}{\sqrt{(\omega_1^2 + \omega_2^2 + \cdots \ldots + \omega_n^2)}} \quad (3.4)$$

Finally, the final IFI of each country i is obtained as follows, where $IFI_{k,width}$ refers to the IFI width in country i, and $IFI_{k,depth}$ refers to the IFI depth in country i. $\omega_{IFI\ k,width}$ is the weight index of the breadth of financial inclusion, that is, Table 1 shows the weights of the breadth of financial inclusion ω_j Sum of j, $\omega_{IFI\ k,depth}$ is the weight index of financial inclusion depth, and the calculation method is the same as above. The specific calculation method of IFI is as follows:

$$IFI_i = 1 - \frac{\sqrt{\omega_{IFI\ k,width}^2(1 - IFI_{k,width})^2 + \omega_{IFI\ k,depth}^2(1 - IFI_{k,depth})^2}}{\sqrt{(\omega_{IFI\ k,width}^2 + \omega_{IFI\ k,depth}^2)}} \quad (3.5)$$

According to the above methods, the financial inclusion index of each country in 2011, 2014 and 2017 is obtained in turn. The classification and weights are shown in Table 1:

Table 1. Classification and weights of the financial inclusion indicators.

Dimension	Classification	Indicator	Data source	Indicator weight			
				ω_j	2011	2014	2017
IFI width (The outreach dimension)	Financial service accounts	Credit card users (over 15 years old,%)	Global Findex Database	ω_1	0.235	0.254	0.257
		Financial institution accounts (over 15 years old,%)	Global Findex Database	ω_2	0.149	0.131	0.138
		Debit cards (percentage over 15)	Global Financial Development	ω_3	0.190	0.182	0.180
	Financial institution equipment	Number of ATMs (per 100,000 adults)	Global Financial Development	ω_4	0.215	0.217	0.213
		Commercial bank branches (per 100,000 adults)	Global Financial Development	ω_5	0.211	0.215	0.213
IFI depth (The usage dimension)	Depositors	Proportion of deposits in the financial system in GDP (%)	Global Financial Development	ω_6	0.190	0.194	0.217
		Users with deposits in financial institutions (over 15,%)	Global Findex Database	ω_7	0.160	0.187	0.191
		Depositors with commercial banks (per 1,000 adults)	IMF, Financial Access Survey	ω_8	0.152	0.154	0.147
	Borrowers	Proportion of private credit provided by financial institutions in GDP (%)	Global Financial Development	ω_9	0.240	0.183	0.164
		Financial institution borrowers (over 15 years old,%)	Global Findex Database	ω_{10}	0.120	0.144	0.147
		Borrowers from commercial banks (per 1,000 adults)	IMF, Financial Access Survey	ω_{11}	0.139	0.140	0.133

Second, we construct the index of the information and communication technology level (ICT). When selecting relevant indicators to quantify ICT, this paper mainly considers the following factors: first, the indicators must meet the definitions of ICT facilities, access and usage; second, most countries need to have complete measurement data and standards for such indicators; third, indicators should be selected from multiple dimensions. At the same time, this paper also draws on the indicators selected in the Information and Communication Technology Development Index (IDI) released by the International Telecommunication Union (ITU) in 2019. Finally, this paper selects the following indicators: secure Internet servers, fixed broadband users, cellular mobile network subscriptions,

Internet users, fixed telephone users, and ICT commodity exports. The above data are all from the World Development Index database (WDI). Among them, the numbers of fixed broadband users, fixed telephone users, Internet users and cellular mobile network subscriptions are used to measure the access and usage of ICT; the number of secure Internet servers is used to measure the network quality and security in ICT; ICT commodity exports comprehensively reflect the market competitiveness of ICT commodities.

The construction method of the ICT index is the same as that of the financial inclusion Index (IFI); that is, the logarithmic method is used for dimensionless processing, then the weight of each indicator is determined according to the coefficient of variation method, and then the dimensionless sample data are multiplied with the weight of each indicator; finally, the numbers obtained by the multiplication are added. The specific division of ICT indicators and their weights are shown in Table 2.

Table 2. Classification and weights of the ICT indicators.

Classification	Weight		
	2011	2014	2017
Secure Internet servers (per million people)	0.339	0.340	0.319
Number of fixed broadband users (per 100 people)	0.077	0.085	0.073
Cellular mobile subscriptions (per 100 people)	0.176	0.164	0.214
Number of Internet users	0.124	0.116	0.106
Number of fixed telephone subscribers	0.151	0.158	0.148
ICT commodity exports	0.133	0.137	0.140

In addition, this paper also visualized the quantified ICT index. Figure 1 shows the ICT differences among sample countries (taking 2017 as an example, the blank parts show missing data). According to Figure 1, there are significant differences in ICT levels among countries in the world, which can be roughly divided into three tiers: countries in North America, Western Europe and Oceania are in the first tier. Most of the countries in these regions are developed countries with relatively high levels of economic development, and the development level of information and communication technology is also at the forefront of the world. Its ICT index is mostly higher than 4.90. The second tier includes relatively-developed developing countries in Eastern Europe, Asia, and South America. In recent years, the economic development in these countries has grown rapidly, and their international trade, scientific and technological level and comprehensive strength are booming. But the ICT development level is slightly lower than that of the first-tier developed countries. Its ICT index is mostly in the range of 2.50–4.90.The third is of the African region. Most of the countries in this region are relatively underdeveloped developing countries. The economic level is backward, and the national infrastructure and financial service systems relatively drop behind. Its ICT index is mostly lower than 2.50.Therefore, the ICT development level is also relatively lagging behind other regions. To sum up, it can be seen that ICT is consistent with the economic development level. Countries with a high level of economic development generally have higher ICT, while countries with a low level of economic development generally have lower ICT. This phenomenon is consistent with the points of Ghosh [35] and Pradhan et al. [34].
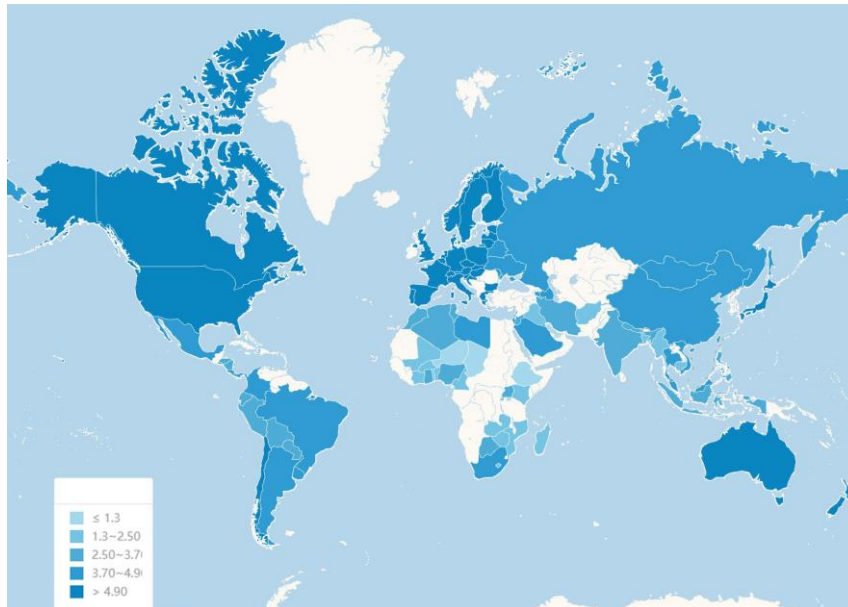
Figure 1. ICT Indexes of sample countries in 2017 (data source: calculated by authors).

3.2. Model setting

3.2.1.   Benchmark regression model setting: ICT level and IFI degree

In order to further explore the relationship between the ICT level and the financial inclusion degree, this paper selects the ordinary least squares (OLS) method for linear regression analysis. The unknown parameters can be easily obtained by using the OLS, and the sum of squares of the errors between these obtained parameters and the actual parameters can be minimized. Referring to previous literature [58–61], adding fixed effects variables to reduce the influence of individual countries and time on the empirical process. This paper finally uses the OLS fixed-effects regression model based on panel data, as shown in Eq (3.6).

$$IFI_{k,i,t} = \alpha + \beta_1 ICT_{i,t} + \sum \beta_j Controls_{i,t} + Year_t + Country_i + \varepsilon_{i,t} \qquad (3.6)$$

where, i represents the ith country or region; t is the statistical year, k represents the financial inclusion dimensions (including the first-level dimension, IFI width and IFI depth dimensions), IFI refers to the international financial inclusion degree, and ICT represents the level of information and communication technology. Controls are five control variables: technological development potential (Ln tech), labor force level (Ln labor), per capita GDP (Ln gdp), inflation (Inflation), and service trade (Trade). Country and Year are sample individual fixed effects and time fixed effects, respectively, and ε is the error disturbance term.

3.2.2.   Mediating model: the mediating effects of digital payments

The mediating effect model is often used to analyze the influence mechanism between two causal variables. In this paper, we refer to the empirical testing steps by scholars such as Judd and Kenny [62], Baron and Kenny [63] and Sobel [64]. In the mediating effect, for the explanatory variable X and the

explained variable Y, if X affects Y through the variable M, then M is called the mediating variable. Here we consider a simplest mediating effect model, that is, the variables X, M, and Y satisfy the following relationship:

$$Y = cX + \varepsilon_1 \tag{3.7}$$

$$M = aX + \varepsilon_2 \tag{3.8}$$

$$Y = c'X + bM + \varepsilon_3 \tag{3.9}$$

From Eqs (3.7)–(3.9), c measures the total effect of X on Y; ab measures the indirect effect of X through M, i.e., the mediating effect, and c' is the direct effect. The relationship between the total effect, the direct effect and the mediating effect satisfy:

$$c = c' + ab \tag{3.10}$$

There are many ways to test the mediation effect. One of the common methods is to test whether the product ab of the regression coefficients is significant. If ab is significantly different from 0, it means that there is a mediating effect; otherwise, there is no mediating effect. According to the analysis in Section 2, ICT can effectively promote the construction and improvement of a country's digital payment system, and the development of a digital payment system can greatly promote the country's financial inclusion. In addition to direct effects, ICT may indirectly contribute to great financial inclusion by improving digital payment systems. This paper constructs the following mediating effect test model to verify this:

$$IFI_{k,i,t} = \alpha + \beta_1 ICT_{i,t} + \sum \beta_j Controls_{i,t} + Year_t + Country_i + \varepsilon_{i,t} \tag{3.11}$$

$$IFI_{i,t} = \alpha + \beta_1 DP_{i,t} + \sum \beta_j Controls_{i,t} + Year_t + Country_i + \varepsilon_{i,t} \tag{3.12}$$

$$IFI_{i,t} = \alpha + \beta_1 ICT_{i,t} + \beta_2 DP_{i,t} + \sum \beta_j Controls_{i,t} + Year_t + Country_i + \varepsilon_{i,t} \tag{3.13}$$

3.3. Data selection and explanation

3.3.1.   Sample country selection

This paper adopts an unbalanced panel to include more national sample data, mainly including countries and regions in Asia, Europe, Africa, the Americas, and Oceania. Table 3 reports in detail the number of sample countries by region in each year:

Table 3 Numbers of sample countries and regions.

Year	Asia	Europe	Africa	Americas	Oceania
2011	32	32	32	19	2
2014	33	34	29	17	2
2017	30	32	25	17	2

As shown in Table 3, the number of sample countries in different regions varies slightly in different years, because some countries or regions have missing data in some years. This paper only keeps the sample countries or regions with the complete data structure in each year.

3.3.2. The Variables

(1) The explained variable, the IFI of each country, measures the availability of financial services. IFI can be further divided into two secondary indicators: IFI width and IFI depth, which are respectively used to measure the coverage and depth of a country's financial services to residents. The former is composed of two sub-variables: financial service accounts and financial institution equipment according to certain rules, while the latter is composed of two sub-variables: depositors and borrowers. The selection and construction methods of the specific sub-variables of the above indicators have been described in sub-section 3.1, which will not be repeated here, the same below.

(2) The explanatory variable, the ICT level, is used to measure a country's information and communication technology and usage. It is determined by six indicators: the secure Internet servers (the secure Internet server refers to the server that uses encryption technology in the process of Internet transactions), the number of fixed broadband users, cellular mobile network subscriptions, Internet users, fixed telephone users, and ICT commodity exports, according to the methods shown in Eqs (3.1)–(3.5).

(3) Control variables. With reference to the research methods of Sarma and Pais [53], Sassi and and Goaied [65], Kara et al. [66], Kouladoum et al. [67], and Sharma and Changkakati [56], the development potential of science and technology (Ln tech), labor participation rate (Ln labor), aging, inflation and trade in services (Trade) are used as control variables. Specifically, Kouladoum et al. [67] studied the relationship between digital technology and financial inclusion in the article; Sarma and Pais (2011) [53] pointed out that there is a correlation between unemployment and financial inclusion. Kara et al. [66] also pointed out that age has a certain impact on financial inclusion in sorting out relevant literature on financial inclusion. Sharma and Changkakati [56], Sassi and and Goaied [65] also used control variables such as inflation and service trade in the study.

The influence of control variables on financial inclusion is as follows: (i) In the field of science and technology: the development potential of science and technology is conducive to the progress of digital technology, and the promotion of digital technology can directly or indirectly promote the innovation of financial products [67], thus improving the financial inclusion level of a country. (ii) Labor: On the one hand, the increase of labor participation rate contributes to the increase of residents' disposable income, thus increasing residents' investment in financial products; On the other hand, it is also conducive to maintaining the normal and stable operation of social economy and increasing the employment of financial services industry (iii) Aging: According to the life cycle theory, in the old age, the accumulation of wealth slows down, the demand for credit also decreases, and some services of financial institutions also have age restrictions [66]. Therefore, the aging of the population will reduce financial inclusion to some extent [68]. (iv) Inflation: inflation affects the value of a country's currency, the appreciation space of financial assets, and indirectly determines investors' investment attitude and behavior choices towards financial products. On the other hand, inflation is also an important factor in the overall monetary policy decision-making, and also affects the operation of domestic financial markets from a macro perspective. (v) Trade: Trade in services measures the competitiveness of a country's commodity markets and the overall strength of its service sector. It may affect financial inclusion through consumption.

(4) Mediating variable. Digital payments (DF) are measured by the proportion of people over the age of 15 in a country who have sent or received digital payments in the past year. Referring to the construction method, this indicator includes the measurement indicators of multiple dimensions related to digital payment, such as the amount of mobile currency, debit card or credit card payment, mobile account payment, past bill payment directly from or through the account of financial institutions, sending or receiving remittances, receiving agricultural products payment, receiving government transfer payment, receiving wages or receiving public sector pensions in the past 12 months. Therefore, it can better measure the development of a country or region's digital payment system.

The meaning, calculation process, and data source of the above variables are shown in Table 4:

Table 4. Descriptive statistics of variables.

Variable Name		Meaning	Description	Data Source
Explained variable	IFI	Financial inclusion	The benefit degree of financial services to domestic residents, which can be divided into two dimensions: the IFI width (financial service accounts, financial institutions and equipment); the IFI depth (depositors, borrowers)	Global Findex Database ; Global Financial Development
Explanatory variable	ICT	Level of information and communication technology	Secure internet servers, fixed broadband users, cellular mobile network subscriptions, Internet users	WDI(World Development Index)
Control variable	Ln tech	Science and technology development potential	The proportion of the added value of high-tech industry in the added value of manufacturing industry (take the logarithm)	WDI(World Development Index)
	Ln labor	Level of labor participation	Labor force participation rate, total (percentage of total population aged 15-64)	World Bank
	Aging	Level of scial aging	The percentage of the population over 65 years old	the World Bank
	Inflation	Inflation rate	Inflation as measured by GDP deflator (annual inflation rate)	the World Bank
	Trade	Service trade	Service trade volume (proportion in GDP)	the World Bank
Mediating variable	DP	Digital payment	Digital payments made or received in the past year (percentage over 15 years old)	Global Findex Database

3.4. Descriptive statistics

Table 5 reports the descriptive statistical results of explanatory variables, explained variables, control variables, and mediating variables in this paper. Specifically, the average, minimum and maximum values of ICT are 3.280, 0, and 6.081, respectively, indicating that the average level of acceptance, usage, security and market competitiveness of ICT services in countries around the world is 3.280. The ICT Level of some countries is still very backward, so the value of the index is 0, which also shows that there are significant differences in the development level of ICT among different countries. The average values of IFI, IFI width and IFI depth are 0.262, 0.296 and 0.240, respectively, and the data gap between the three is small. However, there are great differences between the minimum and maximum values of the above three indicators, indicating that there are also great differences in the degree of financial inclusion among different countries, which is consistent with ICT. At the same time, the standard deviations of IFI width and IFI depth are 0.184 and 0.148, consistent with the result of previous index construction with similar weights, so the index construction is reasonable. In addition, equally significant differences also exist in control variables such as digital payment (DP) and technological development potential (Ln tech), which once again confirms the current situation of uneven development among countries around the world.

Table 5. Descriptive statistics.

Variables	Num	Mean	Std. Dev.	Min	Max
ICT	338	3.280	1.508	0	6.081
IFI	338	0.262	0.155	0.016	0.715
IFI width	338	0.296	0.184	0.008	0.772
IFI depth	338	0.240	0.148	0.019	0.688
Ln tech	281	2.999	0.921	−1.349	4.450
Ln labor	334	4.226	0.156	3.727	4.500
Aging	335	9.351	6.421	0.742	27.109
Inflation	332	5.448	7.193	−11.876	71.039
Trade	324	24.075	31.450	4.001	272.391
DP	213	0.522	0.306	0.038	0.994

4. Empirical results analysis

4.1. Benchmark regression analysis

Table 6 details the results of the impact of ICT on the level of financial inclusion in countries around the world. Columns (1)–(3) show the empirical results of ICT on financial inclusion without fixed effects, and Columns (4)–(6) display the results after adding the fixed effects of individual and year so as to exclude the possible interference caused by unknown factors such as individual country and year change. The explanatory variable of Model (1) and Model (5) is financial inclusion degree (IFI). The explanatory variable of Model (2) and Model (4) is the IFI width, and that of Model (3) and Model (6) is the IFI depth. In general, results of Models (1)–(6) show that the influence direction and significance of ICT and each control variable are consistent, and there are few differences in the coefficients of whether individual and year fixed effects are included. Therefore, this sub-section interprets the regression results based on Models (4)–(6), and the rest of this paper uses them as the benchmark models.

According to the results of Model (4), ICT is significantly positive at the 1% confidence level, indicating that ICT has a significant positive impact on the financial inclusion of a country or region. When ICT rises, the country's financial inclusion also rises significantly, so H1 holds. According to the previous analysis, the main channels for ICT to promote the improvement of financial inclusion are: (1) the popularity of ICT products and the maturity of online financial services so that more groups can receive financial services through mobile phones and computers. This allows regions that don't have relevant financial institutions (such as bank outlets) due to geographical factors to obtain financial services. (2) ICT enables financial institutions to maintain a relatively low cost of financial services and achieve a larger scale and scope of operations. In this way, the service coverage of national or regional financial services is wider, enabling the originally marginalized and vulnerable groups to access and obtain financial services, which to a certain extent expands the country's financial inclusion. (3) The development of information and communication technology has improved people's understanding of financial services and products, especially the increasing popularity of the Internet, reducing the information gap and asymmetry between financial institutions and the served groups. At the same time, information and communication technology also enables financial institutions to use more efficient equipment and technology to analyze data, so as to customize services for a wider range of people, thereby improving the financial inclusion of a country or region. (4) The integration of ICT technology and financial services makes traditional finance more digitalized, thus forming a digital

financial service system. Digital finance contributes to corporate innovation [69], which in turn feeds the performance of financial institutions [70]. This circular mechanism is good for both regional innovation levels and the development of financial institutions. ICT also provides technical support for digital financial markets such as Bitcoin [71,72]. The regression results from the global perspective of this paper are consistent with the previous research conclusions in some countries and regions, indicating that despite great differences in ICT among different countries (shown in Table 5), ICT still has a certain effect on the degree of financial inclusion.

Table 6. Benchmark regression results.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	IFI	IFI width	IFI depth	IFI	IFI width	IFI depth
ICT	0.0593***	0.0539***	0.0192**	0.0781***	0.0886***	0.0716***
	(0.0059)	(0.0082)	(0.0082)	(0.0061)	(0.0075)	(0.0065)
Ln tech	0.0012***	0.0010**	0.0061	0.0071**	0.0008	0.0012***
	(0.0003)	(0.0005)	(0.0058)	(0.0033)	(0.0004)	(0.0004)
Ln labor	0.0679***	0.0458	0.0586**	0.0757***	0.0632***	0.0874***
	(0.0217)	(0.0308)	(0.0270)	(0.0188)	(0.0218)	(0.0225)
Aging	0.0043***	0.0099***	0.0646***	0.0021*	0.0057***	−0.0004
	(0.0012)	(0.0018)	(0.0082)	(0.0012)	(0.0017)	(0.0012)
Inflation	−0.0098**	0.0085	−0.0180***	−0.0133***	−0.0064	−0.0195***
	(0.0049)	(0.0086)	(0.0062)	(0.0042)	(0.0052)	(0.0055)
Trade	0.0778***	0.0739***	0.0874***	0.0639***	0.0466**	0.0772***
	(0.0173)	(0.0251)	(0.0140)	(0.0173)	(0.0233)	(0.0155)
Constant	−0.3050***	−0.2172*	−0.6487***	−0.3285***	−0.2409**	−0.4002***
	(0.0916)	(0.1307)	(0.1180)	(0.0808)	(0.0949)	(0.0950)
Year.F.E	NO	NO	NO	YES	YES	YES
Country.F.E	NO	NO	NO	YES	YES	YES
N	281	281	281	281	281	281
F	186.36	110.84	186.49	171.70	141.49	146.57
R-squared	0.8055	0.7030	0.7901	0.8381	0.8028	0.8060

Note: The standard errors of the coefficients are in brackets; *, **, *** indicate the significance levels of the coefficients at 10%, 5%, and 1%, respectively.

Comparing Model (5) and Model (6), it can be seen that there are differences in the promotion effect of the ICT level on financial inclusion in different dimensions, which is due to its different ways of influencing the width and depth of financial inclusion. On the one hand, ICT improves the service efficiency of financial institutions, and facilitates the storage and transfer of customers' funds [10], thus enabling residents of all countries to use credit cards and other financial service accounts more widely. On the other hand, advanced information and communication technology can improve the risk management capabilities of financial institutions and reduce their risk management costs. Therefore, banks can increase the scope of their financial services by adding more ATMs and branches in marginal areas. However, compared with the "immediate" effect of the first two, ICT can provide more suitable financial products and financial services for residents of a country by promoting the improvement of the service quality and service coverage of financial institutions, and finally promote the overall savings and borrowing of residents of the country. This is obviously a long process, and it takes longer to feed back this effect. Therefore, information and communication technology is more conducive to the improvement of the width of financial inclusion.

In terms of control variables, in models (4)–(6), the influence of Ln labor on financial inclusion is significantly positive at the 1% confidence level, indicating that the higher the labor level, the more stable the job market, the more conducive to the sustainable development of social economy. This

provides a favorable development environment for domestic financial development and helpes to expand financial inclusion to some extent. The regression results of Trade in services are also significantly positive. The more active trade in services, the more conducive it is to domestic and foreign consumption and investment, which to some extent affects the domestic borrowing situation, and thus improves financial inclusion.

4.2. Mediating effect analysis

Based on the benchmark model, this paper further verifies whether the improvement of the ICT level expanding a country's financial inclusion is because ICT promotes the increase in the scope and degree of digital payment in the country, thereby indirectly promoting the degree of financial inclusion improvement. Therefore, this paper uses digital payment as a mediating variable and adopts the causal stepwise regression test to clarify the mechanism of the ICT level on financial inclusion. The specific models are shown in Eqs (3.11)–(3.13).

The regression results in Tables 7 and 8 show the mediating role of digital payment in the impact of ICT on financial inclusion. Table 7 reports the regression results of the mediating effect model test, and Table 7 reports the Sobel test results based on the mediating effect test model of Table 7. According to models (1)–(3) in Table 7, the regression coefficient value of the total effect of ICT on financial inclusion in Model (1) is 0.0804, which is significant at 1% confidence level. In model (3), the regression coefficient of direct effect can be obtained as 0.0521. It can be obtained from model (2) and model (3) that the indirect effect is 0.0291, that is, the coefficient value of ICT in model (2) is multiplied by the coefficient value of DP in model (3). And the relationship between total effect, direct effect and intermediary effect satisfies the relationship result of Eq (3.10) (i.e., $0.0804 \approx 0.0521 + 0.0291$). At the same time. The sobel test in Table 7 is significant at the 1% confidence level, with a Z-value greater than 2.58. This indicates that the mediating effect of ICT on the improvement of financial inclusion through digital payment (DP) is significant, assuming H2 is true.

Table 7. Mediating effect.

VARIABLES	(1)	(2)	(3)
	IFI	DP	IFI
ICT	0. 0804***	0. 1267***	0. 0521***
	(0.0073)	(0. 0203)	(0. 0064)
DP			0. 2296***
			(0. 0228)
Constant	−0. 364***	−1. 7122***	−0. 0550***
	(0.1148)	(0. 3141)	(0.1023)
Control variables	YES	YES	YES
Year.F.E	YES	YES	YES
Country.F.E	YES	YES	YES
N	193	193	193
F	123.56	129.38	135.72
R-squared	0.8310	0.7785	0.8766
Sobel test results of the mediating effect			
Coefficient	0.0291***	Std Err 0.0052	Z 5.591

Note: Since data of the mediating variable digital payment are only available in 2014 and 2017, this empirical analysis only uses the samples of these two years. The standard errors of the coefficients are in brackets; *, **, *** indicate the significance levels of the coefficients at 10%, 5%, and 1%, respectively.

When the ICT level of a country or region improves, it will not only help the popularization of internet and mobile phones, but also facilitate the promotion of digital currency by technology enterprises, such as central bank digital currency (CBDC) [73].This enables residents and businesses to transfer money online through digital payments, such as paying bills through mobile money accounts, sending or receiving remittances. That is to say, the improvement of information and communication technology has greatly promoted the improvement and coverage of the digital payment system. Further, the widespread application of digital payment systems has relieved financial institutions and customers from the constraints of time and space, which not only helps financial institutions realize the externalities of the network and the economy but also reduces transaction costs and the threshold of financial services, thereby optimizing financial services. The operating efficiency of the market has also helped the users to provide faster, more convenient, and lower-cost financial services, enabling them to obtain financial services at a lower cost and higher efficiency, and ultimately expanding financial inclusion from both the supply and demand sides. It is worth noting that the application time and service price of digital payment vary from country to country, which will also lead to the heterogeneity of the intermediary effect of digital payment.

4.3. Heterogeneity test analysis

4.3.1. Differences in the impact of banking structure on financial inclusion

According to the previous theoretical analysis, different banks have different capital scale, business structure and strategic motivation, and whether a country's banking structure has a significant difference in the effect of ICT on financial inclusion is the common result of the above factors. Table 8 reports the regression results for countries with high banking concentration and countries with low banking concentration. Bank concentration refers to the proportion of the total assets of the three major commercial banks in the country to the total assets of commercial banks. In this paper, the bank concentration degree is sorted from small to large, and the sample countries or regions below the median are defined as the low bank concentration country group, and the sample countries or regions above the median are divided into the high bank concentration country group.

As can be seen from Table 8, there are significant differences between countries with high and low banking concentration in terms of financial inclusion degree (IFI), financial inclusion width (IFI width) and financial inclusion depth (IFI depth). Specifically, in the samples with high bank concentration, the increase of the ICT level leads to a higher increase in the coefficients of IFI, IFI width and IFI depth than that of the samples with low bank concentration. Heterogeneity exists in the impact of ICT on the degree of financial inclusion and its two dimensions among countries or regions with different bank concentration. Therefore, H3a holds.

Further, the results in Table 8 can be interpreted as follows. On the one hand, in countries with high bank concentration, funds and resources are concentrated in a few banks. This has increased their profitability to a certain extent and is also more conducive to increasing their service accounts and equipment improvement, expanding the degree of financial inclusion and its width and depth in those countries. According to the hypothesis in H3a, although the business structure is relatively disadvantaged in countries with high bank concentration, the strong capital strength still provides sufficient financial support for the medium and large banks in countries with high bank concentration to use information and communication technology to improve the financial service innovation. At the

same time, in countries with high bank concentration, the risk prevention capability of large banks is more prominent. They are more capable of resisting various risks encountered in the advancement of information technology, such as an increase in the bad debt rate. Therefore, the degree of financial inclusion and its width and depth in countries with high bank concentration is still significantly greater than those in countries with low bank concentration. However, despite the empirical evidence for the above description, it cannot be ignored that if the social capital and assets are too concentrated in a small number of large banks, it will be detrimental to the survival and development of small and medium-sized banks. If big banks raise loan interest rates to prevent corresponding risks or turn loans to high-net-worth individuals, it will be unfavorable for small and medium-sized enterprises and individuals obtaining loans, which may also reduce the country's financial inclusion.

Table 8. Bank concentration effect.

VARIABLES	High bank Concentration			low bank Concentration		
	IFI	IFI width	IFI depth	IFI	IFI width	IFI depth
ICT	0.0871***	0.0968***	0.0812***	0.0629***	0.0774***	0.0536***
	(0.0078)	(0.0098)	(0.0081)	(0.0097)	(0.0115)	(0.0108)
Constant	0.2833***	0.2464*	−0.3084***	−0.4783***	−0.3786**	−0.5792***
	(0.1067)	(0.1263)	(0.1177)	(0.1384)	(0.1760)	(0.1557)
Control variables	YES	YES	YES	YES	YES	YES
Year.F.E	YES	YES	YES	YES	YES	YES
Country.F.E	YES	YES	YES	YES	YES	YES
N	139	139	139	142	142	143
F	137.98	108.12	130.94	107.39	76.97	69.07
R-squared	0.8675	0.8052	0.8643	0.8253	0.8254	0.7605

Note: The standard errors of the coefficients are in brackets; *, **, *** indicate the significance levels of the coefficients at 10%, 5%, and 1%, respectively.

4.3.2. Differences in the impact of economic development levels on financial inclusion

Table 9 reports the regression results grouped by the median per capita income. Referring to the practice in Table 8, countries or regions are ranked from low to high according to per capita GDP. Those below the median are included in the sample group of low-income countries, and those above the median are included in the sample group of high-income countries. Table 9 reports the specific regression results of these two categories of countries.

From the results in Table 9, it can be seen that in the regression coefficients of the explanatory variable ICT on the IFI, the IFI width and the IFI depth, the regression coefficients of samples with higher economic development level are significantly higher than those of samples with lower economic development level. This shows that countries with high levels of economic development do have a higher degree of financial inclusion, hypothesis H3b holds. Take the depth of financial inclusion as an example: in the group with a high level of economic development, each increase in the ICT will lead to a 0.0845 increase in the depth of financial inclusion (IFI depth). In the group with low level of economic development, each increase in ICT will only bring about a 0.0578 point increase in IFI depth. It can be seen that in regions with good economic development, ICT plays a stronger role in financial inclusion.

Table 9. Income heterogeneity effect.

VARIABLES	High gdp			Low gdp		
	IFI	IFI width	IFI depth	IFI	IFI width	IFI depth
ICT	0.0865***	0.0920***	0.0845***	0.0583***	0.0595***	0.0578***
	(0.0138)	(0.0166)	(0.0157)	(0.0085)	(0.0115)	(0.0082)
Constant	−0.5478**	−0.3951	−0.6516**	−0.1137	−0.0092	−0.2009**
	(0.2567)	(0.3208)	(0.3245)	(0.0823)	(0.0912)	(0.1009)
Control variables	YES	YES	YES	YES	YES	YES
Year.F.E	YES	YES	YES	YES	YES	YES
Country.F.E	YES	YES	YES	YES	YES	YES
N	141	141	141	140	140	140
F	42.06	31.85	42.53	24.42	32.60	18.06
R-squared	0.6566	0.5420	0.6670	0.6754	0.6925	0.6232

Note: The standard errors of the coefficients are in brackets; *, **, *** indicate the significance levels of the coefficients at 10%, 5%, and 1%, respectively.

Further, the following explanations can be made in combination with the results in Table 9 and the previous theoretical analysis: on the one hand, when a country or region's economic development level improves, it will invest more R&D (Research and development) support in the ICT sector, thereby promoting the rapid rise of its ICT level. In turn, the improvement of information and communication technology has significantly improved the financial inclusion of the country or region by improving the coverage of financial services and risk management capabilities. On the other hand, the improvement of information and communication technology in a country or region can directly or indirectly promote the growth of the economic development level, which can directly or indirectly drive the development and innovation of the financial service system, thereby improving the degree of financial inclusion. In addition, some countries may need to focus on more fundamental issues, rather than focusing on high technology development goals, which may lead to a delay in domestic ICT development. In South Africa, for example, school administration is facing a severe financial crisis [74], which may lead the country to reduce its focus on ICT.

4.3.3. Differences in the impact of the international financial environment on financial inclusion

According to the previous theoretical analysis, the operating mechanism, risk beliefs and governance structure of the OIC countries are quite different from those of traditional banks. Similarly, Latin American (LA) countries are also quite different from other countries due to economic development, capital control and uneven social development. Therefore, this paper speculates that the effect of information and communication technology (ICT) on financial inclusion (IFI) may be heterogeneous in these two types of countries. Table 10 reports the corresponding empirical test results, in which Columns (1) and (2) show the regression results of OIC countries and Non-OIC countries, respectively, and Columns (3) and (4) display the regression results of Latin American countries (LA) and non-Latin American countries (Non-LA), respectively.

According to Columns (1) and (2) in Table 10, the influence coefficients of ICT on the financial inclusion of the OIC and the Non-OIC countries are 0.0807 and 0.0763, respectively, which are significantly positive at the 5% confidence level, and the former is greater than the latter. This indicates that the effects of ICT on IFI are heterogeneous between Islamic and non-Islamic countries, so hypothesis H3c is true. One possible reason lies in the unique business philosophy and risk attitude in OIC countries. Islamic banks have always been guided by the "Islamic doctrine" and regard interest

and uncertain income as shameful and immora. Therefore, although Islamic banks cannot compare with traditional banks in terms of profitability, they have indeed formed a risk management system that traditional banks cannot compare, making them have a more keen ability to identify risks. In this way, even if ICT is applied to traditional financial services, Islamic countries will be more cautious, thus avoiding more unknown risks and ultimately achieving greater growth in the overall financial inclusion of the country.

Table 10. Heterogeneous impact of the international financial environment.

VARIABLES	(1) OIC IFI	(2) Non-OIC IFI	(3) LA IFI	(4) Non-LA IFI
ICT	0.0807***	0.0763***	0.0380**	0.0862***
	(0.0073)	(0.0072)	(0.0143)	(0.0060)
Constant	−0.3119**	−0.5184***	0.4964	−0.3957***
	(0.1308)	(0.1465)	(0.4706)	(0.0859)
Control variables	YES	YES	YES	YES
Year.F.E	YES	YES	YES	YES
Country.F.E	YES	YES	YES	YES
F	51.31	145.36	11.48	185.59
N	43	238	37	244
R-squared	0.8808	0.8243	0.7741	0.8489

Note: The standard errors of the coefficients are in brackets; *, **, *** indicate the significance levels of the coefficients at 10%, 5%, and 1%, respectively.

It can be seen from Columns (3) and (4) in Table 10 that the regression result of ICT to LA is significant at the level of 5%. The coefficient on the impact of ICT on financial inclusion in Non-LA is significantly positive at the 1% confidence level. This suggests that the impact of ICT in IFI is weak in LA, so H3d is true. On the one hand, over the years, LA have implemented strict capital controls, foreign capital investment has been severely hindered, and financial development has been slow. In addition, hindered by geographical factors such as tropical rain forests, domestic financial resources are concentrated in a small number of areas, making it even more difficult for poor and rural areas to receive financial services. On the other hand, although the development of information and communication technology has led to the rise of fintech and digital finance, this phenomenon has not been clearly manifested in Latin America. The reason is that Latin America is a late starter in fintech and has a lower global share of fintech activity [52]. At the same time, due to political, economic and financial instability, lack of financial supervision and other factors, FinTech has not had a significant impact on the low level of financial integration in Latin America. Second, the innovation power of digital financial community is insufficient. The investment of international capital often has a positive impact on innovation output [75], while most departments in LA countries have implemented a relatively strict capital flow control system, which inhibits the innovation of these countries in the fields of information and communication technology.

5. Robustness analysis

5.1. Robustness was tested by replacing explanatory variables

In order to avoid the error and contingency of regression results due to the particularity of the index construction method, this paper uses the entropy method to reconstruct the ICT EVM, and uses

this index to test the robustness of the benchmark regression in Table 6.

In information theory, entropy represents the disorder degree of the system, which can be used to measure the effective information of data. The Entropy value method (EVM) is a method to determine the weight of each indicator according to the amount of information it sends out. For example, the greater the data difference in an indicator is, the smaller the entropy value of the indicator, the more information it contains and transmits, and the greater the corresponding weight. The index ICT EVM is constructed as follows:

(i) First, we standardize the data. Where j is the index; i is the sample; y is the index value after the extreme difference processing; x is the original data of the sample, Min is the minimum value of the index j, and Max is the maximum value of the index j.

$$y_{i,j} = \frac{x_{i,j} - Min_j}{Max_j - Min_j} \tag{5.1}$$

(ii) Then, we calculate the probability matrix P. Each element p_{ij} is expressed as the proportion of the i-th sample under the j-th indicator. It is regarded as the probability used in the calculation of information entropy.

$$p_{i,j} = \frac{y_{i,j}}{\sum y_{i,j}} \tag{5.2}$$

(iii) Further, the information entropy e is calculated. The larger e_j is, the larger the information entropy of the j-th indicator is, and the smaller the amount of information it corresponds to. n is the number of indicator j.

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{i,j} \ln(p_{i,j}) \tag{5.3}$$

(iv) Finally, we define the information effect value d_j and normalize the information effect value to obtain the weight w. According to the weighted value and the normalized data, the index ICT EVM based on the entropy method is synthesized.

$$d_j = 1 - e_j \tag{5.4}$$

$$w_j = \frac{d_j}{\sum d_j} \tag{5.5}$$

It can be seen from Table 11 that the empirical results in this paper are robust. (1)–(3) is the empirical result of replacing original explanatory variables with ICT EVM. The results show that all regression results are significantly positive, and the confidence level is within 1%, which is consistent with the regression results of the benchmark model in Table 6. The influence of ICT on IFI width is greater than IFI depth. This shows that the regression results of the benchmark model in this paper are robust. In addition, the goodness of fit (R square) of the model is also similar to the benchmark model, indicating again that the regression results of the benchmark model in this paper are robust.

Table 11. Robustness test results.

VARIABLES	(1)	(2)	(3)
	IFI	IFI width	IFI depth
ICT EVM	0.0599***	0.0675***	0.0551***
	(0.0049)	(0.0060)	(0.0052)
Ln tech	0.0073**	0.0012	0.0012***
	(0.0033)	(0.0040)	(0.0034)
Ln labor	0.0680***	0.0545**	0.0804***
	(0.0188)	(0.0217)	(0.0225)
Aging	0.0022*	0.0058***	−0.0043
	(0.0013)	(0.0017)	(0.0012)
Inflation	−0.0123***	−0.0054	−0.0186***
	(0.0041)	(0.0049)	(0.0056)
Trade	0.0607***	0.0432*	0.0853***
	(0.0169)	(0.0229)	(0.0138)
Constant	−0.2483***	−0.1499	−0.3269***
	(0.0796)	(0.0932)	(0.0943)
Year.F.E	YES	YES	YES
Country.F.E	YES	YES	YES
N	281	281	281
F	167.69	135.50	149.66
R-squared	0.8412	0.8046	0.8099

Note: The standard errors of the coefficients are in brackets; *, **, *** indicate the significance levels of the coefficients at 10%, 5%, and 1%, respectively.

5.2. Discussion on endogeneity

Due to the continuous expansion of financial inclusion in some regions, financial services have been continuously improved, the level of social development has been improved, and its information and communication technologies and services may also be developed. This will cause the level of information and communication technology to play a feedback role in financial inclusion, and there may be a causal relationship between the explanatory variables and the explained variables. At the same time, missing variables may also affect the empirical results. In order to solve this kind of endogenous problem, this paper uses two-stage least squares (2SLS) model, and uses ICT index lag of three periods (sample interval is 3 years) as a tool variable to test its endogenous.

Table 12. Endogenous inspection(2SLS model).

VARIABLES	(1)	(2)	(3)
	IFI	IFI width	IFI depth
ICT	0.0967***	0.0972***	0.0964***
	(0.0104)	(0.0128)	(0.0102)
Constant	−0.4097***	−0.2735*	−0.5241***
	(0.1306)	(0.1506)	(0.1455)
Control variables	YES	YES	YES
Year.F.E	YES	YES	YES
Country.F.E	YES	YES	YES
N	179	179	179
Wald F	130.04	130.04	130.04
R-squared	0.7881	0.7583	0.7408
First stage regression results			
VARIABLES	ICT		
L3.ICT	0.8905***(0.0780)		

Note: The standard errors of the coefficients are in brackets; *, **, *** indicate the significance levels of the coefficients at 10%, 5%, and 1%, respectively.

Table 12 reports the regression results of the two-stage least squares method. The regression results of the first stage were significantly positive, and ICT was positively correlated with the lag period. In the second stage, the regression results in columns (1)–(3) are all significantly positive 1%.The regression results of the second stage were all significantly positive at 1%. In the regression using tool variables, the Craig-Donald Waldf statistic identifying weak tool variables is greater than the 10% level threshold, indicating that there is no weak tool variable problem. This shows that ICT can still significantly improve the IFI level after considering endogenous problems.

6.   Research conclusions and policy implications

Based on the existing literature and the sample data of countries around the world in 2011, 2014, and 2018, this paper first uses a linear regression model to test the impact of ICT on the degree, width, and depth of financial inclusion, then the mediating effect is explored that ICT indirectly promotes the improvement of financial inclusion by promoting the establishment and improvement of the digital payment system. Further, the heterogeneous impact of ICT on financial inclusion is analyzed from the dimensions of banking structure, economic development level, and international financial environment. Finally, based on the entropy value method and the independence weight method, the ICT index is reconstructed and applied in the robustness test process. The main conclusions of this study are as follows:

(1) The improvement of the level of information and communication technology helps to improve the degree of financial inclusion in a country or region. However, its effect on the width of financial inclusion is significantly greater than its effect on the depth of financial inclusion. (2) In the process of ICT affecting the degree of financial inclusion, in addition to the direct effect, it can also indirectly improve the degree of financial inclusion by promoting the construction and improvement of the digital payment system, allowing financial institutions and users to trade financial services at lower costs and risks, thereby indirectly improving financial inclusion. (3) The difference in banking structure will significantly affect the effect of ICT on the degree of financial inclusion. However, due to capital scale, business structure, and strategic motivation, the heterogeneous impact of banking structure on the effect of ICT has different directions on the degree, width, and depth of financial inclusion. (4) ICT has a stronger effect on financial inclusion in countries with higher levels of economic development. (5) Compared with other countries, the impact of ICT on financial inclusion is more significant in the OIC countries than in Latin American countries.

To sum up, ICT is a key driver of financial inclusion. Based on the above conclusions, this paper puts forward the following policy implications. First, policymakers in various countries need to pay attention to financial inclusion. As mentioned above, financial inclusion plays an important role in maintaining financial market stability, promoting social and economic growth, grasping economic macro-control, and improving residents' living standards. Second, on the one hand, countries need to expand investment in the development of ICT facilities to improve the security and affordability of their domestic Internet; on the other hand, they should increase investment in ICT research, provide technical support and formulate talent training programs. These measures can contribute to developing national information and communication services and thus improve financial inclusion. Third, policymakers need to expand the efficiency of the provision and usage of financial services such as digital payment to meet the needs of domestic residents and enterprises. For example, countries should support the incubation of digital financial start-ups and the digitization of traditional banking

businesses, thereby strengthening the role of digital financial services and products in the development of financial services. Fourth, countries should increase the national economic income to realize the mutual promotion effect of economic development and ICT development, which can jointly promote the improvement of financial inclusion. Fifth, countries need to adjust the concentration of domestic banks appropriately. While ensuring the stable development of the financial market, countries should seek a balance point where the structure of the banking industry promotes the degree, width, and depth of financial inclusion. Sixth, the role of national alliances in financial inclusion and information and communication technology should be strengthened to provide technical and financial support to member countries. Cooperation among the alliances should be reinforced to complement the efforts of governments to improve information and communication technology and create a better environment for financial development.

Subsequent research on the impact of ICT on financial inclusion can still be expanded and explored from the following aspects. First, from the angle of internal environmental factors in each country, follow-up research can explore the relationship between ICT and financial inclusion growth from the perspective of the heterogeneity of urban-rural gaps. Further analysis can be done on how the development of ICT affects household consumption and saving decisions. At the same time, regarding the research on how the characteristics of the banking system affect the impact mechanism, follow-up research can further analyze the influence of inter-bank competitiveness or risk control capabilities. Second, from the angle of external environmental factors, the policy measures selected by countries in economic and trade exchanges, such as exchange rate regulation, can be used to analyze their impact on ICT and financial inclusion.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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