Journal of Human-Social Nexus

Contents lists available at: journals.absresearchacademy.com

Research Article

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Balancing Blockchain and FDI: Implications for Financial Development Derived from Machine-learning Analysis

Mymuna Akter Nipu[1*], Alifa Shaira Nejhom[2*], Md Nazim[3]

[1] *Department of Economics and Banking, International Islamic University Chittagong, Chittagong, 4318, Bangladesh*

[2] *Business School, Zhengzhou University, Zhengzhou, 450001, China*

[3] *School of Business, China West Normal University, Sichuan, 637002, China*

[*] *Corresponding author.*

Article info

Received: 2025-10-25

Revised: 2026-04-04

Accepted: 2026-04-05

Published: 2026-04-06

Keywords

Blockchain; FDI; Financial development; financial depth; OECD

DOI

https://doi.org/10.64939/jhsn.1.1.0006

A B S T R A C T

This study empirically investigates the relationship between blockchain technology and Foreign Direct Investment (FDI) and their combined impact on financial development in 27 OECD countries from 2010 to 2022. Employing 2-step system GMM to control for endogeneity, unobserved heterogeneity, and machine learning techniques, we analyze their effects on overall Financial Development (FD), Financial Institutions Depth (FID), and Financial Markets Depth (FMD). Our findings reveal that blockchain adoption significantly enhances all three dimensions of the financial system by fostering efficiency, transparency, and security. Conversely, while FDI independently contributes to the depth of financial institutions and markets, its interaction with blockchain exhibits a significant negative moderating effect. This suggests a "crowding-out" phenomenon, where high levels of FDI may dampen the positive contributions of domestic blockchain innovation. These results underscore the necessity for nuanced policymaking that strategically promotes blockchain integration while managing the composition and impact of FDI inflows to optimize financial system development in advanced economies.

HOW TO CITE

Nipu, M. A., Nejhom, A. S., & Nazim, M. (2026). Balancing Blockchain and FDI: Implications for Financial Development Derived from Machine-learning Analysis. Journal of Human-Social Nexus, 1(1). https://doi.org/10.64939/jhsn.1.1.0006

Introduction

In recent decades, the global financial system has undergone significant transformation driven by rapid technological advancements and increasing cross-border capital flows. Within this context, financial development can be understood as the enhancement of financial systems' ability to perform key functions such as information production, resource allocation, risk management, and savings mobilization by reducing information, enforcement, and transaction costs (Levine, 2005), and is commonly measured in terms of the depth, access, and efficiency of financial institutions and markets reflecting the overall performance of the financial system (Svirydzenka, 2016). Security and privacy concerns have long constrained internet-based business activities,

as sensitive financial and personal information remains vulnerable to data breaches, often requiring intermediaries that reduce efficiency (Khatwani et al., 2023) . In response, blockchain technology initially developed as the underlying protocol for the digital currency Bitcoin has emerged as a decentralized and encrypted system that ensures transparency, trust, and transaction security without central authority (Khatwani et al., 2023; Underwood, 2016). Consequently, blockchain has become a disruptive innovation in financial systems, reducing transaction costs and enhancing efficiency (Autore et al., 2024), while streamlining banking, insurance, and capital market operations and strengthening the depth of financial institutions and markets (Cotugno et al., 2024; Kaniadakis & Foster, 2024).Its core features, including immutability, decentralized consensus, and real-time data sharing, further improve data integrity and operational reliability (Autore et al., 2024).Beyond financial intermediation, blockchain applications extend to broader economic domains; for instance, blockchain-based electronic invoicing systems in China, supported by Tencent's BaaS platform, integrate transaction processing, invoicing, reimbursement, and tax payments, thereby improving paperless practices and regulatory oversight (Cui et al., 2024) .Although the technology has a scope of being leveraged in various enterprises, it has shown great potential in the financial industry for FinTech applications (Khatwani et al., 2023) and fintech has accelerated financial inclusion and transformed traditional financial services through innovations such as real-time payments and digital lending (Allen et al., 2022) .

Moreover, by reducing reliance on intermediaries, blockchain lowers trade costs and enhances security in international trade (Siddik et al., 2021). While blockchain technology offers significant potential to transform financial systems, its effectiveness may not occur in isolation but rather depends on broader economic and institutional conditions. In this regard, foreign direct investment (FDI) emerges as a critical factor that can shape, complement, or even constrain the impact of blockchain adoption on financial development. Foreign direct investment (FDI) plays a critical role in shaping financial systems by acting as a conduit for external resources and enhancing the absorptive capacity of host economies (Yeboua, 2019). Beyond providing capital inflows, FDI facilitates the transfer of advanced technologies, managerial expertise, and innovative practices, thereby fostering technological progress and accelerating economic growth (Majeed et al., 2021). Since the 1990s, the rapid expansion of cross-border investment has positioned FDI as a key driver of global economic integration, enabling investors to diversify their portfolios and access high-growth markets, while allowing recipient countries to supplement limited domestic savings with much-needed external capital (Yavas & Malladi, 2020) .Nevertheless, the benefits of foreign capital inflows are accompanied by notable challenges. While direct investments such as infrastructure development and productive capacity expansion tend to generate stable, long-term growth, other forms of capital flows, particularly portfolio investments, are inherently volatile and prone to sudden reversals. These risks are further exacerbated by exchange rate fluctuations and informational asymmetries regarding domestic institutional environments, which may constrain the effective allocation and utilization of foreign capital, particularly in developing and emerging economies (Yavas & Malladi, 2020).

Despite the growing body of research on blockchain technology and foreign direct investment, a comprehensive understanding of how these factors jointly influence financial development remains limited. While existing studies have widely documented the positive contributions of blockchain technology in enhancing financial system efficiency and the role of FDI in promoting financial deepening, their interactive relationship has received relatively little attention. This gap is particularly relevant in OECD countries, where advanced financial systems and substantial cross-border capital flows may generate complex dynamics that influence fi-

nancial development outcomes. Against this backdrop, this study aims to examine the individual and joint effects of blockchain technology and foreign direct investment on financial development within a unified empirical framework. Specifically, it evaluates the impact of blockchain technology on multiple dimensions of financial development, including overall financial development, financial institutions depth, and financial markets depth, while also assessing the contribution of FDI as a key driver. More importantly, by incorporating an interaction term, the study investigates whether FDI conditions the effectiveness of blockchain technology, providing new evidence on the potential crowding-out effect whereby higher levels of foreign direct investment may weaken the positive impact of blockchain technology on financial development, financial institutions depth, financial market depth in advanced economies. Moreover, our research contributes to the existing literature by evidencing, through both econometric and machine learning methods, the direct impact of blockchain on financial development and depth, highlighting blockchain's role in enhancing transparency, efficiency, and access in financial systems.

The remainder of this paper is organized as such: Section 2 reviews the relevant literature. Section 3 outlines the data sources and methodological framework. Section 4 examines and discusses empirical results. Finally, Section 5 concludes the study and draws out the associated policy implications.

Literature Review and Hypothesis Development

Literature Review

Blockchain Technology and Financial Development

Prior studies have extensively examined the role of financial technologies, particularly blockchain and related digital innovations, in shaping financial development. Blockchain technology is increasingly recognized as a transformative force in modern financial systems due to its ability to enhance transparency, security, and operational efficiency. For instance, Chi et al., (2025) demonstrate that blockchain significantly promotes the digital economy, while Zhou et al., (2020) find a positive effect of blockchain on digital asset transactions. Similarly, Yiran Wang, (2020) highlights that blockchain facilitates financial services development across multiple domains, including equity crowdfunding, cross-border remittance, and supply chain finance, thereby strengthening the overall financial development and it improved financial inclusion and stability in emerging markets (Harakeh et al., 2024) while others note its role in streamlining banking and insurance processes in developed economies (Cotugno et al., 2024). Using a generalized linear model, Siddik et al., (2021) show that blockchain enhances international trade which indirectly supports financial development. In capital markets (FMD), applications in trade finance, securities settlement, and asset tokenization are poised to increase market liquidity and transparency(Cui et al., 2024).Furthermore, Allen et al., (2022) and Ozili, (2023) reveal that innovations such as central bank digital currencies (CBDCs), cryptocurrencies, and FinTech significantly improve financial inclusion and stability. Chang et al., (2020) and Khatwani et al., (2023) confirm that blockchain technology drives financial sector innovation, particularly within banking, financial services, and insurance industries. Moreover, Vincent & Evans, (2019) provide cross-country evidence that cryptocurrency adoption enhances financial inclusion and financial sector development.

Foreign Direct investment and Financial Development

A substantial body of literature has explored the contribution of foreign direct investment to financial development like according to the, Majeed et al., (2021), Foreign direct investment has a statistically significant relationship with financial development. Empirical evidence indicates that foreign capital inflows, including foreign portfolio investment (FPI) and FDI play a crucial role in deepening financial markets. For instance, Oyerinde, (2019) reports that foreign portfolio investment has a significant long-run positive impact on stock market development in Nigeria. Similarly, Khattak & Khan, (2023) find that foreign direct investment significantly enhances financial development in Belt and Road Initiative (BRI) countries. The relationship between FDI and financial development is well-trodden ground in economics. The conventional view, rooted in the financial development theory pioneered by authors like Levine, (2005) ,posits that FDI fosters financial deepening by introducing competition, transferring advanced risk management practices, and stimulating the demand for more sophisticated financial services (Alfaro et al., 2004). This typically leads to a positive impact on both FID and FMD. However, this view is not monolithic. Critics point to potential downsides, including the "crowding out" of domestic firms and the possibility that foreign subsidiaries may rely on internal capital markets or their parent companies' financial networks, thereby limiting their positive spillovers to the host country's domestic financial system.

Finally, although existing studies provide substantial evidence on the individual effects of blockchain technology and foreign direct investment on financial development, limited research has examined their interactive relationship, particularly in the context of OECD countries. Most prior studies focus on either financial technology or foreign investment in isolation, neglecting the potential moderating role of FDI in shaping the effectiveness of blockchain technology adoption. Therefore, this study contributes to the literature in three key ways. First, it empirically investigates the impact of blockchain technology on financial development, financial institution depth, financial market depth across OECD countries. Second, it examines the role of foreign direct investment as a driver of financial development, financial institution depth, financial market depth Third, and most importantly, it explores the moderating effect of FDI on the relationship between blockchain technology and financial development, financial institution depth, financial market depth thereby providing new insights into the potential crowding-out dynamics within advanced financial systems. Our study advances the existing literature by demonstrating using both econometric and machine learning approaches the direct effect of blockchain on financial development and depth. Specifically, it underscores blockchain’s capacity to improve transparency, enhance operational efficiency, and expand access within financial systems

Theoretical Nexus and Hypothesis Development

The theoretical underpinning for the interaction between blockchain and FDI can be drawn from Institutional Theory and the Resource-Based View (RBV). From an RBV perspective, blockchain represents a valuable, rare, and imperfectly imitable resource that can provide a competitive advantage to a country's financial system. FDI, bringing its own bundle of resources (capital, technology, expertise), could theoretically be complementary, accelerating the adoption and scaling of blockchain and the first hypothesis is;

The positive impact of blockchain technology on financial development:

Blockchain technology enables financial institutions to perform core functions like payments, clearing, settlement, securitization, and lending without relying on intermediaries, thereby reducing administrative costs, enhancing efficiency, and limiting opportunities for data manipulation (Oh & Shong, 2017) .Operating through a decentralized and synchronized ledger system, it ensures transparency, immutability, and secure

verification of transactions, which reduces risks such as fraud and double-spending while minimizing the need for costly audits and external oversight (Khatwani et al., 2023) Furthermore, by enhancing traceability and data integrity, blockchain strengthens governance, auditability, and ownership verification in global trade and capital markets, contributing to more reliable and efficient financial operations (Khatwani et al., 2023) . Its applications also improve financial access and monitoring such as in lending and peer-to-peer platforms thereby supporting better risk management and accountability. However, the extent to which blockchain improves outcomes like financial reporting quality or reduces accounting manipulation remains contingent on firm-level implementation strategies and institutional contexts (Autore et al., 2024). In light of the above analysis, this study proposes the first hypothesis:

H1: Blockchain technology has a significant positive impact on FD, FID and FMD.

The positive impact of foreign direct investment on financial development:

FDI contributes to financial development by increasing the availability of capital in the domestic economy and strengthening financial intermediation through banking and money markets, thereby facilitating firms' access to external finance (Desai et al., 2006).The presence of foreign ownership further enhances banking sector performance, as it reduces interest rate margins and borrowing costs while improving loan portfolio management and risk assessment, leading to more efficient capital allocation for firms (Eller et al., 2005). Unlike domestic institutions engaged in relationship-based lending, foreign-owned banks typically adhere to international standards, thereby improving allocative efficiency, strengthening institutional development, and enhancing long-term financial stability; although their behavior may occasionally amplify credit cyclicality, their superior risk management and operational efficiency can ultimately reduce financial vulnerabilities and support sustainable economic development (Eller et al., 2005).Furthermore, international capital flows, including both foreign direct and portfolio investments, enhance stock market performance and expand the pool of investable funds, enabling countries to supplement domestic savings and support higher levels of investment and economic integration into global markets (Oyerinde, 2019; Yavas & Malladi, 2020). thereby, the second hypothesis is articulated as follows:

H2: Foreign direct investment has significant positive impact on FD, FID and FMD.

The moderating effect of foreign direct investment on the relationship between blockchain technology and financial development:

Institutional Theory suggests that the interaction between foreign direct investment and domestic innovation may generate conflict-driven dynamics, as resource-rich foreign firms can influence regulatory frameworks in ways that favor incumbents over local enterprises, thereby constraining domestic technological development (Autore et al., 2024). So ,the entry of foreign firms may induce a crowding-out effect, whereby domestic firms particularly those with limited resources are displaced from the market due to intensified competition and superior capabilities of foreign firms, ultimately reducing domestic investment and productive capacity (Farla et al., 2016; Choi, 2018) . For instance, foreign financial institutions with greater access to capital and skilled labor may dominate blockchain adoption and innovation, thereby limiting the growth and scalability of domestic blockchain initiatives and weakening their contribution to financial development. Alfaro et al., (2004) emphasize, the ability of domestic firms to benefit from foreign presence depends on their access to financial resources; in the absence of well-developed financial markets, limited absorptive capacity restricts their ability to adopt new technologies and internalize spillovers, thereby reinforcing the crowding-out effect

and weakening the positive impact of foreign investment on domestic innovation and financial development. In light of the foregoing arguments, the following hypothesis is advanced:

H3: FDI negatively moderates the relationship between blockchain technology and FD, FID and FMD, indicating a crowding-out effect.

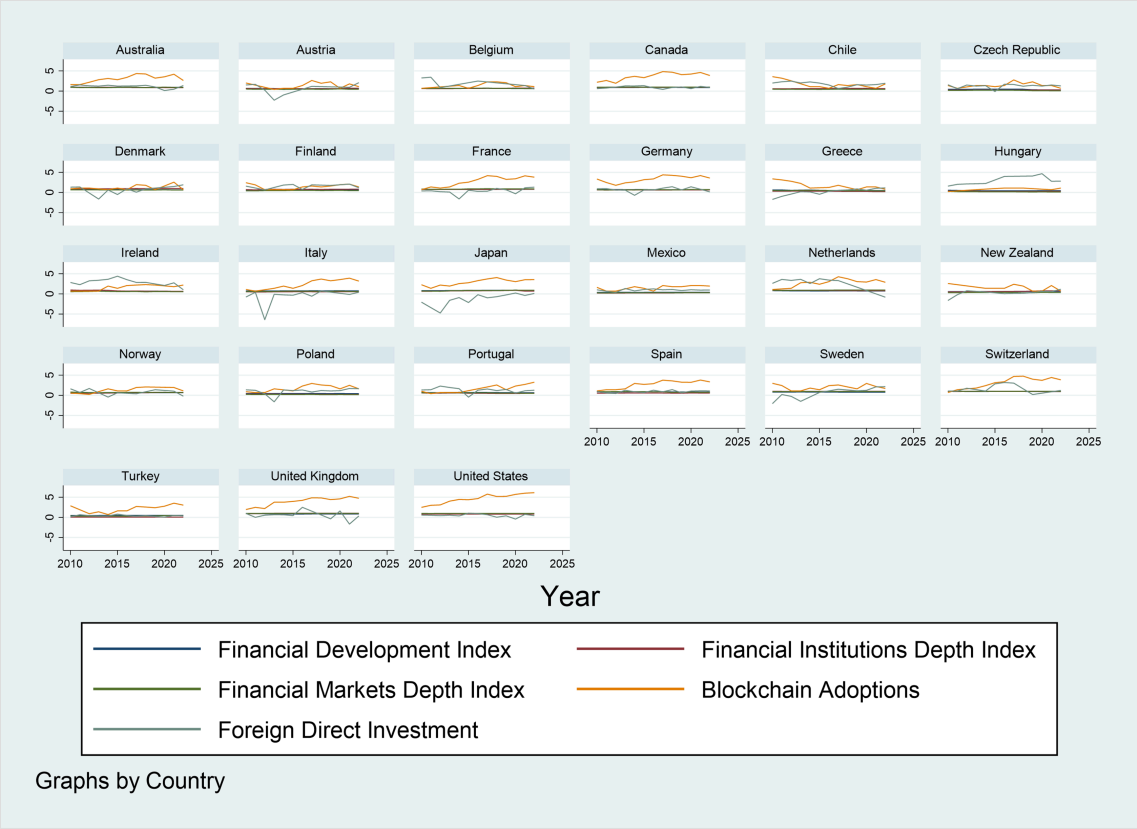

Figure 1. *Trends of Blockchain startups, FD, FID, FMD, and FDI in OECD.*

Data and Methods

Data Descriptions

To examine the impact of Blockchain on financial development and depth in OECD countries, we collected data from various sources for the period 2010 to 2022. The selection of OECD countries is justified not merely by data availability, but because they represent a homogenous group of advanced economies with established financial systems, allowing for a clearer examination of the marginal effects of technological innovation and capital inflows. Using a consistent group also helps control for vast differences in institutional quality that are present in global samples.

The dependent variables FD, FID, and FMD are comprehensive indices sourced from the IMF. These are preferred over single metrics (e.g., private credit) as they capture multidimensional aspects of development, including depth, access, and efficiency. The core independent variable, Blockchain (BC) measured and compiled a Blockchain using data from Crunchbase, including startups related to Bitcoin, Blockchain, cryptocurrency, decentralized finance, Ethereum, non-fungible tokens, smart contracts, and Web3. Crunchbase is a comprehensive database providing detailed information on businesses, startups, funding rounds, investors, and industry trends. Additionally, we developed a composite index for DFI using principal component analysis

(PCA), incorporating ATMs, BR, and DP. All other variables, along with their sources and descriptions, are detailed in Table 1, and trends are shown in Figure 1.

Table 1: Variable's descriptions.

Table 1. Variable's descriptions.

Variables	Descriptions	Sources
FD	Financial Development index: ranks countries on financial institutions and markets depth, access, and efficiency.	IMF
FID	Financial Institutions Depth index: includes bank credit, pension fund assets, mutual fund assets, and insurance premiums to GDP.	IMF
FMD	Financial Markets Depth index: includes stock market capitalization, stocks traded, and debt securities to GDP.	IMF
BC	Number of Blockchain startups each year.	Crunchbase, author's calculation
FDI	Foreign direct investment, net inflows (% of GDP).	WDI
DFI	Digital financial inclusion is a composite index of (ATM, BR, DP).	Author's calculation
ATM	ATMs per 100,000 adults.	GFDD
BR	Bank branches per 100,000 adults.	GFDD
DP	Outstanding deposits with commercial banks (% of GDP).	GFDD
BNPL	Bank nonperforming loans to gross loans (%).	IMF
GDP	GDP per capita growth (annual %).	WDI
NI	Adjusted net national income (current US$).	WDI
ACCOUNT	Voice and Accountability: Percentile Rank.	WDI
GOV	Government Effectiveness: Percentile Rank.	WDI
RD	Research and development expenditure (% of GDP).	WDI

Model Specifications

To test our hypotheses, we specify two dynamic panel models. The use of a dynamic model (including the lagged dependent variable) is standard in financial development literature, as financial systems are inherently persistent.

Model 1: direct impact of Blockchain on financial development and depth, we specify the following equation:

$$Yit = \alpha + \beta 1\, BCit + \beta 2\, BNPLit + \beta 3\, DFIit + \beta 4\, GDPit + \beta 5\, NIit + \beta 6\, ACCOUNTit + \beta 7\, GOVit + \beta 8\, RDit + \varepsilon it$$

where: *Yit* represents the dependent variables (FD, FID, FMD) for country i at time t. *BC*it is the Blockchain variable. Other variables include BNPL, DFI, GDP, NI, ACCOUNT, GOV, and RD. εit is the error term.

Model 2: indirect impact of Blockchain through the moderating role of FDI, we extend the model by including interaction terms:

$$Yit = \alpha + \beta 1\, BCit + \beta 2\, FDIit + \beta 3\, (BCit \times FDIit) + \beta 4\, BNPLit + \beta 5\, DFIit + \beta 6\, GDPit + \beta 7\, NIit + \beta 8\, ACCOUNTit + \beta 9\, GOVit + \beta 10\, RDit + \varepsilon it$$

where: $BC_{it} \times FDI_{it}$ is the interaction term capturing the moderating effect of FDI on Blockchain's impact. Both models use the GMM approach to address potential endogeneity, ensuring robust and reliable estimates by using lagged values of the explanatory variables as instruments.

Estimation method

We employ the two-step system GMM estimator developed by Blundell & Bond, (1998) . This method is particularly justified here for several reasons: Endogeneity: Blockchain development and financial depth are likely jointly determined. The GMM uses internal instruments (lagged levels and differences) to address this. We ensure the robustness of our GMM models by adhering to standard diagnostics: the Arellano-Bond test for AR (1) and AR (2) processes in errors (where rejecting AR (1) but not AR (2) is desired) and the Sargan test for over-identifying restrictions (a non-significant p-value is preferred). We also address collinearity by calculating Variance Inflation Factors (VIFs) for all models, confirming that multicollinearity is not a concern (all VIFs < 5).

Figure 1: Trends of Blockchain startups, FD, FID, FMD, and FDI in OECD.

Table 2. Descriptive statistics.

Variable	Obs	Mean	Std. dev.	Min	Max
FD	351	0.687	0.165	0.317	0.987
FID	351	0.639	0.263	0.049	1.000
FMD	351	0.635	0.273	0.073	1.000
BC	351	2.209	1.247	0.223	6.125
FDI	351	0.973	1.242	-6.394	4.669
BNPL	351	1.339	0.743	0.371	3.841
DFI	351	0.250	1.415	-2.033	4.909
GDP	351	0.792	0.801	-3.738	3.198
NI	351	27.146	1.200	25.267	30.606
ACCOUNT	351	4.415	0.257	3.144	4.605
GOV	351	4.427	0.184	3.628	4.605
RD	351	0.553	0.570	-1.259	1.310

Results and Discussion

Results

Table 2 summarizes descriptive statistics for study variables across 351 observations. The FD has a mean of 0.687. Both FID and FMD indices have similar means around 0.639 and 0.635. BC average 2.209. FDI has a mean of 0.973 with a wide range. The DFI shows high variability. GDP and NI indicate moderate growth. Governance metrics and RD expenditure show less variability.

Our findings show a strong positive impact of Blockchain on FD, FID, and FMD in OECD countries. Blockchain coefficients are 0.038, 0.032, and 0.068, all significant at the 1% level, indicating significant enhancements in financial system depth and efficiency and confirms the hypothesis H1 (Table 3). Blockchain improves financial transactions and services by increasing access, transparency, and efficiency, fostering a robust

financial environment (Cahill et al., 2020 ; Kaniadakis & Foster, 2024). Specifically, it enhances financial institutions through efficient credit provision, asset management, and trust, and boosts financial markets by increasing market capitalization, trading activity, and debt security management.

Furthermore, the interaction term BC*FDI is negative and significant for FD, FID, and FMD, with coefficients of -0.018, -0.019, and -0.026, respectively, suggesting that higher FDI levels weaken Blockchain's positive impact due to a crowding-out effect which supports the hypothesis H3. However, FDI positively affects FID and FMD, with coefficients of 0.044 and 0.058, significant at 5% and 1% levels, respectively, enhancing financial institutions and markets by introducing capital, expertise, and technology and validates the hypothesis H2. Its impact on overall FD is not significant. Additionally, DFI consistently positively influences all indices, underscoring the importance of integrating digital technologies into financial systems.

Table 3. The impact of Blockchain on financial development and depth.

Variables	M1: FD		M2: FID		M3: FMD	
BC	0.038***	0.050***	0.032***	0.047***	0.068***	0.086***
	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
FDI		0.033		0.044**		0.058***
		(0.115)		(0.027)		(0.001)
BC*FDI		-0.018*		-0.019**		-0.026***
		(0.070)		(0.038)		(0.001)
DFI	0.043***	0.048***	0.033**	0.050***	0.056***	0.054***
	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)	(0.000)
BNPL	0.002	-0.011	-0.062**	-0.061***	-0.009	-0.016
	(0.789)	(0.247)	(0.002)	(0.001)	(0.480)	(0.221)
GDP	-0.025***	-0.031***	-0.021**	-0.016**	-0.038***	-0.031***
	(0.000)	(0.001)	(0.005)	(0.018)	(0.000)	(0.000)
NI	0.017*	0.020**	-0.013	-0.009	0.047**	0.044**
	(0.059)	(0.002)	(0.336)	(0.522)	(0.004)	(0.032)
ACCOUNT	0.067**	0.026	0.291***	0.339	0.153**	0.115*
	(0.022)	(0.437)	(0.000)	(0.000)	(0.004)	(0.067)
GOV	0.154**	0.209***	0.414**	0.378**	0.219**	0.247**
	(0.004)	(0.000)	(0.002)	(0.003)	(0.010)	(0.011)
RD	0.030**	0.034**	0.091**	0.059*	0.037	0.039**
	(0.007)	(0.009)	(0.008)	(0.074)	(0.122)	(0.037)
cons	-0.845**	-1.013***	-3.175***	-2.341***	-2.421***	-2.332***
	(0.006)	(0.000)	(0.001)	(0.001)	(0.000)	(0.001)
AR(1)	-3.140**	-2.14**	2.070**	-0.58	-3.140**	-2.94**
	(0.002)	(0.032)	(0.039)	(0.565)	(0.002)	(0.003)
AR(2)	-0.190	-0.25	0.950	0.97**	-0.570	-0.15
	(0.849)	(0.806)	(0.344)	(0.030)	(0.571)	(0.882)
Sargan Chisq.	175.310***	123.07***	201.220***	159.21***	209.120***	252.83***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

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

Machine-learning outcomes

We conduct various artificial neural networks and machine learning methods to test the validity of blockchain and FDI-led financial development, including institutional and market development, as suggested by Zhang et al., (2024) .Table 5 describes all the machine learning methods used in the study, describing their respective benefits and limitations.

Table 4. The impact of Blockchain on financial development and depth: the moderating role of FDI.

Variables	M1: FD		M2: FID		M3: FMD	
	Coefficient	p-values	Coefficient	p-values	Coefficient	p-values
BC	0.050*** (0.001)	0.001	0.047*** (0.000)	0.000	0.086*** (0.000)	0.000
FDI	0.033 (0.115)	0.115	0.044** (0.027)	0.027	0.058*** (0.001)	0.001
BC*FDI	-0.018* (0.070)	0.070	-0.019** (0.038)	0.038	-0.026*** (0.001)	0.001
DFI	0.048*** (0.000)	0.000	0.050*** (0.000)	0.000	0.054*** (0.000)	0.000
BNPL	-0.011 (0.247)	0.247	-0.061*** (0.001)	0.001	-0.016 (0.221)	0.221
GDP	-0.031*** (0.001)	0.001	-0.016** (0.018)	0.018	-0.031*** (0.000)	0.000
NI	0.020** (0.002)	0.002	-0.009 (0.522)	0.522	0.044** (0.032)	0.032
ACCOUNT	0.026 (0.437)	0.437	0.339 (0.000)	0.000***	0.115* (0.067)	0.067
GOV	0.209*** (0.000)	0.000	0.378** (0.003)	0.003	0.247** (0.011)	0.011
RD	0.034** (0.009)	0.009	0.059* (0.074)	0.074	0.039** (0.037)	0.037
Cons	-1.013*** (0.000)	0.000	-2.341*** (0.001)	0.001	-2.332*** (0.001)	0.001
AR (1)	-2.14** (0.032)	0.032	-0.58 (0.565)	0.565	-2.94** (0.003)	0.003
AR (2)	-0.25 (0.806)	0.806	0.97** (0.030)	0.030	-0.15 (0.882)	0.882
Sargan Chisq.	123.07*** (0.000)	0.000	159.21*** (0.000)	0.000	252.83*** (0.000)	0.000

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

Figures 2 (a-e) to 4 (a-e) present the results of different machine learning algorithms in predicting FD, FID, and FMD using blockchain and FDI for a sample of OECD economies. All machine learning techniques used in the study show positive trends. These figures illustrate the expected role of blockchain adoption and FDI on FD, FID, and FMD along with digital financial inclusion, bank non-performing loans, accountability, govern-

ment effectiveness, GDP, national income, and research and development. This comprehensive analysis highlights the significant potential of blockchain and FDI in advancing various dimensions of financial and institutional development in OECD countries, paving the way for more sustainable and inclusive economic growth.

Figure 2. *Machine-learning methods to predict financial development from blockchain and FDI.*

Table 5. Comparison of various machine learning methods.

Method	Merits	Limitations
Support Vector Machine (SVM)	SVMs provide high accuracy and fast classification. They handle irrelevant and redundant attributes well and manage highly interdependent attributes. They are suitable for both linear and nonlinear problems, have robust learning speed, and can handle missing values. They are resistant to noise, minimize overfitting, and can attempt incremental learning. SVMs offer good explanation ability and manage model parameters effectively.	SVMs require significant memory and complex parameter tuning. They are not inherently interpretable.
Decision Tree	Decision Trees learn and classify rapidly. They handle missing values and interdependent attributes well. They are easy to explain, manage model parameters, and minimize overfitting. They work with attributes of different costs and are generally accurate. Decision Trees handle redundant attributes and noise well and can perform incremental learning. They provide an upper bound on error.	Decision Trees can be overfit in small datasets, be biased towards dominant classes, and create complex trees that are hard to interpret.
Gradient Boosting Trees (GBT)	GBTs provide high accuracy and handle complex relationships well. They prevent overfitting by combining multiple weak learners and improve performance iteratively. GBTs can handle various data types and are robust to noise.	GBTs are computationally intensive and require careful parameter tuning. They are less interpretable and can be prone to overfitting if not properly regularized.

Random Forest	Random Forests prevent overfitting by aggregating multiple tree predictors. They provide an upper bound on error, are robust against noise, and are the fastest among tree-based methods. They are less sensitive to node split variables.	Random Forests act as a black box and have limited interpretability. They are computationally intensive.
Deep Learning	Deep Learning provides high accuracy and rapid classification. It manages both binary and continuous attributes and is capable of incremental learning.	Deep Learning functions as a black box, requires large datasets, has high computational costs, and is challenging to interpret.
Generalized Linear Model (GLM)	GLMs are generally accurate and support categorical predictors. They are flexible with constrained scales and are less prone to overfitting.	GLMs are poor at capturing outliers and clusters, unable to model heterogeneity, and limited to linear relationships.

Figure 3. *Machine-learning methods to predict financial institutions development from blockchain and FDI.*

Discussion

This study provides important insights into the relationship between blockchain technology, FDI, and financial development in OECD countries. The results show that blockchain has a strong and positive effect on financial development, financial institutions depth, and financial markets depth. This finding aligns with theoretical expectations and prior literature emphasizing blockchain's ability to reduce transaction costs, enhance transparency, and improve security in financial systems (Khatwani et al., 2023; Underwood, 2016). By enabling decentralized financial processes, blockchain strengthens intermediation and supports innovation in banking and capital markets (Cotugno et al., 2024; Allen et al., 2022). Applications such as digital payments, trade finance, and asset tokenization further enhance liquidity and reduce operational risks (Cui et al., 2024; Siddik et al., 2021) , reinforcing its role in financial system transformation (Harakeh et al., 2024) .The strong positive direct effect of blockchain (H1) is also consistent with evidence that its core attributes disintermedia-

tion, enhanced security, and transparency deepen financial institutions and markets in advanced economies (Cahill et al., 2020) . In contrast, the impact of FDI is mixed. While FDI significantly enhances financial institutions and markets depth, its effect on overall financial development is not robust. This provides partial support for H2 and reaffirms the traditional role of FDI as a source of capital, technology, and expertise that strengthens specific segments of the financial system (Majeed et al., 2021; Alfaro et al., (2004) . However, its benefits may remain concentrated in particular sectors rather than the entire financial system (Yavas & Malladi, 2020).

Figure 4. *Machine-learning methods to predict financial-market development from blockchain and FDI.*

The core contribution of this study lies in the strong support for H3. The negative and significant interaction term indicates that FDI weakens the positive impact of blockchain, suggesting that their relationship is not complementary but characterized by tension. This crowding-out effect can be explained through both Resource-Based View and Institutional Theory. Large foreign multinational firms may absorb scarce domestic resources such as skilled labor and capital, thereby limiting opportunities for local blockchain innovation (Farla et al., 2016; Choi, 2018) . At the same time, they may influence regulatory frameworks in ways that favor established players, constraining the growth of emerging technologies (Autore et al., 2024) . Additionally, reliance on internal financing by multinational firms reduces engagement with domestic financial systems, limiting spillover effects and weakening the integration of blockchain innovations (Desai et al., 2006) . These findings challenge the conventional assumption that foreign investment is always beneficial for technological advancement. The machine learning results further reinforce these findings by providing consistent predictive evidence across multiple models. Techniques such as support vector machines, random forests, and gradient boosting capture complex and nonlinear relationships, confirming the robustness of the econometric results. The consistency across methods highlights blockchain as a key driver of financial development, while also revealing the conditional and context-dependent role of FDI (Zhang et al., 2024) . Finally, the negative coefficient of GDP growth observed in some models, although counterintuitive, may reflect the structural characteristics of OECD economies. During periods of high economic growth, investment may shift toward traditional

sectors, while financial innovation particularly blockchain adoption follows a longer-term trajectory not directly linked to short-term business cycles (Levine, 2005; Svirydzenka, 2016).

Conclusion and policy implications

We examine how blockchain influences financial development and depth using 2-step GMM as well as several machine-learning approaches. Findings for a sample of OECD countries show blockchain enhances financial system efficiency and transparency, promoting financial development and depth. However, higher FDI levels can diminish Blockchain's positive effects due to a crowding-out effect, although FDI positively contributes to financial institutions' and markets' depth. Policy implications for regulators include supportive legislation, investment in Blockchain infrastructure, and fostering a favorable environment for startups. Regulators should balance FDI inflows with domestic Blockchain development by encouraging collaborations between foreign investors and local firms. Promoting DFI should also be prioritized to expand access to digital financial service

The empirical findings of this study provide several important policy directions for OECD countries seeking to enhance financial development through blockchain technology while effectively managing the role of FDI. First, policymakers should prioritize the development of robust digital and institutional infrastructure to support blockchain technology within financial development. Strengthening regulatory clarity, promoting interoperability, and investing in secure digital platforms will enable financial institutions and markets to fully leverage blockchain’s potential to improve transparency, efficiency, and operational reliability. Enhancing digital infrastructure will also facilitate broader integration of blockchain applications across banking, insurance, and capital markets, thereby deepening financial institutions depth and financial markets depth. Second, given the positive impact of blockchain technology on financial development, governments should actively promote domestic innovation ecosystems. This can be achieved through increased investment in research and development (R&D), incentives for blockchain-based startups, and stronger collaboration between financial institutions, technology firms, and academic institutions. Supporting local innovation capacity is essential to ensure that the benefits of blockchain adoption are internally generated and sustained within the domestic financial system. Third, the negative moderating effect of FDI highlights the need for more strategic management of foreign capital inflows. While FDI contributes positively to financial development, excessive reliance on foreign investment may crowd out domestic technological innovation. Therefore, policymakers should design selective and quality-oriented FDI policies that encourage technology transfer, knowledge spillovers, and collaboration with domestic firms, rather than fostering competitive displacement. Screening mechanisms and targeted incentives can help align foreign investment with national innovation priorities.

This study has several limitations that chart a path for future research. First, the blockchain proxy, while informative, could be supplemented with alternative measures like venture capital investment or patent data in future robustness checks. Second, the "black box" of the crowding-out mechanism needs to be unpacked; qualitative case studies or firm-level data could explore whether it operates through talent markets, regulatory channels, or direct competition. Third, the study is confined to OECD countries; future research could investigate if similar dynamics exist in emerging markets, where institutional contexts differ markedly. Finally, exploring potential non-linear effects or threshold levels of FDI could provide even more precise policy guidance.

Funding

This research received no external funding.

Author contributions

Mymuna Akter Nipu: Conceptualization, Methodology, Validation, Writing – review & editing, Writing – original draft, Visualization, Investigation.

Alifa Shaira Nejhom: Conceptualization, Methodology, Validation, Writing – original draft, Investigation, Writing – review & editing.

Md Nazim: Validation, Visualization, Writing – original draft, Writing – review & editing, Data curation, Formal analysis.

Declaration of competing interest

The authors declare no conflicts of interest.

Ethics statement

Not applicable.

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