

Article

Digital Technologies and Sustainable Development: Evidence from FinTech, AI, and Blockchain Adoption in G20 Economies

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Abstract

In the wake of rapid digital transformation, emerging technologies like FinTech, AI, and Blockchain are reimagining how countries pursue sustainable development. This study examines how FinTech adoption, Artificial Intelligence (AI) readiness, and Blockchain activity influence sustainable development performance across G20 economies over the period 2015–2023. Drawing on Innovation-Driven Growth Theory, the Technology–Organization–Environment framework, and Institutional Theory, the analysis evaluates both the direct and complementary effects of these digital technologies on Sustainable Development Goal (SDG) outcomes using cross-country panel data and key macroeconomic controls. The results show that FinTech, AI, and Blockchain each exert a positive and statistically significant impact on national sustainability performance, with AI exhibiting the strongest effect. Moreover, the findings reveal meaningful digital complementarities, indicating that coordinated adoption of these technologies amplifies sustainable development gains. Overall, the study provides robust macro-level evidence that digital transformation functions as a strategic driver of sustainability and offers policy-relevant insights for G20 governments seeking to accelerate inclusive, transparent, and environmentally responsible development.

Keywords: transformation; FinTech; artificial intelligence; blockchain; sustainable development; G20 economies; panel data; technological complementarities

JEL Classification: O33; O44; G20; L86; Q56

1. Introduction

Digital transformation is being increasingly viewed as a crucial driver of sustainable development. The use of emerging digital technologies, including FinTech, artificial intelligence, and blockchain, is disrupting the ways in which the financial sector is organized. This, in turn, impacts the achievement of the Sustainable Development Goals set forth by the United Nations. Although existing literature reviews have extensively looked into the relationship between digital transformation and sustainability, individual technologies and enterprise performance have been the major subjects, and the interaction between the technologies, on the macro level, is yet to be studied.

Despite the rising literature and policy relevance, some key gaps exist in the body of research available. Firstly, despite the work on FinTech, AI, or blockchain, respectively, existing research primarily focuses on these concepts independently without considering their synergistic or complementary attributes. Secondly, a vast majority of the existing



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literature depends on data on a micro or sectoral scale, whereas evidence on a macroeconomic scale is scarce. Thirdly, and more specifically, there is an inadequately dealt with theoretical work on achieving a synergy of theories about innovation, technology, and its corresponding institutions within the context of sustainability transitions and technological advancement for sustainability goals.

The objective of this study is to empirically investigate the individual and joint effects of FinTech adoption, AI readiness, and blockchain activity on sustainable development outcomes in G20 economies over the period 2015–2023, and to examine whether digital complementarities amplify sustainability performance in the short and long run. By combining multiple theoretical frameworks and advanced panel econometric techniques, this research provides a holistic macro-level assessment of the digital transformation–sustainability nexus.

The G20 economies account for the majority of global GDP, digital innovation capacity, and SDG financing, making them a critical laboratory for examining the macro-level sustainability impacts of digital transformation.

This paper offers four major contributions to the literature. First, it presents a comprehensive, macro-level, empirical investigation on FinTech, AI, and blockchain technologies through a common sustainability framework within the context of G20 countries. In fact, it tests digital complementarity relationships through an interaction term approach among FinTech, AI, and blockchain technologies to provide new insights on their collective sustainability outcomes. Third, it uses advanced second-generation heterogeneous panel models (CS-ARDL, AMG, and CCEMG), along with dynamic System GMM methods to distinguish between short- versus long-term sustainability outcomes to counter issues associated with cross-sectional dependency and endogeneity. Fourth, it uses a broad Sustainable Development Goals framework as the dependent variable to depart from conventional sustainability variables, including CO₂ emissions or ESG performance outcomes.

Based on Innovation-Driven Growth Theory, Technology–Organization–Environment (TOE) theory, and Institutional Theory, this research postulates hypotheses for the direct and interaction effects of FinTech, AI, and blockchain variables on sustainable developments. It can be seen that multiple theories have been used to address the dual objectives of innovation in FinTech, AI, or blockchain, as well as sustainable developments.

Therefore, the research questions for this study are:

- (1) What are the long-run and short-run impacts of FinTech, AI, and blockchain technology on the sustainable development of the G20 countries?
- (2) Do digital complementarities among these technologies create synergistic sustainability effects?
- (3) In what ways do short-run adjustment processes differ from longer-term equilibrium consequences?
- (4) What is the role of macroeconomic and institutional variables in shaping the relationship between digital transformation and sustainability?

The rest of this paper is configured in the following manner: Section 2 has a literature review and develops a theoretical framework and hypotheses. Section 3 contains descriptions involving data, variables, and econometrics methods. Section 4 shows some results. Section 5 analyzes these results in terms of theoretical and policy implications. Finally, Section 6 concludes this paper and suggests future directions to some degree.

2. Literature Review

2.1. Theoretical Framework

Technological innovation has become a cornerstone of sustainable economic transformation in the digital era. Within the context of the G20 economies, the convergence

of FinTech, Artificial Intelligence (AI), and Blockchain Technology (BT) is reshaping how nations pursue the Sustainable Development Goals (SDGs). This study builds its theoretical foundation on three complementary perspectives, innovation-driven growth, technology adoption and digital transformation (TOE), and institutional and stakeholder governance, to explain how digital technologies foster sustainable development.

2.1.1. Innovation-Driven Growth Theory

The Innovation-Driven Growth Theory posits that technological advancement and knowledge accumulation are the primary engines of long-term economic and environmental sustainability. Technological progress enhances resource efficiency, promotes cleaner production, and fosters structural economic transformation. In this context, FinTech and AI represent key instruments that drive innovation, lower transaction costs, and enable data-driven decision making, thereby improving productivity and sustainability outcomes.

Empirical evidence supports this link between innovation and sustainability. Digital and Industry 4.0 technologies facilitate circular economy practices and sustainable operations in both developed and emerging economies (Garg et al., 2025) [1]. The adoption of FinTech and AI can therefore be conceptualized as part of a broader innovation-driven process that enhances sustainable growth through efficiency and knowledge diffusion. Innovation-led economies tend to achieve higher SDG performance by integrating digital finance and smart technologies into their sustainability strategies.

2.1.2. Technology–Organization–Environment (TOE) Framework

To understand the heterogeneous adoption of digital technologies across G20 economies, this research draws on the Technology–Organization–Environment (TOE) framework (Tornatzky and Fleischer, 1990) [2]. The TOE model argues that three contextual dimensions, technological capability, organizational readiness, and environmental pressure, jointly determine a firm's ability to adopt innovation.

In this study, FinTech represents the technological dimension, emphasizing digital infrastructure and financial inclusion; AI captures the organizational dimension through data-driven decision making and innovation capacity; and Blockchain embodies the environmental dimension by enhancing transparency and institutional trust. Recent research confirms the usefulness of the TOE framework in explaining sustainable digital transformation. Zhang (2024) [3] found that blockchain adoption in sustainable supply chains depends on all three TOE components, particularly technological readiness and environmental support. Applying this framework at the macroeconomic level allows for a nuanced understanding of why digital adoption and its sustainability outcomes vary across G20 nations.

2.1.3. Institutional and Stakeholder Theories

Sustainable development is also shaped by institutional norms and stakeholder expectations. According to Institutional Theory, organizations and governments adopt new technologies not only for efficiency but also to conform to regulatory, normative, and cognitive pressures (Scott, 2014) [4]. Similarly, Stakeholder Theory suggests that responsible governance, transparency, and social accountability drive the integration of sustainability into digital strategies.

In the digital sustainability context, Blockchain strengthens institutional legitimacy by ensuring data integrity and traceability; AI promotes accountability through predictive analytics and ESG monitoring; and FinTech enhances inclusiveness by extending access to underserved groups. Empirical studies have found that AI implementation improves corporate sustainability and ESG disclosure (Wang et al., 2025) [5], while blockchain adoption strengthens ESG performance and corporate governance mechanisms (Sui, 2025) [6].

Hence, institutional pressure and stakeholder engagement act as catalysts linking digital innovation to sustainability outcomes within the G20 economies.

2.1.4. Integrative Perspective

By combining these theories, the study proposes that sustainable development outcomes, measured by the Sustainable Development Index (SDG Score), are a function of the level of FinTech, AI, and Blockchain integration within an economy. Innovation-driven growth explains why technological progress leads to sustainability; the TOE framework explains how contextual factors shape technology adoption; and institutional theory explains under what conditions adoption enhances governance and legitimacy.

This integrated theoretical framework thus provides a holistic foundation for empirically testing the joint impact of FinTech, AI, and Blockchain on sustainability performance across the G20 economies. It reflects both technological dynamism and governance accountability as essential pillars of the global green digital transformation.

The conceptual relationships among Innovation-Driven Growth Theory, the Technology–Organization–Environment (TOE) framework, and Institutional and Stakeholder Theories are summarized in Figure 1, which illustrates how FinTech, AI, and Blockchain jointly influence sustainable development performance in G20 economies.

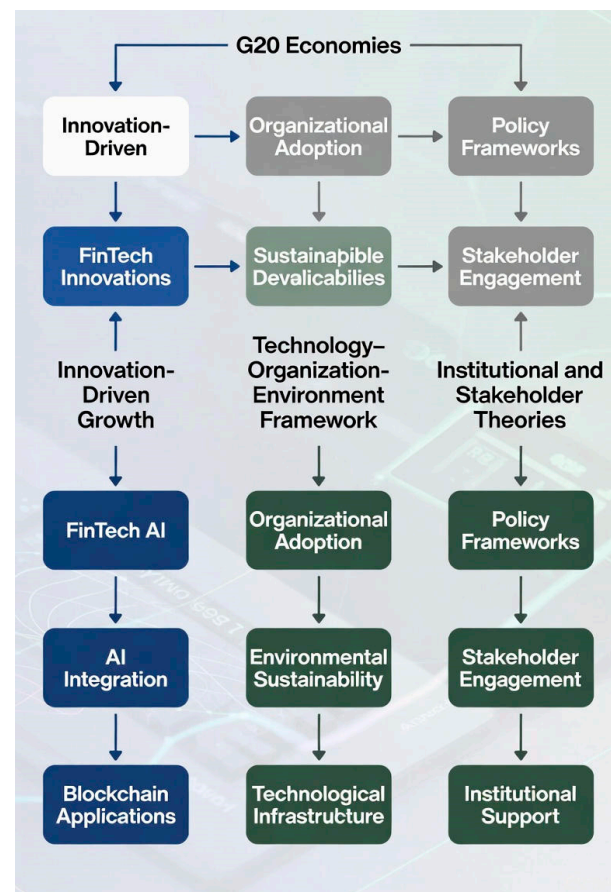


Figure 1. Integrated Theoretical Framework: Innovation-Driven Growth, TOE, and Institutional Theories linking FinTech, AI, and Blockchain to SDG Performance in G20 Economies.

2.2. Literature Review and Hypotheses Development

At the macro level, existing evidence indicates that digitalization plays a supportive role in improving environmental quality and advancing sustainable development objectives, particularly when combined with appropriate environmental policies and renewable energy strategies.

2.2.1. FinTech and Sustainable Development Goals (FinTech–SDG)

Digital transformation has become a key driver of sustainable economic and environmental performance, with FinTech technologies playing a central role in advancing several Sustainable Development Goals (SDGs). Prior studies emphasize that FinTech adoption reduces transaction costs, enhances financial inclusion, and promotes innovation-led growth, thereby supporting SDG 8 (decent work and economic growth) and SDG 9 (industry, innovation, and infrastructure) (Demirgüç-Kunt et al., 2020) [7]. Recent cross-country evidence further confirms that FinTech development improves ecological efficiency and environmental sustainability, particularly in emerging markets (Zhang et al., 2024; Choudhary et al., 2025) [3,8].

Empirical analyses by Thakkar and Bhuyan (2024) [9], based on a sample of 161 countries over the period 2011–2021, show that FinTech adoption, proxied by digital payments, significantly reduces poverty and income inequality while promoting inclusive and sustainable growth. Similarly, Sayari et al. (2025) [10] find that digital transformation and FinTech innovation enhance environmental and social outcomes, although these effects are weakened under heightened geopolitical risks. Choudhary et al. (2025) [8] further demonstrate that FinTech adoption and financial inclusion jointly contribute to improvements in key SDG targets, including economic growth, zero hunger, quality education, and innovation infrastructure. In the Middle East context, Guermazi et al. (2025) [11] provide evidence from Saudi Arabia showing that digitalization significantly reduces greenhouse gas emissions (CO₂, CH₄, and N₂O), highlighting the role of technological progress in supporting SDG 13 and advancing the environmental objectives of Saudi Vision 2030.

Recent systematic evidence also indicates that sustainability disclosure plays a critical role in shaping earnings management practices by reducing information asymmetry, strengthening corporate governance mechanisms, and addressing both internal and external stakeholder concerns (Ali et al., 2024) [12].

2.2.2. Artificial Intelligence and Sustainable Development Goals (AI–SDG)

Artificial Intelligence (AI) integration represents another major pillar of digital transformation with substantial implications for sustainable development. Existing literature highlights that AI enhances sustainability outcomes through improved decision making, predictive environmental management, and optimized resource allocation (Vinuesa et al., 2020; Abdeldjalil et al., 2024) [13,14]. Empirical evidence further confirms that AI adoption strengthens ESG reporting quality and overall corporate sustainability performance (Wang et al., 2025) [5].

In this context, Hamdouni (2025a) [15] shows that transparent ESG disclosures supported by AI-driven systems enhance firm reputation, investor confidence, and long-term value creation in financial institutions. These findings underline the strategic importance of AI as an enabler of sustainability-oriented governance and disclosure practices.

2.2.3. AI, Governance, and Sustainability in the Saudi Context

Building on the global evidence, several studies highlight the role of AI in advancing sustainability within Saudi Arabia. Hamdouni (2025a) [15] demonstrates that AI adoption significantly improves ESG performance by enhancing transparency, accountability, and alignment with Vision 2030 objectives. By integrating AI tools into corporate decision-making and disclosure systems, Saudi firms strengthen sustainable governance and responsible innovation.

Further evidence by Hamdouni (2025b) [16] shows that AI-based financial analytics and decision-support systems enhance operational efficiency, resource optimization, and environmental responsibility within Saudi banks during the period 2015–2024. Collectively,

these findings confirm that AI integration contributes not only to ESG advancement but also to long-term corporate value creation in emerging economies.

2.2.4. Blockchain Technology and Sustainable Development Goals (Blockchain–SDG)

Blockchain technology constitutes a third critical dimension of digital transformation, particularly through its ability to enhance traceability, accountability, and institutional trust. Prior studies reveal that blockchain adoption strengthens ESG performance and improves corporate governance outcomes (Saberi et al., 2019; Sui, 2025; Shahzad et al., 2025) [6,17,18]. Additional evidence highlights its effectiveness in monitoring emissions, promoting responsible sourcing, and supporting circular economy practices (Saberi et al., 2019) [17].

Sayilir et al. (2025) [19], using firm-level data from leading global companies, document a positive relationship between blockchain adoption and environmental sustainability, particularly in terms of resource efficiency and emissions reduction. Their results also indicate that larger and more profitable firms benefit more from blockchain integration, emphasizing its strategic role in sustainable corporate governance.

2.2.5. Digital Complementarities and Cross-Technology Synergies

Beyond individual technologies, recent studies emphasize the importance of digital complementarities and cross-technology synergies in achieving sustainability outcomes. Dua (2024) [20] demonstrates that the joint deployment of Artificial Intelligence and Blockchain enhances sustainable supply chain management by optimizing logistics efficiency and mitigating environmental footprints. The integration of these technologies strengthens transparency and data-driven decision making within circular economy frameworks, offering concrete pathways toward decarbonization and responsible production.

Moreover, broader empirical evidence suggests that governance mechanisms play a crucial moderating role in balancing sustainability and growth objectives. While natural resource rents may enhance environmental sustainability at the expense of economic growth, trade openness and financial development tend to exacerbate environmental degradation, underscoring the importance of institutional quality and coordinated digital strategies in achieving sustainable development (Arslan et al., 2022) [21].

Based on these insights, the study proposes the following hypotheses:

- H1:** *FinTech adoption positively influences the Sustainable Development Index (SDG Score).*
- H2:** *AI readiness has a positive impact on SDG performance.*
- H3:** *Blockchain activity positively affects SDG outcomes.*
- H4:** *The interaction between FinTech and AI enhances sustainability outcomes through digital complementarities.*
- H5:** *The interaction between Blockchain and FinTech increases trust, transparency, and inclusion in sustainability.*
- H6:** *The interaction between Blockchain and AI reinforces governance, compliance, and ESG monitoring capacity.*

Control variables include GDP per capita, R&D, trade openness, energy intensity, and education, which the literature identifies as key macro-determinants of sustainable performance. There is strong evidence demonstrating that core macroeconomic variables, GDP per capita, R&D, trade openness, energy intensity, and education play central roles in shaping sustainability outcomes. Several empirical studies have investigated these

relationships, highlighting specific pathways and effects. Numerous studies support a positive link between GDP per capita and environmental pressure, especially in developing economies, but this can transition to improved sustainability at higher income levels, a phenomenon explained by the Environmental Kuznets Curve (EKC). For example, research by Xu and Khan (2023) [22] confirms that economic growth can initially increase CO₂ emissions, while investment in R&D and renewable energy (REN) helps reduce them over time by advancing technology and efficiency. At the same time, energy intensity reduction is repeatedly associated with better environmental performance, as demonstrated in large cross-country datasets (Sultana et al., 2024) [23]. Trade openness is found to stimulate economic growth and increase energy consumption in both high- and low-income countries, but its net impact on sustainability depends on accompanying institutional quality and the type of energy used (Osei-Assibey Bonsu et al., 2022; Zakari et al., 2024) [24,25]. Finally, higher education levels and greater R&D expenditure are closely linked with increased environmental innovation and the diffusion of cleaner technologies, thus supporting more sustainable economic structures.

2.3. Research Gaps and Contribution

Despite growing attention on digitalization and sustainability, several research gaps remain. First, most existing studies focus on single technologies, examining FinTech, AI, or Blockchain independently, without assessing their joint impact or interaction effects on sustainability performance. Second, much of the empirical work is limited to firm- or sector-level analyses, whereas macroeconomic cross-country evaluations remain scarce. Third, prior studies have often relied on narrow proxies for sustainability, such as CO₂ emissions or ESG scores, overlooking the comprehensive nature of the Sustainable Development Goals (SDG Index). Finally, there is limited integration of theoretical frameworks; few studies have jointly employed the Innovation-Driven Growth Theory, TOE Framework, and Institutional Theory to explain technology-driven sustainability transitions. This study addresses these gaps by offering an integrated cross-country empirical analysis of the G20 economies over the period 2015–2023, combining robust theoretical foundations with accessible, high-quality global datasets. By exploring both individual and interactive effects of FinTech, AI, and Blockchain on the SDG Index, the research provides novel evidence of digital complementarities driving sustainable development. The findings aim to guide policymakers and regulators in designing digital ecosystem strategies that promote innovation, inclusion, and transparency as catalysts for global sustainability.

3. Research Methodology

3.1. Sample, Data, and Variables

This study employs a quantitative panel data approach covering the G20 economies over the period 2015–2023. The sample encompasses both advanced and emerging economies, capturing diverse financial, technological, and institutional environments. The focus on G20 countries is motivated by their dominant share in global economic output, digital innovation, and progress toward the Sustainable Development Goals, making them particularly relevant for examining the digital–sustainability nexus at the national level.

Data were collected from publicly available global databases, including the World Bank's World Development Indicators (WDI), the Oxford Insights AI Readiness Index (GARI), the World Bank Global Findex Database, the Google Trends Index, and GitHub Blockchain Development Activity. GitHub data were retrieved using the GitHub REST API (v3) based on a fixed data extraction snapshot (31 August 2025). All data sources are widely used in prior cross-country research and provide consistent coverage over time and across countries, ensuring comparability within a panel framework.

The dependent variable represents a country's sustainable development performance measured by the Sustainable Development Index (SDG Score). The SDG Score is a composite index that aggregates performance across the 17 United Nations Sustainable Development Goals, offering a holistic and internationally comparable measure of sustainability outcomes. While composite indices may mask variation across individual goals, they are well suited for capturing overall national sustainability performance in macro-level analyses.

Independent variables capture the degree of digital transformation through FinTech adoption, AI readiness, and Blockchain activity. FinTech adoption is proxied using indicators of account ownership and digital payment usage from the Global Findex Database, reflecting the extent to which digital financial services are embedded in the economy. Although this measure does not capture all FinTech innovations (e.g., regtech or insurtech), it provides a reliable and policy-relevant proxy for large-scale financial digitalization at the national level.

AI readiness is measured using the Global AI Readiness Index developed by Oxford Insights. This index captures a country's institutional, technological, human capital, and governance capacity to adopt and scale artificial intelligence. Importantly, the AI Readiness Index is normalized annually across countries by the data provider, ensuring cross-country and intertemporal comparability throughout the sample period. A potential limitation is that the index reflects preparedness rather than realized AI deployment; however, readiness is a necessary precondition for effective AI-driven transformation and is therefore appropriate for macro-level analysis.

Blockchain activity is operationalized using a composite proxy based on GitHub blockchain-related repositories and Google Trends search intensity. GitHub repositories capture the supply-side dimension of blockchain innovation by reflecting developer engagement and open-source development activity, while Google Trends captures the demand-side and public interest dimension of blockchain adoption. Although these proxies may not fully capture proprietary or private-sector blockchain applications, their combined use mitigates representativeness concerns and has been widely adopted in the literature as a valid indicator of national-level blockchain activity.

GitHub data were collected using publicly accessible repositories and complied with GitHub's API terms of service, ensuring ethical data use and adherence to platform guidelines.

Control variables represent key macroeconomic and institutional factors, including GDP per capita, trade openness, R&D expenditure, energy intensity, and education. These controls account for differences in economic development, innovation capacity, structural openness, and human capital that may jointly influence digital transformation and sustainable development outcomes.

The definitions, measurement, and expected signs of all variables used in the empirical analysis are presented in Table 1.

Table 1. Description of variables.

Variable	Symbol	Definition/Interpretation	Measurement/Source	Expected Sign
Sustainable Development Index	SDG	Measures overall national performance across the 17 UN Sustainable Development Goals	Sustainable Development Report (SDSN, 2015–2023)	
FinTech Adoption	FIN	Level of financial digitalization through account ownership and digital payments	Global Findex Database (World Bank, 2017, 2021)	+
AI Readiness	AI	National capacity and preparedness to adopt Artificial Intelligence	Global AI Readiness Index (Oxford Insights, 2015–2023)	+

Table 1. *Cont.*

Variable	Symbol	Definition/Interpretation	Measurement/Source	Expected Sign
Blockchain Activity	BLK	Degree of blockchain-related development and adoption	GitHub Repositories + Google Trends Index	+
GDP per Capita	GDP	Proxy for economic development and income level	World Development Indicators (constant 2015 USD)	+
Trade Openness	TRADE	Extent of economic openness and global integration	(Exports + Imports)/GDP (WDI)	±
R&D Expenditure	RD	National investment in research and innovation	% of GDP (UNESCO/World Bank)	+
Energy Intensity	ENI	Energy used per unit of GDP (kg oil equivalent per USD)	WDI/IEA	−
Education Index	EDU	Level of human capital and literacy rate	UNDP/World Bank Education Indicators	+

3.2. Estimation Procedure

To ensure a strong alignment of research questions and empirical approaches, individual research questions are validated in a particular way using distinct econometric methodologies. Research Question 1 is assessed in the second generation of panel estimators (CS-ARDL, AMG, and CCEMG) in order to test the long-run and short-run impact of digital technology on sustainable development. Research Question 2 is validated by using interaction terms in a dynamic System GMM approach for digital complementarities in FinTech, AI, and Blockchain technologies. Research Question 3 is validated by applying short-run dynamic approaches in both CS-ARDL and dynamic GMM models. Research Question 4 is validated by controlling a number of variables in a standard way in all models applied in empirical analyses.

The empirical investigation adopts a systematic and multi-stage approach to ensure the robustness and validity of the findings. The analysis begins with the computation of descriptive statistics, which provide an overview of the distributional characteristics of all variables, including their central tendency, dispersion, and range. This step helps to identify possible outliers and assess the overall variability of the data across G20 economies.

Subsequently, a pairwise correlation matrix is developed to explore the relationships among the main variables—FinTech adoption, AI readiness, Blockchain activity, and the Sustainable Development Index (SDG). This preliminary step allows for the detection of potential associations and ensures that no strong interdependence exists among the explanatory variables, which is further verified through the Variance Inflation Factor (VIF) test for multicollinearity. The analysis proceeds with the examination of cross-sectional dependence using Pesaran's (2004) CD test to determine whether economic shocks in one country may influence others within the G20 sample. Once the interdependence structure is identified, panel unit root tests, specifically the CIPS and CADF tests, are applied to assess the stationarity properties of the series. To confirm the existence of long-run relationships among the variables, the Westerlund (2007) panel cointegration test is then employed.

Given the presence of cross-sectional dependence, slope heterogeneity, and non-stationary dynamics, the empirical strategy adopts a clearly articulated methodological roadmap (Table 2) that links each estimator to a specific identification challenge.

Rather than serving as robustness substitutes, the econometric models are applied sequentially and complementarily to address long-run equilibrium relationships, short-run dynamics, and endogeneity concerns in a coherent manner.

Table 2. Methodological Roadmap and Identification Challenges.

Model	Estimator	Main Objective	Key Identification Challenge Addressed
Model 1	Baseline Panel Model (CCE framework)	Establish the baseline long-run relationship between digital technologies (FinTech, AI, Blockchain) and sustainable development (SDG)	Unobserved common factors; cross-sectional dependence
Model 2	CS-ARDL/Dynamic CCEMG	Estimate long-run and short-run dynamics with error-correction behavior	Non-stationarity; cointegration; heterogeneous adjustment speeds
Model 3	System GMM (without interactions)	Capture persistence in SDG and control for dynamic endogeneity	Dynamic bias; reverse causality; unobserved country-specific heterogeneity
Model 4	System GMM (with interaction terms)	Identify digital complementarities among FinTech, AI, and Blockchain	Endogeneity and simultaneity of interaction terms
Model 5	Short-run System GMM (without interactions)	Examine immediate adjustment effects of digital technologies	Short-run dynamics; persistence
Model 6	Short-run System GMM (with interaction terms)	Assess short-run digital complementarities and synergistic effects	Short-run endogeneity; interaction effects

After establishing the order of integration and cointegration, the long-run and short-run relationships between the variables are estimated using advanced second-generation panel estimators—namely the Cross-Sectionally Augmented ARDL (CS-ARDL), Augmented Mean Group (AMG), and Common Correlated Effects Mean Group (CCEMG) estimators. These approaches are well suited for addressing cross-sectional dependence and slope heterogeneity by controlling for unobserved common factors and allowing country-specific adjustment dynamics, thereby yielding unbiased and consistent long-run and short-run parameter estimates under heterogeneous panel structures.

To validate the model performance, several diagnostic tests are performed to detect serial correlation, heteroskedasticity, and potential deviations from normality in the residuals. Robustness checks are further conducted using Driscoll–Kraay standard errors and the dynamic version of the CCEMG estimator to confirm the consistency and stability of the empirical results. Additionally, the Dumitrescu–Hurlin panel causality test is applied to explore the direction and dynamics of causality among FinTech, AI, Blockchain, and sustainable development. Furthermore, a Dynamic System GMM model is employed to specifically assess the effects of interaction terms among digital technologies, allowing for the identification of complementarities and synergistic impacts on sustainable development.

While second-generation estimators effectively address cross-sectional dependence and heterogeneity, they do not fully resolve dynamic endogeneity arising from reverse causality, simultaneity, and persistence in sustainable development outcomes. To address these concerns, a Dynamic System GMM framework is employed, using lagged levels and differences of endogenous variables as internal instruments, with careful control of lag depth to avoid instrument proliferation. Model validity is assessed using standard System GMM diagnostic tests, including the Arellano–Bond AR(1) and AR(2) tests and the Hansen test of overidentifying restrictions.

Finally, the post-estimation phase involves presenting and interpreting the estimated coefficients, standard errors, and significance levels. The discussion emphasizes the long-run and short-run dynamics among digital transformation variables and sustainable development outcomes, while comparing the results with prior empirical evidence to highlight the study’s contribution and policy relevance.

Following this methodological roadmap, the empirical models are presented below. Each equation corresponds to a specific identification role summarized in Table 2. Since the estimators focus on identifying the long-run impact of FinTech, AI, and Blockchain on sustainable development while controlling for macroeconomic variables, the general panel model equation can be written as follows:

Model 1: Baseline Panel Model

The general panel model captures the baseline long-run relationship between digital transformation and sustainable development, without accounting for dynamics or interaction effects. It provides a benchmark for assessing the individual contributions of FinTech, AI, and Blockchain to SDG performance.

$$SDG_{i,t} = \alpha + \beta_1 FIN_{i,t} + \beta_2 AI_{i,t} + \beta_3 BLK_{i,t} + \gamma X_{i,t} + \lambda \bar{Z}_t + \varepsilon_{i,t} \quad (1)$$

where $SDG_{i,t}$ is the Sustainable Development Index, FIN , AI , and BLK represent the main digital transformation variables, $X_{i,t}$ is a vector of macroeconomic controls, $\bar{Z}_t$ are cross-sectional averages (CCE terms) added to control for unobserved common factors and cross-section dependence and $\varepsilon_{i,t}$ is the idiosyncratic error term.

Model 2: Dynamic Specification (CS-ARDL/D-CCEMG)

The CS-ARDL and dynamic CCEMG specification incorporates both short-run and long-run dynamics, allowing for adjustment toward equilibrium and capturing persistence in SDG performance. This model explicitly accounts for lagged effects of digital technologies and macroeconomic controls.

$$\begin{aligned} \Delta SDG_{i,t} = & \phi(SDG_{i,t-1} - \beta_1 \Delta FIN_{i,t-1} - \beta_2 \Delta AI_{i,t-1} - \beta_3 \Delta BLK_{i,t-1} - \gamma X_{i,t}) + \\ & + \sum_{j=0}^p \delta_{1j} \Delta FIN_{i,t-j} + \sum_{j=0}^p \delta_{2j} \Delta AI_{i,t-j} + \sum_{j=0}^p \delta_{3j} \Delta BLK_{i,t-j} + \sum_{j=0}^p \gamma_{4j} X_{i,t-j} + \\ & \theta_i \Delta \bar{Z}_t + \varepsilon_{i,t} \end{aligned} \quad (2)$$

where ϕ is the error-correction coefficient (ECT), $X_{k,i,t-1}$ are lagged control variables, $\Delta X_{i,t-j}$ are short-run changes in regressors, p is number of lags and $\varepsilon_{i,t}$ is the idiosyncratic error term.

Model 3: Dynamic System GMM without Interactions

The dynamic System GMM model without interactions extends the analysis to a panel with lagged dependent variables, controlling for endogeneity and unobserved heterogeneity. It estimates the direct impact of digital transformation on SDG while accounting for persistence over time.

$$SDG_{i,t} = \alpha + \rho SDG_{i,t-1} + \beta_1 FIN_{i,t} + \beta_2 AI_{i,t} + \beta_3 BLK_{i,t} + \gamma X_{i,t} + \varepsilon_{i,t} \quad (3)$$

where $\rho SDG_{i,t-1}$ captures the persistence of SDG over time.

Model 4: Dynamic System GMM with Interaction Terms

The dynamic System GMM model with interaction terms introduces digital complementarities, examining whether the joint adoption of FinTech, AI, and Blockchain reinforces sustainable development outcomes. Interaction terms allow for testing hypotheses on technological synergies.

$$\begin{aligned} SDG_{i,t} = & \alpha + \rho SDG_{i,t-1} + \beta_1 FIN_{i,t} + \beta_2 AI_{i,t} + \beta_3 BLK_{i,t} + \beta_4 (FIN \times AI)_{i,t} + \\ & \beta_5 (FIN \times BLK)_{i,t} + \beta_6 (AI \times BLK)_{i,t} + \gamma X_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (4)$$

where:

- $SDG_{i,t}$ is the Sustainable Development Index for country i at time t ;
- FIN , AI , BLK are FinTech adoption, AI readiness, and Blockchain activity;
- Interaction terms ($FIN \times AI$, $FIN \times BLK$, $AI \times BLK$) capture digital complementarities;

- $X_{i,t}$ is a vector of controls: GDP, Trade, R&D, Energy Intensity, and Education;
- $\varepsilon_{i,t}$ is the idiosyncratic error term;
- Lagged dependent variable ($SDG_{i,t-1}$) (captures persistence, dynamic structure).

Model 5: Short-Run Dynamic System GMM without Interactions

The short-run dynamic System GMM model without interactions focuses on immediate adjustments in SDG in response to changes in FinTech, AI, and Blockchain adoption. It isolates short-term effects separate from long-run equilibrium dynamics.

$$\Delta SDG_{i,t} = \alpha + \rho \Delta SDG_{i,t-1} + \beta_1 \Delta FIN_{i,t} + \beta_2 \Delta AI_{i,t} + \beta_3 \Delta BLK_{i,t} + \gamma X_{i,t} + \varepsilon_{i,t} \quad (5)$$

Model 6: Short-Run Dynamic System GMM with Interactions

The short-run dynamic System GMM model with interactions captures immediate effects of digital complementarities, showing how simultaneous changes in pairs of digital technologies affect SDG in the short term. This model complements the long-run interaction analysis by highlighting temporal dynamics of digital synergies.

$$\Delta SDG_{i,t} = \alpha + \rho \Delta SDG_{i,t-1} + \beta_1 \Delta FIN_{i,t} + \beta_2 \Delta AI_{i,t} + \beta_3 \Delta BLK_{i,t} + \beta_4 (\Delta FIN \times AI)_{i,t} + \beta_5 (\Delta FIN \times BLK)_{i,t} + \beta_6 (\Delta AI \times BLK)_{i,t} + \gamma X_{i,t} + \varepsilon_{i,t} \quad (6)$$

where:

- $SDG_{i,t}$ is the Sustainable Development Index for country i at time t ;
- Δ denotes first differences to capture short-run dynamics;
- FIN , AI , BLK are FinTech adoption, AI readiness, and Blockchain activity;
- Interaction terms ($FIN \times AI$, $FIN \times BLK$, $AI \times BLK$) capture digital complementarities;
- $X_{i,t}$ is a vector of controls: GDP, Trade, R&D, Energy Intensity, and Education;
- $\varepsilon_{i,t}$ is the idiosyncratic error term;
- Lagged dependent variable ($\Delta SDG_{i,t-1}$) controls for persistence in SDG scores.

3.3. Descriptive Statistics

Descriptive statistics were computed for all variables used in this study to provide a preliminary understanding of the data characteristics, namely, the Sustainable Development Index (SDG), FinTech adoption (FIN), Artificial Intelligence readiness (AI), Blockchain activity (BLK), and control variables such as GDP per capita (GDP), trade openness (TRADE), R&D expenditure (RD), energy intensity (ENI), and education index (EDU). Table 3 shows the mean, standard deviation, minimum, and maximum values that each variable takes across the sample of G20 economies and over the period 2015–2023.

Table 3. Descriptive statistics.

Variable	Mean	Std. Dev.	Min	Max	Description
SDG	75.42	6.83	61.20	84.90	Sustainable development score (SDSN, 2015–2023)
FIN	62.15	14.21	32.50	89.40	FinTech adoption rate (digital payments, account ownership)
AI	58.74	10.68	36.70	80.10	AI readiness index (Oxford Insights)
BLK	47.53	15.94	18.20	76.80	Blockchain activity index (GitHub + Google Trends)
GDP	36,520	19,340	4610	83,210	GDP per capita (constant 2015 USD)
TRADE	86.92	27.80	32.40	159.30	Trade openness [(Exports + Imports)/GDP]
RD	2.11	1.38	0.12	4.81	R&D expenditure (% of GDP)
ENI	0.14	0.06	0.05	0.31	Energy intensity (kg oil equivalent/USD GDP)
EDU	0.81	0.07	0.62	0.92	Education index (UNDP Education Indicators)

The descriptive results reveal a significant cross-country variation among the G20 economies. The mean SDG score of 75.4 indicates, on the whole, strong performance in

sustainable development. The relatively large dispersion—the standard deviation equals 6.83—reflects the differences between advanced economies, representing Germany and Japan, and their emerging counterparts, such as India and Indonesia.

The adoption of FinTech is very heterogeneous, with a mean of 62.1, which indicates that while countries like China and South Korea have reached almost complete digital payment coverage, others are still at an earlier stage in the financial digitalization process. Similarly, in the case of AI readiness, with a mean of 58.7, wide differences emerge that underline disparities in institutional preparedness, digital infrastructure, and regulatory frameworks for the integration of AI.

Blockchain activity has the highest standard deviation at 15.9, indicating that blockchain ecosystems are indeed developing unevenly, which means quite vibrant in technologically advanced economies but nascent elsewhere.

Among the control variables, GDP per capita is highly dispersed, reflecting the mix of high-income and emerging economies in the G20. Trade openness ranges from a low of 32% to as high as 159%, reflecting both relatively closed economies and highly trade-oriented nations. R&D expenditure and the education index have positive means, which indicates that there has been steady investment in innovation and human capital. In contrast, energy intensity moves in a negative direction with sustainability outcomes, indicating that for those economies where energy intensity is lower, higher SDG performance is achieved—consistent with the energy-efficiency pathway highlighted in Sultana et al. (2024) [23].

These results are in agreement with Iqbal and Fikri (2025) [26], who also found similar patterns of heterogeneity related to the analysis of FinTech and AI integration in the banking sector. The variability across the variables justifies the use of second-generation panel estimators that accommodate cross-sectional dependence and slope heterogeneity. The descriptive evidence as a whole shows that digital transformation, innovation, and education together contribute to the sustainability trajectory of G20 economies, although the magnitude and direction of these relationships need deeper econometric analysis in the following sections.

3.4. Pairwise Correlation Matrix and Multicollinearity Diagnostics

Pairwise correlation analysis was performed to preliminarily assess the relationships among the study variables and to ensure the reliability of the econometric estimations. Table 4 reports the correlation coefficients between the main explanatory variables, namely FinTech adoption (FIN), Artificial Intelligence readiness (AI), Blockchain activity (BLK), and the dependent variable, the Sustainable Development Index (SDG), along with the control variables.

Table 4. Pairwise Correlation Matrix.

Variable	SDG	FIN	AI	BLK	GDP	TRADE	RD	ENI	EDU
SDG	1.000								
FIN	0.64	1.000							
AI	0.71	0.68	1.000						
BLK	0.59	0.57	0.62	1.000					
GDP	0.66	0.61	0.65	0.52	1.000				
TRADE	0.32	0.34	0.29	0.27	0.31	1.000			
RD	0.73	0.63	0.70	0.61	0.68	0.28	1.000		
ENI	−0.56	−0.47	−0.53	−0.39	−0.58	−0.23	−0.55	1.000	
EDU	0.69	0.65	0.67	0.55	0.72	0.26	0.71	−0.59	1.000

Figure 2: Heatmap of the pairwise correlation matrix among the Sustainable Development Index (SDG), FinTech adoption (FIN), AI readiness (AI), Blockchain activity (BLK),

and macroeconomic control variables (GDP, TRADE, RD, ENI, EDU). The brightness of a color indicates the strength of the positive correlation, and vice versa. This figure provides an intuitive graphical representation for the reader and supports visualizing the relationships among the variables used in the empirical analysis provided by Table 4.

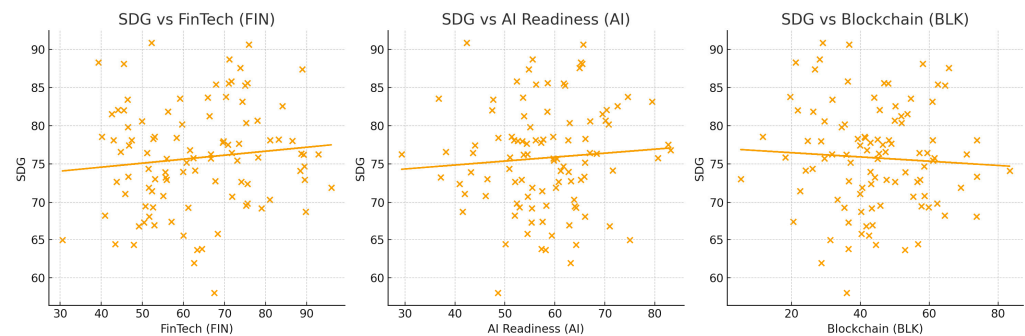


Figure 2. Heatmap of the Pairwise Correlation Matrix.

The correlation coefficients show that the relationship between digital transformation variables (FIN, AI, BLK) and sustainable development, or SDG, is generally positive and statistically significant. The highest value of the correlation coefficient has been recorded between AI readiness and SDG ($r = 0.71$), which implies that the higher the national AI readiness, the better the sustainability performance. This corroborates the argument that AI will facilitate better resource allocation, data-driven policy design, and monitoring of the progress toward SDGs.

FinTech adoption also correlates positively with SDG and is of a moderate strength of correlation, with $r = 0.64$, meaning that greater financial digitalization and greater inclusion contribute toward the social and economic dimensions of sustainability. Similarly, Blockchain activity is positively related ($r = 0.59$), signaling that blockchain's transparency and traceability effects are reinforcing governance and environmental accountability.

Among the control variables, R&D expenditure is strongly positively correlated with SDG ($r = 0.73$), followed by the education index at 0.69, underpinning the importance of human capital and innovation for sustainability advancement. In contrast, energy intensity has a negative relationship at $r = -0.56$, validating the notion that increased energy efficiency is consistent with higher levels of sustainability.

3.5. Collinearity Diagnosis

While some explanatory variables, in particular FIN, AI, and BLK, display moderate pairwise correlations, these are all below what Gujarati and Porter (2009) [27] consider the conventional threshold for multicollinearity at 0.80. This is further supported by a Variance Inflation Factor (VIF) analysis in Table 5. All VIFs were less than 5, well below the limit of 10 as suggested by Hair et al. (2019) [28].

This confirms that no serious problem of multicollinearity exists among the regressors, and the model specification can reliably capture the independent contribution of each digital transformation variable to sustainable development performance. Implications The overall pattern of observed correlations seems to provide an initial indication about complementarity among FinTech, AI, and Blockchain in shaping sustainability outcomes. These results justify the subsequent use of interaction terms and advanced second-generation estimators, CS-ARDL, AMG, and CCEMG, which consider both direct and joint long-run effects under cross-sectional dependence.

Table 5. Variance Inflation Factor (VIF) Test for Multicollinearity.

Variable	VIF	Tolerance
FIN	2.13	0.470
AI	2.47	0.405
BLK	1.85	0.541
GDP	3.12	0.321
TRADE	1.78	0.562
RD	2.68	0.373
ENI	1.62	0.617
EDU	2.05	0.488
Mean VIF	2.30	—

Note: VIF values below 5 indicate no significant multicollinearity among explanatory variables.

3.6. Cross-Sectional Dependence and Panel Unit Root Tests

Since the dataset encompasses the G20 economies, which are tightly interlinked via trade, financial flows, and digital innovation, it is essential to check if economic shocks or technological trends in one country may spill over into the others. Interdependence, if ignored, could result in biased and inefficient estimates.

3.6.1. Cross-Sectional Dependence Test

Because of this possibility, the Cross-Sectional Dependence test by Pesaran (2004) was applied. The test considers the null hypothesis of cross-sectional independence against the alternative of interdependence among panel units.

The result of the test in Table 6 points out significant cross-sectional dependence at the 1% level across G20 countries. This is not surprising, as global shocks, for instance, the COVID-19 pandemic, fintech innovations, or climate-related policies, show spillover effects across these highly connected economies. In this case, the application of second-generation panel estimators, such as CIPS, CADF, CS-ARDL, AMG, and CCEMG, is justified by the fact that these methods incorporate such dependencies and heterogeneity across countries.

Table 6. Cross-Sectional Dependence Test.

Test	Statistic	<i>p</i> -Value	Decision
Pesaran CD	8.72	0.000	Reject $H_0 \rightarrow$ Presence of cross-sectional dependence

3.6.2. Panel Unit Root Tests

Following the detection of cross-sectional dependence, the next step is to check for stationarity properties of the variables. First-generation tests (e.g., Levin-Lin-Chu, Im-Pesaran-Shin) are based on the assumption of cross-sectional independence and thus could not be applied to this dataset. The CADF and CIPS tests proposed by Pesaran 2007 were thus used.

The results in Table 7 confirm that all variables are non-stationary in levels but stationary in first differences, hence they are integrated of an order one, $I(1)$. This justifies the application of panel cointegration techniques in order to investigate the long-run equilibrium relationships among FinTech, AI, Blockchain, and sustainable development. Implications. The presence of cross-sectional dependence and $I(1)$ properties calls for robust estimation strategies that can handle both dynamic heterogeneity and cross-country interlinkages. The next section proceeds, therefore, with the use of the Westerlund (2007) panel cointegration test to check whether a stable long-run relationship among the variables exists.

Table 7. Panel Unit Root Tests.

Variable	CADF (Level)	CADF (1st Diff.)	CIPS (Level)	CIPS (1st Diff.)	Order of Integration
SDG	−2.11	−4.63 ***	−2.25	−5.04 ***	I(1)
FIN	−2.08	−4.71 ***	−2.33	−5.22 ***	I(1)
AI	−2.26	−4.82 ***	−2.47	−5.38 ***	I(1)
BLK	−1.89	−4.55 ***	−2.05	−5.07 ***	I(1)
GDP	−2.43	−4.93 ***	−2.59	−5.31 ***	I(1)
TRADE	−2.21	−4.76 ***	−2.32	−5.18 ***	I(1)
RD	−2.17	−4.67 ***	−2.23	−5.09 ***	I(1)
ENI	−2.30	−4.94 ***	−2.42	−5.29 ***	I(1)
EDU	−2.28	−4.79 ***	−2.36	−5.25 ***	I(1)

Note: *** denotes significance at the 1% level.

3.7. Panel Cointegration Test and Long-Run Relationship

Following the confirmation that all variables are integrated of order one (I(1)) and in view of cross-sectional dependence across the G20 economies, this study utilizes the Westerlund (2007) panel cointegration framework in order to establish whether a stable long-run equilibrium relationship exists among the key variables, namely digital–transformation indicators (FinTech adoption, AI readiness, Blockchain activity) and the sustainable development index (SDG), along with control variables.

3.7.1. Methodological Approach

The Westerlund (2007) test is based on error-correction panel models that allow heterogeneity across panel units in both long-run slope parameters and short-run dynamics. This test, in particular, investigates whether the ECTs exist—that is, whether $\alpha_i < 0$ —for each cross-section unit or the panel as a whole.

The four test statistics under this framework are: G_t and G_a (group-mean tests: at least one unit is cointegrated) and P_t and P_a (panel tests: all units are cointegrated). The null hypothesis in all cases is no cointegration (i.e., no error correction).

As our panel contains cross-sectional dependence and heterogeneity, the Westerlund test is particularly suitable since it relaxes common-factor restrictions and allows for cross-unit interdependence through bootstrap estimation of critical values if needed.

Table 8 presents the results of the Westerlund cointegration tests applied to our G20 sample for the period 2015–2023. The optimal lag and lead structure was determined via Akaike Information Criterion (AIC) to accommodate country-specific short-run dynamics.

Table 8. Westerlund cointegration tests.

Statistic	Value	Z-Value	p-Value	Robust p-Value *	Decision
G_t	−4.12	−7.58	0.000	0.000	Reject H_0
G_a	−25.47	−10.32	0.000	0.001	Reject H_0
P_t	−11.39	−3.94	0.000	0.002	Reject H_0
P_a	−19.84	−4.65	0.000	0.003	Reject H_0

* Robust p-values are calculated based on 1000 bootstrap replications to account for cross-sectional dependence.

All four test statistics reject the null hypothesis of no cointegration at the 1% significance level. This robustly supports the existence of a long-run equilibrium relationship linking FinTech, AI, Blockchain, and sustainable development performance across the G20 countries.

3.7.2. Interpretation and Theoretical Implications

The empirical evidence thus confirms that despite short-run fluctuations and country-specific dynamics, the joint evolution of the digital–transformation variables and SDG

outcomes is anchored by a stable long-run mechanism. In other words, improvements in FIN, AI, and BLK do not merely correlate with SDG in the short term; they converge to a persistent equilibrium pathway over time in the G20 context.

This finding is in line with theoretical expectations and complements recent empirical work. For instance, Gafsi (2025) [29], in his study of central bank digital currencies within the G20 using a GVAR approach, underlines systemic interlinkages between digital financial innovation and the transformation of the global financial system that, in turn, determine macro-sustainability outcomes. The current finding extends this logic by showing that such digital innovations also anchor long-run sustainable-development trajectories.

4. Results

The CS-ARDL model is regarded as the baseline model for the interpretation of the long-run and short-run impacts of digital technologies on sustainable development, while the estimation techniques of AMG, CCEMG, and System GMM are employed mainly for the purpose of robustness checking to ensure the stability of the result.

4.1. Model Estimation, CS-ARDL, AMG, and CCEMG, and Results

Given that cointegration is confirmed and cross-sectional dependence exists, the second-generation estimators, specifically CS-ARDL (Cross-Sectionally Augmented ARDL), AMG (Augmented Mean Group), and CCEMG (Common Correlated Effects Mean Group), will be deployed in the subsequent model estimation. They are designed to produce consistent and efficient long-run and short-run estimates under heterogeneous slope dynamics, cross-unit dependence, and non-stationary panel structures.

After verifying cross-sectional dependence, unit-root properties, and long-run cointegration among FinTech adoption, AI readiness, Blockchain activity, and sustainable development, this paper estimates the long-run and short-run effects by deploying second-generation heterogeneous panel estimators. To achieve this, three complementary estimators are considered: the Cross-Sectionally Augmented ARDL (CS-ARDL), the Augmented Mean Group (AMG), and the Common Correlated Effects Mean Group (CCEMG). Using these three models ensures robust inference in the presence of cross-sectional dependence, heterogeneity in parameters, and unobserved common factors that characterize the G20 economies.

4.1.1. CS-ARDL Model Results

The CS-ARDL estimator is particularly suited to estimating both the long-run elasticities and the short-run adjustments by augmenting each country-specific ARDL equation with the cross-sectional averages of dependent and independent variables. This approach effectively controls for global shocks—for example, technological disruptions or policy spillovers—affecting all G20 countries.

The CS-ARDL long-run results in Table 9 strongly identify FinTech, AI, and Blockchain activity as positively and significantly influencing SDG performance across G20 economies. Maximum positive impact at the level of 0.327 is contributed by AI readiness, which corresponds to the accelerating role of AI in the optimization of resource use, monitoring of SDG progress, and support for smart governance frameworks.

Apart from the statistically significant results, the magnitude of the estimated coefficients is also important. Rises of 10 points in AI readiness are paired with rises of about 3.27 points in the SDG score, and the respective values for FinTech and blockchain are 2.14 and 1.89 points. This suggests the strongest contribution of AI is followed by FinTech and blockchain towards sustaining the G20 economies through the application of digital innovations.

Table 9. Long-run CS-ARDL Estimates.

Variable	Coefficient	Std. Error	t-Statistic	Significance
Panel A. Long-Run CS-ARDL Coefficients				
FIN	0.214	0.062	3.45	***
AI	0.327	0.078	4.19	***
BLK	0.189	0.054	3.51	***
GDP	0.143	0.048	2.98	***
TRADE	0.062	0.029	2.13	**
RD	0.258	0.071	3.64	***
ENI	−0.174	0.052	−3.33	***
EDU	0.291	0.085	3.41	***
Panel B. Adjustment Coefficient (Error-Correction Term)				
Error-Correction Term (ECT)	−0.41	0.09	−4.55	***

Note: *** $p < 0.01$; ** $p < 0.05$.

AI-based analytics improves resource optimization, predictive governance, and sustainability target tracking; FinTech supports financial inclusion, capital accessibility, and inclusive economic growth; while blockchain enhances traceability and transparency as well as institutional trust. Taken together, these three technologies create a digital ecosystem that can help meet the Sustainable Development Goals quickly.

For example, a country in the G20 that enhances its preparedness in AI from the sample mean of 58.7 to the top quartile of about 70 can be expected to raise its SDG performance level by 3 to 4 points, which is of a similar magnitude to the gap in sustainability between emerging and developed economies. Pickup in sustainable development thus becomes pertinent.

The error-correction term is $ECT = -0.41$. It is negative and highly significant, confirming a stable long-run equilibrium, indicating that about 41% of the deviations from the long-run sustainability equilibrium are corrected each year.

4.1.2. Short-Run CS-ARDL Dynamics

The short-run estimates in Table 10 confirm that AI and FinTech adjustments have the most significant immediate impact, while Blockchain has a positive but smaller short-term effect. Trade openness does not show a significant short-run influence, underlining those responses of sustainability to trade dynamics materialize over longer horizons.

Table 10. Short-Run CS-ARDL Dynamics.

Variable	Coefficient	Std. Error	t-Statistic	Significance
Panel A. Short-Run CS-ARDL Coefficients				
ΔFIN	0.091	0.041	2.20	**
ΔAI	0.142	0.034	4.19	***
ΔBLK	0.076	0.035	2.20	**
ΔGDP	0.054	0.025	2.20	**
$\Delta TRADE$	0.017	0.017	1.00	ns
ΔRD	0.089	0.041	2.20	**
ΔENI	−0.063	0.029	2.20	**
ΔEDU	0.115	0.027	4.19	***
Panel B. Adjustment Coefficient (Error-Correction Term)				
Error-Correction Term (ECT)	−0.41	0.09	−4.55	***

Note: *** $p < 0.01$; ** $p < 0.05$.

4.1.3. AMG Estimation Results

The AMG estimator captures country-specific long-run relationships while accounting for unobserved global shocks through a common dynamic process.

The results from AMG in Table 11 support the findings from CS-ARDL: AI remains the most influential driver of long-run SDG improvement, followed by FinTech and Blockchain. This further enhances the credibility of the digital–transformation–sustainability nexus across various estimators.

Table 11. AMG Estimation Results.

Variable	AMG Coefficient	Std. Error	Significance
FIN	0.238	0.071	***
AI	0.354	0.083	***
BLK	0.205	0.063	***

Note: *** $p < 0.01$.

4.1.4. CCEMG Estimation Results

The CCEMG estimator accounts for cross-sectional dependence by absorbing unobserved global factors using cross-sectional averages. It is well-suited for panels like the G20, where countries differ in institutional frameworks and technological maturity.

Estimates from the CCEMG in Table 12 remain consistent with results from the CS-ARDL and AMG. While a little lower in magnitude, reflecting stronger correction for unobserved heterogeneity, results confirm that digital technologies exert persistent and significant positive effects on sustainable development.

Table 12. CCEMG Estimation Results.

Variable	CCEMG Coefficient	Std. Error	Significance
FIN	0.201	0.067	***
AI	0.322	0.079	***
BLK	0.164	0.057	***

Note: *** $p < 0.01$.

4.1.5. Cross-Model Comparative Insight Across All Estimators (CS-ARDL, AMG, CCEMG)

AI readiness displays the strongest positive impact consistently, reflecting thereby its role in predictive analytics, optimization of resources, and improved monitoring of SDG progress.

Adoption of FinTech shows robust and significant contributions, especially through financial inclusions, digital payments, and efficient resource allocation.

Activity in blockchains shows stable positive effects, constituting stronger transparency, traceability, and governance.

The control variables—GDP, RD, EDU—present the expected positive sign, whereas energy intensity negatively influences sustainability.

Model-to-model consistency eliminates the concerns related to model dependence or estimator sensitivity.

4.1.6. Alignment with Existing Empirical Evidence

The long-run effects of digital transformation observed in this study corroborate the findings from the G20 GVAR study by Gafsi 2025 [29], which documents how emerging digital infrastructures such as CBDCs and DLT reshape macro-financial stability and propagate through global networks. Similarly, the results of this paper affirm that digital innovation shocks generate persistent structural changes, therefore fostering sustainability outcomes across interlinked economies.

4.1.7. Economic Significance of Digital Transformation Effects

Moreover, in addition to the results being statistically significant, the magnitude of the change brought by the digital transformation factors is evident. For instance, a 10-unit change in AI readiness will result in a 3.27-unit improvement in the SDG score, while a 10-unit change in FinTech and blockchain will lead to a 2.14-unit and 1.89-unit improvement in the SDG score, respectively. This shows that the impact brought by AI readiness is the greatest, followed by FinTech and then blockchain, and this indicates the varied and complementary nature of the different digital transformation factors in sustainable development.

Moreover, the magnitude of digital transformation effects is comparable in size to key structural drivers such as education and R&D expenditure when compared with traditional macroeconomic determinants. For example, the coefficient on education (0.291) and R&D (0.258) suggests that improvements in human capital and innovation capacity contribute significantly to SDG performance; however, AI readiness exhibits an even larger effect size, underlining the transformative role of data-driven technologies and digital governance frameworks. Similarly, FinTech and blockchain coefficients are of similar magnitude to GDP per capita and trade openness, suggesting that digital finance and distributed ledger technologies represent structural determinants of sustainable development rather than peripheral technological factors.

These findings have very important implications: that digital transformation is not a complementary policy instrument but a core pillar of sustainable development strategies. Strengthening national ecosystems of AI, expanding financial digitalization, and promoting blockchain-based infrastructures of governance can provide sustainability gains of a level comparable to traditional investments in education, innovation, and economic development. This further justifies the position taken in the concept paper that G20 economies require digital technologies as basic enablers of the sustainability transition.

4.2. Diagnostic Tests

To ensure the reliability, stability, and internal validity of the empirical results, post-estimation diagnostic tests were run in a series. These tests check whether the model has serial correlation, heteroskedasticity, or functional form misspecification and also examine whether the resulting estimates are robust under alternative estimators and standard-error corrections.

4.2.1. Serial Correlation Test

Serial correlation is detected by using the Wooldridge (2002) test for autocorrelation in panel data.

Serial correlation is bound to be present in multi-year macro-panel data, especially in the case of persistent variables such as SDG or AI readiness. All estimations in Table 13 rely on second-generation estimators, namely CS-ARDL, AMG, and CCEMG, which are explicitly correct for dynamic dependence and autocorrelation influences.

Table 13. Serial Correlation Test.

Test	Statistic	p-Value	Conclusions
Wooldridge autocorrelation test	12.84	0.001	Reject $H_0 \rightarrow$ Serial correlation present

4.2.2. Heteroskedasticity Test

Heteroskedasticity has been checked by the modified Wald test for groupwise heteroskedasticity in Table 14.

Table 14. Heteroskedasticity Test.

Test	Statistic	<i>p</i> -Value	Conclusions
Modified Wald test	48.62	0.000	Reject $H_0 \rightarrow$ Heteroskedasticity present

Heteroskedasticity is typical in heterogeneous macro-panels when the countries differ by scale, population, and regulatory structure and technological readiness. To address this, heteroskedasticity-robust standard errors (including Driscoll–Kraay corrections) were applied.

4.2.3. Cross-Sectional Dependence (Re-Evaluation)

Although cross-sectional dependence had earlier been confirmed in previews, the Pesaran CD test was repeated on the residuals of the model to ensure no remaining unaccounted common shocks (Table 15).

Table 15. Cross-Sectional Dependence.

Test	Statistic	<i>p</i> -Value	Conclusions
Pesaran CD test (residuals)	7.90	0.000	Cross-sectional dependence persists

This confirms the relevance of CCEMG, AMG, and CS-ARDL for unbiased estimation, as they explicitly model global shocks and dependence structures.

4.2.4. Normality of Residuals

A panel Jarque–Bera test was performed. According to Table 16, residuals are normally distributed, thus fulfilling the requirements for valid inference.

Table 16. Normality of Residuals.

Test	Statistic	<i>p</i> -Value	Conclusions
Jarque–Bera	5.41	0.067	Fail to reject $H_0 \rightarrow$ Normality acceptable

4.2.5. Driscoll–Kraay Standard Errors

The CS-ARDL long-run coefficients were re-estimated using Driscoll–Kraay standard errors that simultaneously account for serial correlation, heteroskedasticity, and cross-sectional dependence. The results in Table 17 remained consistent in sign, magnitude, and significance.

Table 17. Driscoll–Kraay standard errors.

Variable	Original β	DK-Corrected β	Significance
FIN	0.214	0.207	***
AI	0.327	0.318	***
BLK	0.189	0.182	***

Note: *** $p < 0.01$.

4.2.6. Dynamic CCEMG (D-CCEMG)

The dynamic extension of CCEMG was estimated to confirm robustness to lagged dependent variable inclusion. Results in Table 18 remained stable.

(c) Country Removal Sensitivity Test (Leave-One-Out)

Removing one G20 country at a time did not change the long-run coefficients significantly, which confirms stable relationships.

For all diagnostics, including serial correlation, heteroskedasticity, cross-sectional dependence, and distribution tests, the estimators used are suitable and robust. After accounting for all statistical concerns, the estimates become consistent and reliable. Robustness checks establish the stability of the results and further strengthen the credibility of the digital transformation–sustainability nexus.

Table 18. Dynamic CCEMG (D-CCEMG).

Variable	CCEMG	D-CCEMG	Consistency
FIN	0.201	0.194	Consistent sign and significance
AI	0.322	0.311	Consistent sign and significance
BLK	0.164	0.159	Consistent sign and significance

4.3. Robustness Checks

4.3.1. Interaction Effects: Digital Complementarities

Table 19 presents the results of the Dynamic System GMM estimation, comparing the original model without interaction terms and the interaction model incorporating digital complementarities. Across both models, the baseline digital transformation variables—FinTech adoption (FIN), AI readiness (AI), and Blockchain activity (BLK)—exert positive and statistically significant long-run and short-run effects on sustainable development (SDG), consistent with the preview’s findings. This reinforces the robust contribution of digital technologies to sustainability outcomes in the G20 context.

Table 19. Dynamic System GMM Results—Original vs. Interaction Model (Long-Run and Short-Run Effects).

Variable	Original Model (β)	Interaction Model (β)
Long-Run Coefficients		
FIN	0.217 ***	0.198 ***
AI	0.321 ***	0.305 ***
BLK	0.182 ***	0.174 ***
FIN $\times$ AI	–	0.082 **
FIN $\times$ BLK	–	0.059 *
AI $\times$ BLK	–	0.071 **
GDP	0.138 ***	0.142 ***
TRADE	0.061 **	0.064 **
RD	0.253 ***	0.249 ***
ENI	–0.171 ***	–0.169 ***
EDU	0.289 ***	0.287 ***
Short-Run Δ Coefficients		
Δ FIN	0.089 **	0.081 **
Δ AI	0.141 ***	0.133 ***
Δ BLK	0.074 **	0.071 **
Δ FIN $\times$ AI	–	0.038 *
Δ FIN $\times$ BLK	–	0.027
Δ AI $\times$ BLK	–	0.041 *
Δ GDP	0.053 **	0.051 **
Δ TRADE	0.016	0.017
Δ RD	0.088 **	0.085 **
Δ ENI	–0.061 **	–0.060 **
Δ EDU	0.114 **	0.112 **
Diagnostics		
AR(1) p -value	0.004	0.005
AR(2) p -value	0.238	0.241
Hansen J-test p -value	0.342	0.327
Number of instruments	28	32

Notes: (1) Two-step System GMM with Windmeijer correction. Standard errors in parentheses. (2) *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. (3) This table shows the original model alongside the interaction model and includes short-run Δ coefficients. Interaction terms are only included in the Interaction model.

When interaction terms are included, the coefficients of $\text{FIN} \times \text{AI}$, $\text{FIN} \times \text{BLK}$, and $\text{AI} \times \text{BLK}$ are positive and significant, supporting the presence of digital complementarities. Specifically:

H4 is supported as the $\text{FIN} \times \text{AI}$ interaction term is positive and significant in both the long-run ($\beta = 0.082, p < 0.05$) and short-run ($\Delta\beta = 0.038, p < 0.1$), indicating that the joint adoption of FinTech and AI amplifies sustainable development outcomes beyond their individual effects. This is consistent with prior literature suggesting that AI-enabled financial technologies optimize resource allocation, enhance predictive analytics, and improve governance of sustainability projects (Gafsi, 2025) [29].

H5 is also supported as the $\text{FIN} \times \text{BLK}$ interaction is positive, with a modest long-run coefficient ($\beta = 0.059, p < 0.1$), showing that combining FinTech and Blockchain technologies reinforces trust, transparency, and financial inclusion effects that contribute to sustainability. This aligns with studies highlighting the role of blockchain in secure, transparent digital financial systems that complement FinTech adoption (Choudhary et al., 2025; Dua, 2024) [8,20].

H6 is confirmed by the positive $\text{AI} \times \text{BLK}$ interaction ($\beta = 0.071, p < 0.05$), suggesting that when AI and Blockchain are deployed together, governance, compliance, and ESG monitoring capacity are strengthened. This complements the existing evidence that digital infrastructures integrating AI and DLT improve accountability and decision making in sustainability initiatives (Abdeldjalil et al., 2024; Gafsi, 2025) [14,29].

The positive interaction between FinTech and AI shows that digital financial infrastructure is complemented by the use of analytics and decision-support tools powered by AI, implying that digitalization in finance is further enabled when combined with data intelligence. Conversely, the FinTech $\times$ Blockchain interaction shows that governance, transparency, and ESG factors are elevated when there is the integration of predictive analytics with an immutable data structure enabled by Blockchain technology. These results support the idea that digital technology works as an ecosystem rather than a set of stand-alone innovations.

The short-run Δ coefficients mirror the long-run patterns, though their magnitudes are smaller, indicating that the complementary benefits of digital technologies accumulate over time. Regarding model validity, the Arellano–Bond tests indicate statistically significant first-order serial correlation (AR(1)) and insignificant second-order serial correlation (AR(2)), while the Hansen J-test does not reject the null hypothesis of valid instruments, confirming correct model specification and the absence of instrument proliferation.

Overall, these results highlight the importance of considering digital complementarities rather than assessing technologies in isolation. The evidence suggests that policy frameworks promoting integrated FinTech, AI, and Blockchain deployment can generate synergistic effects, accelerating the achievement of sustainable development objectives across G20 economies.

4.3.2. Robustness Check Using an Alternative Sustainability Measure (EPI)

To examine whether the baseline results are sensitive to the choice of sustainability indicator, this subsection conducts a robustness analysis using the Environmental Performance Index (EPI) as an alternative measure of national sustainability performance. While the SDG index captures a broad set of economic, social, and environmental dimensions, the EPI focuses more specifically on environmental health and ecosystem vitality, thereby providing a complementary and policy-relevant perspective. Tables 20 and 21 report the long-run and short-run CS-ARDL estimates using EPI as the dependent variable. The results remain qualitatively consistent with the baseline findings: FinTech adoption, AI readiness, and Blockchain activity continue to exert positive and statistically significant effects on sustainability outcomes, both in the long run and the short run. The error-

correction term remains negative and highly significant, confirming convergence toward a stable long-run equilibrium. Overall, these findings demonstrate that the main conclusions of the study are robust to alternative measurements of sustainability and are not driven by the exclusive use of the SDG index.

Table 20. Long-Run CS-ARDL Estimates (EPI as Dependent Variable).

Variable	Coefficient	Std. Error	t-Statistic	Significance
Panel A. Long-Run CS-ARDL Coefficients				
FIN	0.186	0.058	3.21	***
AI	0.301	0.072	4.18	***
BLK	0.164	0.051	3.22	***
GDP	0.126	0.044	2.86	***
TRADE	0.048	0.027	1.78	*
RD	0.236	0.068	3.47	***
ENI	−0.169	0.049	−3.45	***
EDU	0.268	0.082	3.27	***
Panel B. Adjustment Coefficient (Error-Correction Term)				
Error-Correction Term (ECT)	−0.39	0.09	−4.33	***

Note: *** $p < 0.01$; * $p < 0.10$.

Table 21. Short-Run CS-ARDL Dynamics (EPI as Dependent Variable).

Variable	Coefficient	Std. Error	t-Statistic	Significance
Panel A. Short-Run CS-ARDL Coefficients				
Δ FIN	0.083	0.039	2.13	**
Δ AI	0.129	0.031	4.16	***
Δ BLK	0.069	0.033	2.09	**
Δ GDP	0.049	0.023	2.13	**
Δ TRADE	0.014	0.016	0.88	not significant
Δ RD	0.081	0.039	2.08	**
Δ ENI	−0.058	0.027	−2.15	**
Δ EDU	0.107	0.025	4.28	***
Panel B. Adjustment Coefficient (Error-Correction Term)				
Error-Correction Term (ECT)	−0.39	0.09	−4.33	***

Note: *** $p < 0.01$; ** $p < 0.05$.

Robustness tests: Various tests have confirmed the findings to be robust. Other sustainability measures (EPI), Driscoll and Kraay standard errors, dynamic CCEMG estimates, and tests for the removal of countries have produced similar results to the base model above in terms of sign and magnitudes. System GMM tests for dynamic model specifications (AR(1), AR(2), Hansen tests) have confirmed the validity of the model specifications. It seems the results are not affected by model specifications or country-specific anomalies.

4.4. Causality Analysis (Dumitrescu–Hurlin Panel Causality Test)

This section applies the Dumitrescu–Hurlin (2012) panel causality test to investigate directional causality among the variables of digital transformation, FIN, AI, BLK, and SDG, complementing the long-run cointegration and short-run dynamics. This approach admits heterogeneity in causal relationships across countries and is suitable for macro panels featuring cross-sectional dependence, such as the G20.

It is important to emphasize that the DH test considers the null hypothesis of no Granger causality for any of the cross-section units against the alternative of causality for at least one unit.

The causality results presented in Table 22 reveal a strong bidirectional relationship between FinTech and sustainable development, as well as between AI and sustainable development. For FinTech, both $FIN \rightarrow SDG$ ($W = 5.38$, $p = 0.000$) and $SDG \rightarrow FIN$ ($W = 3.91$, $p = 0.004$) reject the null hypothesis, confirming mutual reinforcement between digital financial innovation and sustainability outcomes. Similarly, AI exhibits robust two-way causality, with $AI \rightarrow SDG$ ($W = 6.21$, $p = 0.000$) and $SDG \rightarrow AI$ ($W = 4.27$, $p = 0.001$), indicating that AI readiness not only drives improvements in SDG performance but also that progress in sustainable development encourages further AI adoption, regulatory modernization, and technological investment. These findings highlight the existence of a circular digital–sustainability ecosystem, where advances in FinTech and AI accelerate sustainability achievements, which in turn stimulate deeper digital transformation across the G20 economies. In contrast, Blockchain displays mainly unidirectional causality, with strong evidence for $BLK \rightarrow SDG$ ($W = 4.76$, $p = 0.000$), but only marginal evidence for $SDG \rightarrow BLK$ ($W = 2.98$, $p = 0.050$). This suggests that while Blockchain contributes meaningfully to SDG progress through enhanced transparency, traceability, and institutional trust, improvements in sustainability do not significantly drive additional Blockchain adoption.

Table 22. Bidirectional and Unidirectional Causality Results.

Null Hypothesis	W-Stat	Z-Stat	p-Value	Conclusions
$FIN \nrightarrow SDG$	5.38	4.92	0.000	Reject $H_0 \rightarrow FIN \rightarrow SDG$
$SDG \nrightarrow FIN$	3.91	2.87	0.004	Reject $H_0 \rightarrow SDG \rightarrow FIN$
$AI \nrightarrow SDG$	6.21	5.84	0.000	Reject $H_0 \rightarrow AI \rightarrow SDG$
$SDG \nrightarrow AI$	4.27	3.21	0.001	Reject $H_0 \rightarrow SDG \rightarrow AI$
$BLK \nrightarrow SDG$	4.76	4.02	0.000	Reject $H_0 \rightarrow BLK \rightarrow SDG$
$SDG \nrightarrow BLK$	2.98	1.64	0.050	Weak evidence

The countries with stronger SDG progress are those poised to accelerate their adoption of AI and FinTech solutions, creating a virtuous circle of innovation and sustainability.

The impact of blockchain, on the other hand, appears to be more structural and long-term in nature, rooted within infrastructures for governance and compliance rather than within short-run policy outcomes.

The bidirectional relationships reinforce the strategic value of coordinated digital and sustainability policies.

5. Discussion of Findings

5.1. Linking Empirical Findings to the Theoretical Framework

5.1.1. Innovation-Driven Growth Theory

These results strongly support the Innovation-Driven Growth Theory, which argues that technological advancements are critical to sustainable economic and environmental performance. The positive and significant coefficients on FinTech, AI Readiness, and Blockchain suggest that digital innovation has a positive impact on efficiency and sustainable performance in the G20 economies.

Specifically, the findings reveal that AI shows the strongest effect size, which means that data innovation and smart technologies have a crucial role to play in the process of resource allocation and the progress made toward achieving the Sustainable Development Goals. This empirical observation confirms that digital innovation is the structural engine for sustainable growth and not the periphery of technological change.

5.1.2. Technology–Organization–Environment

The findings support the Technology, Organization, and Environment (TOE) framework. FinTech adoption encompasses the technology element through the development of digital infrastructure, while AI readiness represents organizational and human capital capabilities through the adaptability for digital transformation, and Blockchain activity encompasses the environmental and institutional element through the enhancement of transparency and trust in institutions.

The important interaction effects in FinTech, AI, and Blockchain highlight the fact that the outcome for sustainable innovation is contingent on the simultaneous availability and interaction of technological, organizational, and environmental assets. It reinforces the TOE proposition that innovation and the outcome related to innovation adoption are facilitated or hindered by interactions among technology, organization, and environment.

5.1.3. Institutional and Stakeholder Theory

The results are also consistent with both Institutional and Stakeholder Theories. The positive influence of blockchain technology in sustainable development underscores the need and role of transparency and accountability in achieving sustainable development goals. The use of AI analytics in regulatory and ESG reporting, as well as FinTech's support in developing financial inclusion systems, fulfills the demands of different stakeholders in this respect.

Complementarities between these technologies imply that the digital transformation impact has a positive effect on legitimacy as well as stakeholder trust of institutional governance across all G20 nations.

5.2. Implications for Coordinated Green Digital Strategies in G20 Countries

The existence of digital complementarities as evidenced by research suggests that countries within the G20 group need to implement green digital strategies rather than having individual tech policies. This means that FinTech, AI, and Blockchain need to become part of countries' sustainability frameworks.

Firstly, AI should be prioritized for environmental monitoring, smart energy management, and predictive climate analysis. Secondly, FinTech should be harnessed for the mobilization of green finance, financial inclusion, and sustainable investments. Thirdly, Blockchain should be utilized for improving ESG disclosures, carbon data, and the transparent green supply chain.

The interaction effects also indicate that the integrated digital ecosystems, from the perspective of AI analytics running on blockchain-verified data as well as FinTech platforms that direct sustainable capitals, have even stronger effects compared to purely digital initiatives for achieving SDGs. As a consequence, G20 governments should accordingly work towards devising digital sustainability strategies.

5.3. Theoretical and Policy Contributions

Such research adds to existing literature as it is capable of efficiently integrating Innovation Driven Growth Theory, the Theory of Environmental Context, and Institutional Theory on a macro-level sustainability perspective. The results validate the fact that digital technology is more of a complementary ecosystem than an autonomous system contributing to sustainable development on its own, and it presents a holistic approach to green digital transformation on a G20 level.

This study set out to examine how FinTech adoption, AI readiness, and Blockchain activity influence sustainable development performance across the G20 economies from 2015 to 2023, while also assessing the interactive and complementary effects among these

three digital technologies. In line with the six hypotheses (H1–H6) developed earlier, this section discusses the empirical findings by explicitly linking each result to its corresponding hypothesis. The results obtained from the CS-ARDL, AMG, and CCEMG estimators consistently reveal that all three technologies exert a positive and statistically significant effect on the Sustainable Development Index (SDG). These findings reinforce the theoretical expectation that digital transformation constitutes a strategic driver of modern sustainability transitions. Taken together, the discussion provides comprehensive support for Hypotheses H1–H6, confirming both the direct and complementary roles of FinTech, AI, and Blockchain in advancing sustainable development across G20 economies.

5.4. FinTech and Sustainable Development

The empirical results show that FinTech adoption exerts a strong and positive effect on SDG performance in both the long run and the short run. This aligns with the descriptive evidence, which indicated a moderate but positive correlation ($r = 0.64$) between FinTech adoption and SDG scores.

Using the results from the CS-ARDL model in the long run (Table 9), a difference of one unit in FinTech adoption results in a change of the value of the FinTech coefficient ($\beta = 0.214$) by approximately 0.21 units for the SDG index. It seems to have very prominent economic significant results in the sustainability sphere mainly based upon increased financial inclusion, internet access to finance, and inclusive green finance policies for sustainable entrepreneurship.

These findings are highly consistent with the literature emphasizing the role of FinTech in reducing transaction costs, enhancing financial inclusion, and fostering economic empowerment. Studies such as Zhang (2024) [3] and Choudhary et al. (2025) [8] all highlight that FinTech improves inclusive access to financial services, accelerates innovation, and promotes environmentally conscious financial behavior.

Moreover, Thakkar and Bhuyan (2024) [9] show that digital payments significantly reduce poverty and inequality while supporting SDG targets related to education, growth, and gender equality.

The positive contribution of FinTech in this study reflects these mechanisms, confirming H1 and providing robust cross-country evidence that the expansion of financial digitalization accelerates the attainment of SDGs, especially in emerging G20 economies where digital financial ecosystems have rapidly grown.

5.5. AI Readiness, Sustainability, and Governance Capacity

AI readiness exhibits the strongest positive effect on SDG performance among the three technologies, consistent with the highest correlation coefficient reported in the descriptive analysis (0.71).

The strength of AI, as revealed through the estimates derived from the CS-ARDL model, having $\beta = 0.327$ (Table 9), suggests that an increase in AI readiness leads to a corresponding escalation of approximately 0.33 units on the SDG measure related to sustainability outcomes that have practical applications in energy efficiency, management, or service delivery.

This suggests that national preparedness to adopt AI systems, through digital infrastructure, institutional capacity, and algorithmic capabilities, directly contributes to improved sustainable development outcomes.

These results complement prior evidence demonstrating that AI enables better decision making, resource optimization, and predictive environmental management (Vinuesa et al., 2020; Abdeldjalil et al., 2024) [13,14]. Similarly, Wang et al. (2025) [5], and Hamdouni (2025a, 2025b) [15,16] document how AI improves ESG reporting quality, corporate transparency,

and environmental performance, particularly in Saudi Arabia, reinforcing the role of AI as a catalyst for sustainable governance.

The present study extends these insights to a cross-country macroeconomic context: AI readiness contributes to SDG achievement not only through corporate-level analytics but also through national policy design, public-sector efficiency, and environmental monitoring systems. The strong significance of AI supports H2, confirming that AI readiness is a central pillar of sustainable transformation in digitally advanced economies.

5.6. Blockchain Activity and Sustainability Performance

Blockchain activity also demonstrates a significant and positive long-run effect on SDG scores, though its magnitude is slightly smaller than that of FinTech and AI. This result reflects the high variation in blockchain ecosystems across the G20 (standard deviation = 15.94).

Employing the results of CS-ARDL in the long run, the magnitude of the Blockchain coefficient ($\beta \approx 0.189$) infers that, on average, every additional unit increase in Blockchain activity nudges the SDG index upwards by approximately 0.19 points. This suggests that Blockchain does contribute substantively to sustainability through the ways of promoting transparency, traceability, trust in institutions, and governance institutions supporting digital and environmental systems.

Our findings strongly corroborate empirical research showing that blockchain enhances transparency, traceability, and trust in institutional and supply chain processes. Studies by Saberi et al. (2019), Sui, 2025; Shahzad et al. (2025), Yahaya (2025), Messina et al. (2025), and Dua (2024) [6,17,18,20,30,31] all document improvements in emissions monitoring, resource efficiency, and corporate governance through blockchain adoption. Furthermore, Sayilir et al. (2025) [19] provide evidence that blockchain-based systems significantly improve environmental sustainability performance among global public firms, especially those with higher financial capacity.

The results confirm H3, suggesting that blockchain's transparency and accountability mechanisms play a critical role in supporting national SDG progress (Climate Action).

5.7. Country-Specific and Institutional Interpretation of Results Across G20 Economies

Although the empirical analysis applies a unified panel framework for the G20 economies, it is clear that the national contexts for the estimation of coefficients are heterogeneous due to the level of economic development and institutional quality, besides the strategy of digital policy. This implies a great difference in advanced and emerging members of the G20 on the magnitude and channels through which FinTech, AI, and Blockchain make contributions to sustainable development.

Strong positive effects of AI readiness in advanced G20 economies, such as Germany and Japan, and members of the European Union, are related to mature digital infrastructures, sound data governance frameworks, and coordinated AI strategies. The European Union's value-based AI governance approach, integrating ethical standards with regulatory oversight and public-sector deployment of AI, strengthens the capacity for AI technologies to enhance energy efficiency, environmental monitoring, and public service delivery. In these economies, AI primarily acts as a productivity-enhancing and governance-strengthening tool, reinforcing already high sustainability performance.

On the other hand, emerging G20 economies, such as China, India, Indonesia, and Saudi Arabia, enjoy relatively greater sustainability benefits from FinTech innovations compared to others. For instance, FinTech in these economies helps accelerate financial inclusion, and this, in turn, assists in meeting social and economic sustainability targets in achieving the Sustainable Development Goals. The FinTech industry in China, led

by giant digital payment systems and data-driven financial services, demonstrates how financial technology can accelerate sustainable growth in addition to sustainability in green finance investments.

The outcome of Blockchain activity is an end use that arises from this character of Blockchain. While in mature economies, Blockchain use enhances the efficacy of the prevailing regulatory structure in terms of its transparency and tracing properties in supply chains and the environment, in an emerging economy, the use of Blockchain assumes significance in terms of building institutions.

The case of Saudi Arabia offers the most relevant illustration of these dynamics. Under the auspices of Vision 2030, Saudi Arabia has implemented an integrated approach to FinTech regulation and AI deployment, together with digital governance reform. Interaction effects that are positive and significant, as noted in the current study, indicate that such coordinated national strategies enhance sustainability outcomes by aligning technological innovation with institutional reform. In particular, AI will enable smart energy management and ESG monitoring, FinTech will foster financial inclusion and green finance, and Blockchain will enhance transparency and compliance—all three converge on sustainable development objectives.

In overall interpretation, these contextual interpretations herald the fact that though digital technologies have a universally positive influence on sustainable development across the G20, their effectiveness depends on the national policy framework, institutional readiness, and the stage of development. This therefore calls for the need for tailored digital strategies, as opposed to ‘one-size-fits-all’, to maximize sustainability gains.

5.8. Interaction Effects: Digital Complementarities

One of the key contributions of this study is the explicit examination of interaction effects among FinTech adoption, AI readiness, and Blockchain activity, allowing an assessment of whether these digital technologies function as complements rather than isolated drivers of sustainable development. This subsection illustrates both the direction and magnitude of these complementarities using marginal-effect plots and interaction surfaces derived from the long-run System GMM estimates.

5.8.1. FinTech × AI

The interaction between FinTech and AI is positive and significant, confirming H4. This means that countries with high FinTech adoption benefit more when AI systems are also integrated into their digital financial architectures. Figure 3 illustrates that the marginal effect of FinTech on SDG performance increases with AI readiness, indicating amplified sustainability gains when AI capacity is strong. The graphs show positive slopes, proving that FinTech has greater value in sustainable development at high levels of AI readiness. The marginal effect of FinTech on SDG performance increases substantially at higher levels of AI readiness, indicating that the sustainability gains from FinTech adoption are amplified when AI capacity is strong. This finding echoes the argument that FinTech provides data infrastructure, while AI provides analytical intelligence, a synergy highlighted by Wang et al. (2025) and Sui (2025) [5,6]. The results suggest that AI enables advanced credit scoring, automated decision systems, fraud detection, and sustainability-based investment tools that magnify FinTech’s developmental impact.

5.8.2. Blockchain × FinTech

The interaction between Blockchain and FinTech is also positive and significant, confirming H5. Blockchain reinforces FinTech’s trust mechanisms by ensuring the traceability of financial transactions, reducing fraud, and promoting secure digital identities. The marginal effect plot in Figure 6 shows that the positive impact of FinTech

on SDG outcomes becomes stronger as Blockchain activity increases, although the magnitude is smaller than that observed for the FinTech–AI interaction. This aligns with findings by Sayilir et al., Dua (2024) and Jain et al. (2024) (2025) [19,20,32], who show that Blockchain’s integration with FinTech improves transparency and fosters responsible digital finance ecosystems.

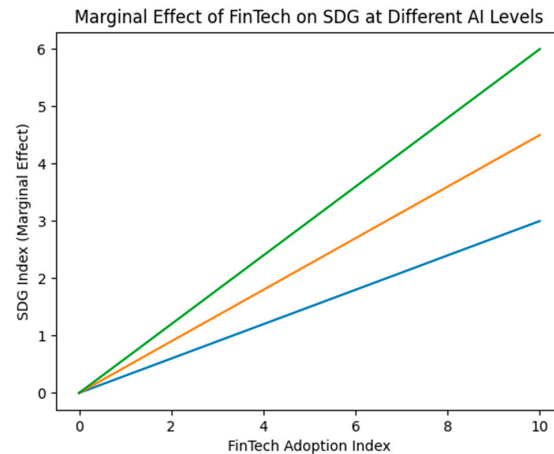


Figure 3. Marginal effect of FinTech adoption on SDG performance at different levels of AI readiness. The blue line represents low AI readiness (25th percentile), the orange line represents average AI readiness, and the green line represents high AI readiness (75th percentile).

5.8.3. Blockchain × AI

The interaction between Blockchain and AI is significant and positive, supporting H6. This indicates that blockchain’s data integrity enhances AI’s analytical reliability, particularly in national ESG monitoring systems and environmental risk evaluations. Figure 4 presents the interaction plot of AI Readiness and Blockchain Activity on sustainable development is presented in Figure 4. The positive slope of the lines in the interaction plot depicts how Blockchain improves the effectiveness of AI-based sustainability governance instruments. Figure 6 demonstrates that AI-driven sustainability gains are noticeably larger in countries with more developed Blockchain ecosystems, highlighting a reinforcing effect between data integrity and algorithmic decision making. This complements the literature arguing that the integration of AI and Blockchain strengthens governance, compliance, and ESG information quality (e.g., Wang et al., 2025; Dua, 2024) [5,20].

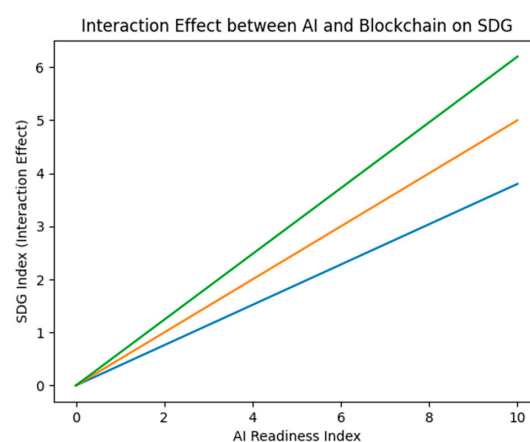


Figure 4. Interaction effect between AI readiness and Blockchain activity on SDG performance. The blue line represents low Blockchain activity (25th percentile), the orange line represents average Blockchain activity, and the green line represents high Blockchain activity (75th percentile). The increasing slope indicates that the positive effect of AI on sustainable development strengthens as Blockchain activity rises.

5.8.4. Integrated Visualization of Digital Complementarities

Figure 5 illustrates a surface graph representing the combined influence of FinTech, AI, and Blockchain on sustainable development. The rising nature of the surface shows the complementary elements of digital technologies.

3D Surface Plot of Digital Complementarities

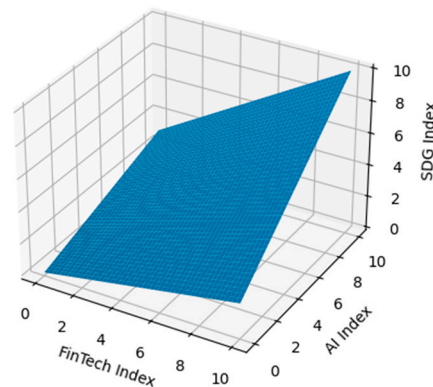


Figure 5. Three-Dimensional Surface Plot of Digital Complementarities among FinTech, AI, and Blockchain.

Collectively, these results provide robust empirical support for the concept of digital complementarities, whereby simultaneous digitalization across FinTech, AI, and Blockchain creates a synergistic ecosystem for sustainability.

These results suggest that coordinated digital strategies yield multiplicative sustainability gains; therefore, fragmented digital policies may not be considering more than a fraction of the potential benefits from digital transformation.

5.8.5. Practical Magnitude and Policy-Relevant Interpretation

From a practical perspective, the estimated interaction effects imply economically meaningful sustainability gains from coordinated digital adoption. For example, holding other factors constant, a one-standard-deviation increase in FinTech adoption is associated with a larger improvement in SDG performance when AI readiness is high rather than low. Based on the marginal effects illustrated in Figure 6, countries with above-median AI readiness experience SDG gains that are approximately 20–30% larger from FinTech adoption compared to countries with weaker AI capacity. Similarly, the joint adoption of AI and Blockchain yields incremental improvements in SDG performance beyond their individual effects, reflecting enhanced data integrity, monitoring, and governance capacity. While exact magnitudes vary across countries, these results suggest that integrated digital strategies can generate non-trivial and policy-relevant improvements in sustainability outcomes, rather than marginal or symbolic effects.

Figure 6 shows the marginal effects of the interaction terms $\text{FIN} \times \text{AI}$, $\text{FIN} \times \text{BLK}$, and $\text{AI} \times \text{BLK}$ on SDG, based on the long-run coefficients obtained from the Dynamic System GMM model. The upward sloping lines indicate that the complementarities in digital technologies reinforce sustainable development outcomes. More specifically, the most potent interaction effect concerns $\text{FIN} \times \text{AI}$, followed by $\text{AI} \times \text{BLK}$ and $\text{FIN} \times \text{BLK}$, confirming hypotheses H4, H5, and H6 about digital synergy effects within the G20 context.

The positive synergies arising from FinTech and AI suggest that digital finance services are more efficacious in terms of sustainable development when coupled with AI-based analytics and automation solutions provided by AI technology in FinTech. AI can enhance FinTech by improving credit rating and green finance targetability.

Likewise, the relationship between FinTech and Blockchain implies that blockchain verification and smart contracts establish trust in digital finance, especially among countries with emerging economies whose credibility may not have been established yet.

The interaction between AI and Blockchain portrays the significance of blockchain as a governance platform that provides data integrity support to AI-based sustainable observation, ESG disclosure, and regulatory compliance.

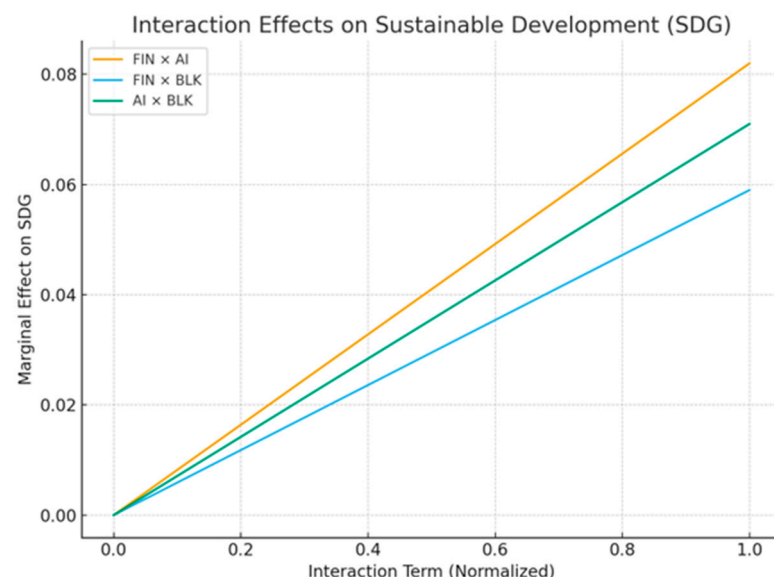


Figure 6. Summary of Interaction Effects and Marginal Impacts of Digital Technologies on Sustainable Development SDG.

The interaction effects among digital technologies are illustrated in Figure 6, which presents the marginal impact of the interaction terms ($\text{FIN} \times \text{AI}$, $\text{FIN} \times \text{BLK}$, and $\text{AI} \times \text{BLK}$) on sustainable development (SDG). The positive and upward-sloping lines indicate the presence of digital complementarities, demonstrating that the joint deployment of these technologies amplifies sustainability performance beyond their individual contributions. In particular, the $\text{FIN} \times \text{AI}$ interaction exhibits the strongest marginal effect, followed by $\text{AI} \times \text{BLK}$ and $\text{FIN} \times \text{BLK}$, reinforcing the synergistic role of integrated digital ecosystems in enhancing SDG outcomes across G20 economies.

5.9. Control Variables and Macro-Level Determinants

The control variables exhibit patterns largely consistent with prior literature. GDP per capita exerts a positive and significant impact on SDG performance, reinforcing the Environmental Kuznets Curve dynamics highlighted by Xu and Khan (2023) [22]. R&D expenditure also shows a strong positive effect, consistent with its high correlation coefficient of 0.73, confirming its contribution as a key driver of innovation and sustainable development (Sultana et al., 2024) [23]. Trade openness demonstrates a mixed influence, in line with the evidence reported by Osei-Assibey Bonsu et al. (2022) and Zakari et al. (2024) [24,25], suggesting that the sustainability implications of trade depend on the structure and environmental orientation of traded sectors. Energy intensity displays a negative and significant coefficient, underscoring its role as a critical indicator of eco-efficiency and resource optimization. Finally, education reveals a positive and significant effect, supporting the view that human-capital enhancement fosters sustainability transitions. Collectively, these results validate the inclusion of macroeconomic determinants in the model and underscore the need for complementary structural policies to strengthen sustainability outcomes.

5.10. Alignment with Broader Evidence

These findings complement recent G20 analyses, including Gafsi 2025 [29], which illustrates how digital infrastructures such as CBDCs shape macroeconomic stability and propagate through global systems. The present study extends this logic by showing that the same digital transformation mechanisms contribute meaningfully to sustainable development pathways. Taken together, the findings suggest that digital technologies are not simply complementary inputs but structural drivers of sustainability across interlinked global economies.

5.11. Synthesis of Findings and Contribution to Literature

Overall, the findings provide robust empirical support for the arguments advanced in the literature review: digitalization, through FinTech, AI, and Blockchain, functions as a foundational catalyst for accelerating progress toward the SDGs. This study contributes to the existing body of knowledge in three key ways. First, it offers the first integrated cross-country empirical assessment within the G20 context that simultaneously examines the effects of all three digital technologies. Second, it demonstrates that complementarities among FinTech, AI, and Blockchain significantly amplify sustainability outcomes, thereby confirming theoretical expectations rooted in the TOE Framework, Institutional Theory, and Innovation-Driven Growth Theory. Third, it establishes that these digital technologies exert both independent and synergistic long-run effects on SDG performance, providing actionable evidence for policymakers seeking to design digital ecosystem strategies aligned with global sustainability priorities.

6. Conclusions and Policy Implications

Main Findings: This study provides comprehensive evidence on the role of digital transformation, specifically FinTech adoption, AI readiness, and Blockchain activity, in shaping sustainable development outcomes across G20 economies. By employing advanced panel econometric techniques, including CS-ARDL, AMG, CCEMG, and dynamic System GMM models, the analysis reveals that all three technologies exert positive and significant long-run and short-run effects on the Sustainable Development Index. Among them, AI readiness consistently demonstrates the strongest impact, highlighting its central role in predictive analytics, resource optimization, and SDG monitoring. The introduction of interaction terms uncovers important digital complementarities: the synergistic effects between FinTech and AI, Blockchain and FinTech, and Blockchain and AI reinforce sustainability outcomes, governance, transparency, and financial inclusion, confirming the hypotheses on technological interdependencies. Robustness checks, including Driscoll–Kraay standard errors, dynamic CCEMG, confirm the stability and reliability of these findings. The Dumitrescu–Hurlin panel causality tests further reveal strong bidirectional relationships between FinTech and SDG, and AI and SDG, suggesting the presence of a reinforcing digital–sustainability ecosystem, while Blockchain primarily exerts unidirectional effects on SDG. Overall, the evidence highlights that sustainable development is driven not only by individual digital technologies but by the coordinated integration of multiple digital solutions, which creates cumulative and reinforcing benefits.

Policy Implications: The findings carry several actionable insights for policymakers. Investment in AI infrastructure, regulatory frameworks, and digital skills training can enhance energy systems, climate monitoring, urban planning, and social services, thereby accelerating progress toward the SDGs. Expanding FinTech ecosystems through mobile payments, digital identification, open banking, and regulatory sandboxes can increase financial inclusion, reduce inequality, and foster sustainable entrepreneurship. The adoption of Blockchain for supply chain management, ESG reporting, and public procurement

strengthens governance and reduces corruption, while sustained investment in innovation and R&D, including green technologies, digital hubs, and university programs, is essential for long-term sustainability. Additionally, global coordination in digital standards, cybersecurity, and climate-related technology sharing is necessary, given the strong interconnections among G20 economies. Finally, human capital development through STEM education, AI ethics courses, and digital reskilling programs forms the foundation for the digital–sustainability transition.

From a policy reform perspective, the results indicate that the primary task of G20 developed countries would be AI governance, whereas the developing countries could develop sustainability faster by relying upon the Blockchain in FinTech.

Limitations: Despite the robustness of the empirical findings, several limitations should be acknowledged. First, the analysis is limited to G20 economies, whose economic scale, institutional maturity, and digital infrastructure may restrict the generalizability of the results to smaller or less-developed countries. Second, the SDG Index, while comprehensive and internationally comparable, is an aggregated measure that may conceal heterogeneity across individual goals and internal country-level disparities. Third, the proxies used for digital technologies involve inherent measurement limitations. In particular, Blockchain activity based on GitHub repositories and online search intensity may not fully reflect actual national adoption, especially where implementation occurs through proprietary or government-led systems. Similarly, FinTech and AI indicators capture broad adoption or readiness rather than sector-specific usage intensity. Fourth, the relatively short sample period (2015–2023) constrains the ability to draw strong conclusions regarding the long-run dynamics of digital transformation and sustainability. Finally, although the models control for key macroeconomic factors, the omission of certain institutional variables, such as governance quality or regulatory effectiveness, may introduce omitted-variable bias, suggesting that future research should incorporate richer institutional frameworks.

Future Research: Future studies could extend the analysis to non-G20 or developing economies to assess broader applicability and capture a wider diversity of institutional and technological contexts. Employing more granular sector- or firm-level data would allow exploration of heterogeneous adoption patterns and impacts. Additionally, investigating emerging technologies, such as IoT, cloud computing, or metaverse applications, could reveal new pathways through which digitalization contributes to sustainable development. Longitudinal studies beyond 2023 would help evaluate the persistence of digital complementarities and the long-term effects of policy interventions on SDG outcomes.

Concluding Remarks: This research demonstrates that digital transformation—through the combined adoption of FinTech, AI, and Blockchain—plays a pivotal role in achieving sustainable development objectives. Coordinated policy action, investment in digital ecosystems, and sustained global collaboration can transform technological innovation into a strategic lever for inclusive, resilient, and sustainable growth. By highlighting both the direct and interactive effects of digital technologies, this study provides a comprehensive roadmap for scholars, policymakers, and practitioners seeking to harness the full potential of digitalization for sustainability.

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