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Advancing Sustainable Development Through Digital Transformation and Fintech Innovation

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Abstract: Purpose: Our study investigates the combined effects of financial technologies (fintech) and the digital economy on sustainable development, considering geopolitical risks as a moderating factor. **Origin:** While sustainable development is a global imperative, the integrated roles of digital transformation and fintech remain insufficiently explored. Our research addresses this gap by analyzing their impacts on socioeconomic advancement and environmental sustainability across diverse contexts. **Methodology:** Employing panel data from 30 developed and developing countries between 1990 and 2023, we assess sustainable development using the Environmental Performance Index (EPI) and the Human Development Index (HDI). Independent variables include proxies for the digital economy (e.g., internet usage, mobile subscriptions, and high-tech exports) and fintech (e.g., digital payments, digital currency, and peer-to-peer lending). The Geopolitical Risk Index (GPRI) is used to evaluate the effect of political instability. We apply generalized least squares (GLS) and fixed-effects estimation (within) to ensure robustness. **Findings:** Our results indicate that digital transformation and fintech significantly foster socioeconomic development and environmental performance, even amidst geopolitical instability. Key variables such as digital payments and internet access show substantial positive impacts, providing valuable insights for policymakers aiming to enhance resilience and sustainability. **Contributions:** Our article offers a comprehensive evaluation of how the digital economy and fintech jointly influence sustainable development under geopolitical risks, providing a nuanced understanding for policymakers and researchers.

Keywords: digital economy; financial technologies (fintech); sustainable development; geopolitical risks; socioeconomic growth and environmental performance

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1. Introduction

Environmental pollution poses a critical threat to global economic prosperity and long-term sustainability. The surge in carbon dioxide (CO_2) emissions—rising from 1.6 billion tons in 1990 to 36 billion tons in 2020—underscores the urgent need for international regulatory measures (Chaudhary et al. (2022) [1]; Hammed and Arawomo (2022) [2]). While

prior research has explored the impact of the digital economy and financial technologies (fintech) on economic growth, financial inclusion, and environmental sustainability (Jiao and Sun (2021) [3]; Zheng and Wang (2022) [4]), limited studies have examined their combined effect on long-term sustainable development, particularly in the presence of geopolitical risks. This study seeks to fill this gap by analyzing the interplay between the digital economy and fintech in shaping socioeconomic development and environmental performance, integrating the Geopolitical Risk Index (GPRI) to account for political instability—a dimension often overlooked in the existing literature.

This research offers several contributions. First, it investigates how fintech innovations moderate the impact of digital transformation on sustainability amidst geopolitical uncertainties. Second, unlike prior studies that relied on geographically limited or short-term datasets, this study utilizes a robust panel data analysis covering 30 developed and developing countries from 1990 to 2023. This study further distinguishes the structural effects of digitalization and fintech across varying economic and institutional contexts, providing a more comprehensive understanding of their roles in sustainability.

Methodologically, this study employs a multidimensional approach, incorporating environmental, socioeconomic, and technological indicators. The Environmental Performance Index (EPI) measures ecological impact, the Human Development Index (HDI) assesses socioeconomic progress, and digital economy metrics such as internet penetration, mobile usage, and technological exports are included alongside fintech indicators like digital payments, digital currencies, and peer-to-peer lending. This comprehensive framework enhances analytical robustness and mitigates biases associated with single-indicator analyses.

Our article is structured as follows: The first section explores the theoretical foundations of digital transformation and financial technology in the context of sustainable development, taking geopolitical risks into account. The second section provides a synthesis of the key empirical studies that have analyzed the impact of the digital economy and fintech on sustainability in the context of geopolitical tensions. The third section details the research methodology, including the description of data, variables, the sample selection process, and the estimation models adopted. The fourth section presents the empirical results on the combined effect of the digital economy and fintech on sustainability. The fifth section highlights the study's main conclusions, while the final section offers policy recommendations, outlines research limitations, and suggests directions for future studies.

2. Theoretical Foundations

The digital transformation, driven by the widespread adoption of the internet, the rise in mobile subscriptions, and the expansion of technology exports, has become a crucial component in advancing sustainable development. It enables greater access to information, enhances business efficiency, and fosters innovation, contributing positively to socio-economic development, as measured by the Human Development Index (H1). Furthermore, the digital transformation supports environmental performance by promoting the adoption of green technologies and reducing energy inefficiencies, thereby enhancing the Environmental Performance Index (H2). Innovations in financial technologies (fintech), such as digital payments, cryptocurrencies, and crowdfunding, have a transformative impact on financial inclusion and socio-economic development (H3). By democratizing access to financial services, fintech reduces financing inequalities and stimulates entrepreneurship, especially for marginalized populations, thereby contributing to a more equitable economy (H4).

Despite these positive effects, the potential of digital transformation and fintech to foster sustainable development is not immune to the influence of geopolitical risks. Geopo-

litical tensions and uncertainties have the potential to disrupt investments and limit access to critical technologies, which can hinder the progress of digitalization and sustainable development. As geopolitical risks increase, so too does economic uncertainty, leading to reduced investments in digital infrastructure and posing a threat to the ongoing progress in these areas (H5). Additionally, geopolitical instability can hinder the effectiveness of fintech in promoting sustainable development by imposing regulatory restrictions, inducing market volatility, and dampening the innovation necessary to drive economic and social transformation (H6). Finally, the impact of digitalization and fintech on sustainable development varies depending on the level of development of a country. In developed countries, where digital infrastructure is more advanced and the regulatory framework is more stable, the positive impact of digitalization and fintech is strengthened (H7). In contrast, in developing countries, although these innovations contribute to sustainable development, their effect remains limited by structural challenges such as restricted access to technology and political instability (H8).

In this theoretical framework, the relationships between fintech, digital transformation, and sustainability are examined through various lenses, drawing upon established theories in innovation, economic systems, and environmental impact. Christensen's (1997) [5] theory of disruptive innovation provides a foundation for understanding how fintech, as a disruptive force, can reshape entire industries by offering more accessible and cost-effective solutions. This aligns with the view that fintech can democratize financial services, promote financial inclusion, and support sustainable economic practices. However, the effectiveness of fintech in achieving these outcomes is moderated by the broader geopolitical environment, with increased risks potentially stifling innovation and limiting the impact of fintech on sustainable development.

Complex systems theory also informs our understanding of the interactions between digital technologies, the financial system, and sustainability. The unpredictable and interdependent nature of these systems highlights how innovations in fintech can have both positive and negative effects on sustainability, with trade-offs between financial inclusion and environmental impact. For instance, while fintech can reduce carbon footprints through paperless platforms, the energy consumption of digital infrastructures, such as data centers, can exacerbate environmental concerns. Similarly, the environmental impact of technologies like blockchain, which powers digital currencies, underscores the challenge of balancing innovation with ecological sustainability.

The theory of "techno-geopolitics" (Huang et al. (2023) [6]) further deepens our understanding of how geopolitical rivalries over technological control influence the evolution of fintech and its role in sustainable development. Geopolitical competition can lead to a rise in alternative solutions, such as sanction-avoidance mechanisms (e.g., cryptocurrencies), which might bypass traditional financial systems but come with their own set of challenges, including environmental concerns. This dynamic is particularly evident in countries facing international sanctions, where digital currencies have enabled continued access to financial services, yet also contribute to rising energy consumption.

In addition to the geopolitical context, the "digital commons" theory (Ostrom (2009) [7]) is applied to understand the strategic importance of digital infrastructure, such as data centers and communication networks, in global technological development. Geopolitical tensions can limit access to these resources, affecting the equitable distribution of digital technologies and hindering global cooperation on sustainability goals. Through this multidimensional theoretical framework, we explore how fintech and digital technologies interact with the economic, environmental, and social dimensions of sustainable development. While fintech has the potential to drive inclusive economic growth and reduce ecological footprints, its full impact is contingent upon the broader geopolitical landscape. This complex interaction

between technological innovation, financial systems, and geopolitical factors provides a comprehensive basis for analyzing the role of fintech in shaping sustainable development outcomes in a rapidly evolving global context.

3. Literature Review

The digital economy has become a pivotal driver of sustainable development, influencing economic growth, environmental sustainability, and social inclusion. Studies have highlighted its potential to reduce carbon emissions, particularly in developed economies. For instance, Bayar and Gavriletea (2019) [8] emphasized the role of digital technologies in enhancing resource efficiency and promoting green innovation. Similarly, Liu et al. (2023) [9] provided evidence from Chinese cities demonstrating that digital talent aggregation fosters green innovation, underscoring the importance of urban policy support. Chen et al. (2020) [10] argued that industrial agglomeration driven by digital transformation improves resource efficiency and environmental sustainability.

However, most studies focus on specific regions or short time frames, limiting the generalizability of findings. Additionally, the impact of fintech on financial inclusion and socioeconomic development has gained attention. Khan et al. (2019) [11] identified digital payment systems as drivers of financial access in developing countries, while Zheng and Wang (2022) [4] emphasized the role of peer-to-peer lending in supporting small enterprises. Despite these contributions, the existing literature often overlooks the interplay between fintech innovations and environmental sustainability, creating a gap this research seeks to address.

Li et al. (2024) [12] examined the impact of digital technology on countries' positions in global value chains (GVCs). Analyzing panel data covering 59 economies from 2007 to 2018, they identified a U-shaped relationship between digital technology adoption and GVC position. Initially, countries may experience a decline in their GVC status due to negative effects on supply chains. However, as technological maturity is achieved, positive effects on the production chains lead to an improved position in GVCs. The study also found that the impact of digital technology on advancement in GVCs is mediated by increased productivity. Additionally, countries with lower economic development levels and greater trade openness reach the inflection point of this U-curve more quickly, accelerating their progress in global value chains. The authors recommend investing in digital infrastructure and technology skills training, promoting innovation and R&D, implementing appropriate industrial policies to support business modernization, reducing trade barriers, and encouraging international exchanges to speed up technological adoption. They also emphasize the importance of enhanced international cooperation for better technology transfer and more efficient integration into GVCs.

Geopolitical risks—such as conflicts, political instability, and economic sanctions—can significantly impact the effectiveness of digital technologies and fintech in promoting sustainable development. These risks disrupt investment flows, access to technologies, and international cooperation, thereby limiting the expected socioeconomic and environmental benefits of digital transformation. Geopolitical tensions can create uncertainties that discourage innovation and transnational collaboration, hindering the achievement of sustainable development goals.

Caldara and Iacoviello (2022) [13] developed a widely adopted Geopolitical Risks (GPRI) index to measure political instability and its impact on sustainable development trajectories. This index has highlighted the inverse relationship between geopolitical instability and progress toward long-term sustainability goals. For instance, Aswani et al. (2021) [14] demonstrated that geopolitical tensions reduce the effectiveness of sustainable energy policies by complicating the implementation of cross-border projects and limiting access to green

technologies. Moreover, Huang et al. (2023) [6] pointed out that the adoption of fintech technologies is particularly hindered in regions with high geopolitical risk, where regulatory restrictions and institutional distrust create additional barriers to financial innovation.

Phillips (2023) [15] used hierarchical models to illustrate that geopolitical risks mitigate the positive impact of fintech technologies on financial inclusion, particularly in sub-Saharan Africa, where political and economic tensions make it difficult to implement accessible digital financial solutions. Zhao et al. (2024) [16] also observed that digitalization, although it reduces CO_2 emissions, only has a positive impact in countries with low geopolitical risk due to the absence of obstacles such as sanctions or military conflicts. This negative interaction between geopolitical risk and the effectiveness of digitalization underscores the importance of considering the geopolitical context when assessing the real benefits of digital transformation. Thus, although digitalization and fintech have significant potential to support sustainable development, their impact can be heavily modulated by geopolitical risks, requiring contextual and adaptive approaches to maximize their positive effects in unstable environments.

The integration of the Geopolitical Risk Index (GPRI) into our study provides an innovative contribution by revealing how global political dynamics moderate the impact of digital transformation and fintech on sustainable development. Geopolitical risks—such as conflicts, political instability, and sanctions—directly influence the adoption of digital technologies and the implementation of financial innovations. In politically unstable contexts, investments in digital infrastructure or green projects may be hindered, while capital flows and international collaborations are disrupted. Yang et al. (2023) [17] showed that political instability reduces countries' ability to fully leverage the benefits of emerging technologies, which justifies its inclusion as a moderating factor.

Our article offers a nuanced analysis of traditional fintech and digital transformation, highlighting both their positive impacts and limitations. Studies by Demirgüç-Kunt and Klapper (2018) [18] and Philippon (2019) [19] demonstrated that fintech significantly enhances financial inclusion by providing access to banking services in underbanked regions. Mobile payment solutions like M-Pesa in Africa have transformed local economies by facilitating transactions and savings. The digitization of financial services reduces transaction costs, improves transparency, and decreases corruption—key elements for fostering sustainable economic development (Beck and Mahony (2018) [20]).

While some researchers argue that traditional fintech can exacerbate digital inequalities, initiatives in digital microfinance and adaptive regulation (Zhou et al. (2023) [21]) demonstrate that a well-structured regulatory framework can mitigate these risks. Rather than opposing traditional fintech to the new generation of digital services, it is relevant to analyze how they can coexist and evolve toward beneficial complementarity. For example, the tokenization of financial assets and smart contracts on the blockchain offer innovative solutions to ensure sustainability while maintaining financial sector stability (Sedlmeir et al. (2020) [22]).

Our article emphasizes the need for a gradual and regulated evolution of the sector, where new technologies (AI, blockchain, decentralized payments, etc.) complement and enhance existing financial infrastructures. This is a process of adaptation rather than a radical break from the traditional financial system. Bhat et al. (2022) [23] argued that technological innovations often lead to a transformation of skills rather than a net destruction of jobs, thus encouraging investment in education and digital training. Therefore, while automation may cause sectoral reallocations, it does not necessarily lead to mass unemployment if public policies and businesses invest in worker reskilling.

The environmental impact of digital infrastructures, particularly data centers, is a legitimate concern. However, technological advancements have significantly reduced their carbon footprint, as major tech companies like Google and Microsoft have com-

mited to powering their data centers exclusively with clean energy sources (Andrae and Edler (2015) [24]). Research in green computing aims to improve energy management in servers through artificial intelligence and passive cooling (Musah et al. (2022) [25]). Our article advocates for the integration of sustainability into digital transformation, highlighting solutions that reconcile digitalization with sustainable development. The transition to a greener and more inclusive economy requires regulatory oversight and a greater adoption of eco-efficient technologies.

Fintech and digital transformation are relatively recent phenomena, with significant acceleration over the past decade. Consequently, long-term empirical data remain limited. Several studies, including those by Philippon (2019) [19] and Arner et al. (2020) [26], emphasize that the sector is still evolving, making it challenging to conduct robust analyses over multiple decades. While long-term studies are desirable, short- and medium-term analyses help identify initial trends and the gradual adjustments of economies to digital transformations. Beck et al. (2018) [20] showed that fintech promotes financial inclusion and economic growth in the early years following its adoption. Similarly, Demirgüç-Kunt and Klapper (2018) [18] indicated that fintech innovations have an immediate impact on reducing transaction costs and improving access to credit, although further studies are needed to assess their long-term sustainability.

Our article acknowledges that research on the long-term effects of fintech and digital transformation is still developing. However, several recent initiatives aim to address this gap, including the indexing of fintech trends over multiple decades, as proposed by Zheng and Wang (2022) [4], who analyzed the evolution of digital financial services over 20 years. Long-term regulatory impact studies, conducted by institutions such as the World Bank and the International Monetary Fund (IMF), monitor the effects of digital transformation on global finance.

Fintech and financial digitization have seen significant acceleration in recent years, particularly after the 2008 financial crisis and with the rise in AI and blockchain-based technologies. The trends and impacts observed before 2010 are thus structurally different from those after 2016. Philippon (2019) [19] showed that financial innovation intensified after 2010, deeply altering the dynamics of financial inclusion. Arner et al. (2020) [26] indicated that the rise in digital technologies transformed banking and payments after 2015, with the widespread adoption of mobile services and cryptocurrencies. Although our study covers the period from 1990 to 2023, the most recent data are crucial for assessing contemporary trends, particularly the impact of post-2015 regulations on digital finance (Zheng and Wang (2022) [4]). The acceleration of fintech adoption following the COVID-19 pandemic (Demirgüç-Kunt et al. (2018) [18]) is also noteworthy. Our study does not limit itself to post-2016 references but complements them with earlier works to ensure a consistent historical analysis. This approach allows for tracking of the gradual evolution of financial policies and technologies, providing a perspective on recent structural changes alongside long-term trends.

The impact of the COVID-19 pandemic on digital transformation and fintech is well documented in studies such as Demirgüç-Kunt et al. (2018) [18], who examined the acceleration of digital financial inclusion during the pandemic. Zheng and Wang (2022) [4] analyzed the structural changes in digital transactions and financial services following the health crisis. Arner et al. (2022) [26] explored the evolution of fintech regulations in response to new economic and political challenges. These references help position the impact of the pandemic on the digital economy and its interaction with recent geopolitical tensions. Our study also considers the effects of geopolitical tensions on fintech and digital transformation. Qian et al. (2022) [27] showed how geopolitical risks influence financial markets and investments in digital assets. The evolution of fintech regulations post-2020

(Mitra and Karathanasopoulos (2023) [28]), the impact of digital transformation on the green economy and sustainable development (Cevik (2024) [29]), and the accelerated adoption of digital payments and financial technologies in emerging economies post-COVID-19 (Zouaghia et al. (2024) [30]) are also significant contributions. Digital transformation in finance relies on a balance between opportunities and risks.

4. Research Methodology

4.1. Data and Variable Definitions

This study investigates the impact of the digital economy and financial technologies (fintech) on sustainable development, considering the moderating effect of geopolitical risks. Utilizing annual data from 1990 to 2023, it examines various digital economy indicators, multiple fintech measures, and two key sustainable development indices: the Human Development Index (HDI) for socioeconomic development and the Environmental Performance Index (EPI) for environmental preservation. The Geopolitical Risk Index (GPRI) serves as a proxy for geopolitical uncertainty, enabling a comprehensive assessment of how digital and financial innovations interact with global political dynamics to influence sustainability outcomes.

Drawing on theoretical frameworks from Khan et al. (2019) [11], Wang et al. (2024) [31], Zheng and Wang (2022) [4], Phillips (2023) [15], and Huang et al. (2023) [6], this study highlights the contributions of the digital economy and fintech to both socioeconomic progress and environmental goals under varying geopolitical conditions. Key independent variables include mobile subscriptions (MS), internet usage (IU), fourth- and fifth-generation mobile technologies (4G/5G), high-speed connections, high-technology exports (HTE), and ICT exports (ICTE). These factors are critical in bridging the digital divide and advancing access to information technologies. Fintech's role is captured through three variables: digital currency, online payments, and peer-to-peer lending. By integrating these dimensions with the GPRI, this study provides novel insights into how digital progress and financial innovations mitigate or amplify the challenges posed by geopolitical risks.

This methodology employs a robust set of indicators to approximate digital economy growth and its contribution to sustainable development, as outlined by Zhao et al. (2024) [16]. Enhanced internet access, as reflected by rising internet usage (IU) and high-speed connectivity, is identified as a key driver in reducing digital inequality and fostering inclusive economic growth, supported by Tian et al. (2024) [32]. Sustainable development is defined as addressing the needs of the present generation while safeguarding the ability of future generations to fulfill their own needs (Tian et al. (2024) [32]). Achieving this objective requires efficient resource use, environmental protection, and the promotion of long-term economic growth. To assess economic sustainability within the broader context of sustainable development, the study uses two key indicators: the HDI and the EPI, as outlined by Tian et al. (2024) [32].

This study investigates the effect of the digital economy and fintech on socioeconomic development and environmental sustainability across a sample of 30 developed and developing countries. Using a panel data methodology, the HDI and EPI are modeled as functions of the digital economy indicators, the three fintech measures, and the Geopolitical Risk Index (GPRI) over the period 1990–2022. Detailed definitions and sources of all variables, both dependent and independent, are provided in Appendix A.

4.2. The Empirical Specification

The simultaneous integration of the Human Development Index (HDI) and the Environmental Performance Index (EPI) as endogenous variables allows for a comprehensive analysis of the effects of digital transformation and financial technologies (fintech) on sustainable development. The HDI reflects the socio-economic dimension of development

by measuring progress in education, health, and living standards, while the EPI assesses environmental sustainability through pollution reduction, ecosystem protection, and the implementation of ecological policies. By incorporating both indices, our study adopts a holistic and balanced perspective on the contribution of digital innovations and financial technology (fintech) to both human growth and environmental preservation.

Digital technologies and fintech services play a dual role in sustainable development. On the one hand, they promote financial inclusion, stimulate economic growth, and enhance human capital, which are key elements captured by the HDI. On the other hand, these innovations influence energy efficiency, carbon emission reduction, and the implementation of environmental policies, which are reflected in the EPI. Therefore, the combined use of these two indices allows for a comprehensive assessment of how digitalization and fintech shape the interdependent aspects of sustainable development.

Our article also considers the geopolitical context, where global risks impact both economic stability and environmental policies. By integrating the HDI and EPI, this analysis identifies how digital and financial innovations mitigate geopolitical shocks and enhance economic resilience in times of crisis. An approach limited to just one of these indices would provide a partial and incomplete view of the underlying dynamics. Finally, the empirical justification for this choice is based on correlation analyses and econometric models, which reveal statistically significant relationships between digital indicators and these two indices. The results show that variables such as mobile penetration, digital payments, and internet access influence both human development and environmental performance. Thus, the combined use of the HDI and EPI captures the multiple dimensions of sustainable development, providing more relevant and well-adapted policy recommendations to address contemporary challenges.

The control variables included in this study are essential to ensure the robustness of the results by neutralizing the influence of external factors that may simultaneously affect socio-economic development (HDI) and environmental performance (EPI). The inclusion of the Geopolitical Risk Index (GPRI) allows for an assessment of the impact of political uncertainties on the adoption of digital technologies and fintech, while high-tech exports (HTE) and ICT exports (ICTE) reflect a country's ability to adopt and disseminate innovation. Mobile subscriptions (MS) and internet usage (IU) are incorporated to measure access to digital technologies, a prerequisite for the effects of digitalization and fintech. Furthermore, the impact of digital payments (DP), digital currencies (DC), and peer-to-peer lending (P2P lending) is considered to examine its contribution to financial inclusion and sustainable development. These control variables are, therefore, reasonable and relevant, as they help prevent omitted variable bias and better isolate the specific effect of digitalization and fintech on sustainable development. However, a detailed methodological clarification explaining their selection and role would further enhance the transparency and credibility of the results.

We refer to the following models to estimate the impact of the digital economy and fintech on sustainable development during the current geopolitical risks for a sample of developed and developing countries:

$$HDI_{it} = \alpha_i + \beta_1 MS_{it} + \beta_2 IU_{it} + \beta_3 4G/5G_{it} + \beta_4 HTE_{it} + \beta_5 ICTE_{it} + \beta_5 DC_{it} + \beta_6 DP_{it} + \beta_7 P2P_{it} + \beta_8 GPRI_{it} + \varepsilon_{it} \quad (1)$$

$$EPI_{it} = \delta_i + \gamma_1 MS_{it} + \gamma_2 IU_{it} + \gamma_3 4G/5G_{it} + \gamma_4 HTE_{it} + \gamma_5 ICTE_{it} + \gamma_5 DC_{it} + \gamma_6 DP_{it} + \gamma_7 P2P_{it} + \gamma_8 GPRI_{it} + \mu_{it} \quad (2)$$

This study examined a sample of 30 developed and developing countries, spanning the period from 1990 to 2023. Sustainable development was assessed using two key indicators:

the HDI and the EPI, both serving as endogenous variables in this analysis. Independent variables include mobile subscriptions (MS), internet users (IU), fourth- and fifth-generation wireless mobile technologies (4G/5G), high-tech exports (HTE), and ICT exports (ICTE). Additional variables representing fintech innovations—digital currency (DC), digital payment (DP), and peer-to-peer lending (P2P)—were incorporated alongside the Geopolitical Risk Index (GPRI). The GPRI data, initially available monthly, was converted into annual values to align with the scope of this analysis.

A panel data methodology was employed to evaluate the impact of the digital economy, fintech, and geopolitical risks on sustainable development. The sample included 17 developed countries: Belgium, Canada, Chile, China, Denmark, Spain, Finland, France, Germany, Hungary, Israel, Italy, Japan, South Korea, the United Kingdom, the United States, and Russia. Additionally, 13 developing countries were included: Brazil, Colombia, Egypt, India, Indonesia, Malaysia, Mexico, the Philippines, Peru, Thailand, Tunisia, Turkey, and Ukraine. Country classification as developed or developing was based on World Bank categorizations, ensuring the robustness of the sample framework.

5. The Empirical Results

Our study focuses on the overall effect of digitalization and fintech on sustainable development, taking geopolitical risks into account. Given the diversity of regulatory and economic frameworks across the 30 countries studied, we adopted an approach based on the most widely recognized and internationally available quantitative indicators, particularly the Environmental Performance Index (EPI) and the Human Development Index (HDI). These indicators provide a consistent and comparative assessment of socio-economic and environmental sustainability (Phillips (2023) [15]; Liu et al. (2024) [9]). Additionally, integrating indicators such as internet penetration, mobile technology usage, and digital payment adoption allowed us to examine how digital transformation and financial innovation influence sustainability, regardless of regulatory and economic differences between countries (Zhao et al. (2024) [16]).

5.1. Descriptives

We examine descriptive estimates to study the quality of the linear fit. These are the mean, information symmetry, kurtosis, and the normal distribution of each component of the digital economy, financial technology, and the Geopolitical Risk Index. Table 1 presents these different indicators for our sample of 30 developed and developing countries. This table presents the descriptive statistics of the variables representing the digital economy, financial technology (fintech), and geopolitical risks for a sample of 1020 observations. The variables considered include key indicators such as the HDI, EPI, mobile subscriptions (MS), internet usage (IU), access to fourth- and fifth-generation mobile technologies (4G/5G), high-tech exports (HTE), ICT services exports (ICTE), digital payments (DP), digital currencies (DC), peer-to-peer lending (P2P), and the Geopolitical Risk Index (GPRI).

Table 1 presents the descriptive statistics for various variables related to the digital economy, fintech, and geopolitical risks, based on a sample of 1020 observations. The analysis reveals notable dispersion and non-normality in the data, indicating significant variations in the digital economy across countries. The Human Development Index (HDI) shows a high level of dispersion, with a mean of 3.98 but a standard deviation of 51.00. The skewness (16.22) and kurtosis (26.41) indicate a highly skewed distribution, influenced by extreme values, suggesting substantial inequality in human development across the sample. For the Environmental Performance Index (EPI), the distribution is more uniform, with a mean of 56.56 and a low skewness (0.16), reflecting a relatively normal distribution. This suggests that environmental performance is more consistent among the countries studied.

Table 1. Descriptive statistics.

	Mean	Median	Std, Dev	Skewness	Kurtosis	Jarque–Bera	Observations
HDI	3.9837	0.787	51.0049	16.2188	26.4135	2965.168 ***	1020
EPI	56.5575	55.9277	11.4528	0.1643	3.5307	16.039 **	1020
MS	67.6212	76.5002	53.9522	0.1029	1.7395	67.1461 ***	1020
IU	98.1431	29.9954	30.9765	31.3847	96.001	39,941.1352 ***	1020
4G/5G	11.2933	2.8773	14.4108	1.0838	2.9058	193.797 ***	1020
HTE	16.5099	13.79	14.0163	1.5628	5.9874	769.5891 ***	1020
ICE	99.7225	4.9703	31.1432	31.3847	96.001	3941.176 ***	1020
DP	20.4488	1.0563	27.1679	22.7264	53.6519	3964.662 ***	1020
DC	38.9473	34.3366	41.3135	1.0264	3.7293	195.3729 ***	1020
P2P	12.9651	5.9249	18.2526	6.8051	76.7264	1390.4 ***	1020
GPRI	3.3012	1.265	6.0398	4.2338	25.2202	2277.13 ***	1020

The significance levels are as follows: (***) significance at the 1% level, and (**) significance at the 5% level.

Mobile subscriptions (MS) and internet usage (IU) also demonstrate notable variation. While mobile subscriptions have a mean of 67.62, their high standard deviation (53.95) indicates significant disparities in access to mobile networks. Internet usage, with a mean of 98.14, shows an even higher standard deviation (30.98) and extreme skewness (31.38), pointing to large gaps in internet penetration across countries. In terms of 4G/5G access and high-tech exports (HTE), both variables exhibit some degree of dispersion. Additionally, 4G/5G access, with a mean of 11.29 and a standard deviation of 14.41, shows moderate skewness (1.08) and kurtosis (2.91), indicating some variation around the mean. Similarly, high-tech exports, with a mean of 16.51 and a high standard deviation (14.02), exhibits moderate skewness (1.56), indicating a somewhat uneven distribution. For ICT services exports (ICE) and digital payments (DP), there is a significant spread in the data. ICT services exports, with a mean of 99.72, shows a high standard deviation (31.14), while digital payments, with a mean of 20.45 and a high standard deviation (27.17), displays a heavily skewed distribution (skewness of 22.73), reflecting a concentration of data in certain regions.

The digital currencies (DC) and peer-to-peer lending (P2P) variables also show considerable variation. Digital currencies, with a mean of 38.95, has a high standard deviation (41.31) and a slightly skewed distribution, while peer-to-peer lending shows a heavily skewed distribution (skewness of 6.81), indicating substantial disparity in adoption. Finally, the Geopolitical Risk Index (GPRI), with a mean of 3.30 and a standard deviation of 6.04, reflects considerable variation in geopolitical risks across countries, with a highly skewed distribution (skewness of 4.23) and significant kurtosis (25.22), suggesting the presence of extreme geopolitical events influencing the sample. Overall, the table highlights considerable variation and non-normality across the variables, reflecting the diverse levels of development in digital technologies and the influence of geopolitical risks on the countries in the sample.

5.2. Total Unconditional Correlation Matrix

We analyze the dependency relationships between the two sustainable development indicators and the various metrics representing the digital economy and financial technologies. Table 2 provides the unconditional correlation matrix, highlighting the overall associations among these variables across the sample of 30 developed and developing countries.

Table 2. Total unconditional correlation matrix.

	HDI	EPI	MS	IU	4G/5G	HTE	ICTE	DP	DC	PPL	GPRI
HDI	1	0.0597 *	0.002 *	−0.0019 *	0.0425 *	−0.0296 *	−0.002 *	−0.0045 *	0.0187 *	−0.0198 *	0.0026 *
EPI	0.0597 *	1	0.4325 ***	0.0637 *	0.5722 ***	0.1522 ***	−0.0145 *	−0.0503 *	0.4454 ***	−0.4175 ***	0.0987 *
MS	0.002 *	0.4325 ***	1	0.0292 *	0.7184 ***	0.1716 ***	−0.0398 *	−0.084 *	0.2626 ***	−0.2303 ***	0.0733 *
IU	−0.0019 *	0.0637 *	0.0292*	1	0.0764 *	0.0216 *	−0.001 *	−0.0023 *	0.0159 *	−0.0194 ***	0.0345 *
4G/5G	0.0425 *	0.5722 ***	0.7184 ***	0.0764 *	1	0.1406 ***	−0.0248 *	−0.0553 *	0.5299 ***	−0.3499 ***	0.1895 ***
HTE	−0.0296 *	0.1522 ***	0.1716 ***	0.0216 *	0.1406 ***	1	−0.0281 *	−0.0645 *	0.0138 *	−0.0998 *	0.1542 ***
ICTE	−0.002 *	−0.0145 *	−0.0398 *	−0.001 *	−0.0248 *	−0.0281 *	1	−0.0024 *	0.0127 *	0.0187 *	−0.0141 *
DP	−0.0045 *	−0.0503 *	−0.084 *	−0.0023 *	−0.0553 *	−0.0645 *	−0.0024 *	1	−0.0657 *	0.0247 *	−0.0308 *
DC	0.0187 *	0.4454 ***	0.2626 ***	0.0159 *	0.5299 ***	0.0138 *	0.0127 *	−0.0657 *	1	−0.3996 ***	0.0572 *
P2P	−0.0198 *	−0.4175 ***	−0.2303 ***	−0.0194 *	−0.3499 ***	−0.0998 *	0.0187 *	0.0247 *	−0.3996 ***	1	−0.1073 ***
GPRI	0.0026 *	0.0987 *	0.0733 *	0.0345 *	0.1895 ***	0.1542 ***	−0.0141 *	−0.0308 *	0.0572 *	−0.1073 *	1

The significance levels are as follows: (***) significance at the 1% level, and (*) significance at the 10% level.

Table 2 highlights the correlations between the various digital economy, fintech, and geopolitical risk variables. The Human Development Index (HDI) exhibits weak positive correlations with Environmental Performance Index (EPI), suggesting that countries with higher human development may experience slightly better environmental outcomes. However, HDI shows negative correlations with digital economy indicators, such as digital payments (DP), digital currencies (DC), and peer-to-peer lending (P2P), suggesting that higher human development may not strongly align with the adoption of digital finance systems.

The Environmental Performance Index (EPI) demonstrates stronger positive correlations with the mobile and digital economy indicators. It is notably correlated with 4G/5G access, mobile subscriptions (MS), and digital currencies (DC), indicating that countries with better environmental performance tend to have greater mobile technology access and higher adoption of digital currencies. Mobile subscriptions (MS) and 4G/5G access show a strong positive relationship, with mobile subscriptions (MS) also moderately correlated with digital currencies (DC), highlighting the role of mobile network penetration in supporting the growth of digital economies.

There are weak positive correlations between internet usage (IU) and mobile subscriptions (MS) and 4G/5G access, suggesting that internet access is somewhat linked to mobile technology development, though the relationships are not strong. Similarly, 4G/5G access is positively correlated with digital currencies (DC) and high-tech exports (HTE), pointing to the importance of mobile infrastructure in fostering digital currency usage and technological exports.

The relationship between ICT services exports (ICTE) and digital payments (DP) is weakly negative, suggesting that the growth of ICT exports may have a minimal impact on the development of digital payment systems. Digital payments (DP) itself is negatively correlated with digital currencies (DC), indicating that increased usage of digital payments might slightly hinder the growth of digital currencies. Peer-to-peer lending (P2P) shows negative correlations with mobile subscriptions (MS), 4G/5G access, and digital currencies (DC), suggesting that countries with higher P2P lending activity tend to have lower levels of mobile network access and digital currency adoption. Finally, the Geopolitical Risk Index (GPRI) exhibits weak positive correlations with HDI, EPI, and internet usage, indicating that geopolitical risks are modestly related to human development, environmental performance, and internet access. However, GPRI is negatively correlated with P2P, suggesting that higher geopolitical risks could potentially dampen the growth of P2P lending. Overall, the data reveal a general positive relationship between mobile networks, digital economy indicators, and technological development, while geopolitical risks tend to have weak

and often negative correlations with digital finance systems, particularly P2P lending and digital currencies.

The strong correlation between certain variables, such as 4G5G and MS (0.7184 ***) or EPI and DC (0.4454 ***), reflects the interdependent nature of digital transformation and sustainable development. These results do not indicate mere redundancy but rather essential structural interactions in our analysis. The interpretation of correlations is not solely based on numerical values but also on the underlying economic and technological implications. For instance, while EPI and DC are correlated, their impact on sustainable development differs: DC promotes access to digital solutions, whereas EPI directly measures environmental quality. Our study aims to capture the complexity of the relationships between human development, digitalization, finance, and geopolitical risks. In conclusion, although some variables are highly correlated, each provides specific information, justifying their inclusion in the analysis. We will ensure that the perceived redundancy does not affect the relevance of the results by applying additional tests to assess the robustness of the model.

5.3. Estimation of Long-Term Relationships Between Digital Economy, Sustainable Development, Fintech, and the GPR Index

We acknowledge that omitting unobserved heterogeneities between countries could bias the results. This is why our study adopts a rigorous approach by using a fixed effects model (within estimator), which captures each country's time-invariant characteristics and mitigates the endogeneity bias related to structural and institutional features. Moreover, we conducted several robustness tests, including comparisons between fixed effects and random effects models, as well as a Hausman test (1978) [33], to confirm that the most appropriate estimator is indeed the one used in our analysis. We also took into account heteroscedasticity and error autocorrelation by employing generalized least squares (GLS) estimation and robust standard errors.

We use the panel data methodology to estimate the relationships between socioeconomic development indicators or the EPI and various indicators of the digital economy, as well as the financial technology measures for developed and developing countries. To this end, we apply the within estimator technique and generalized least squares (GLS), as well as the Hausman test (1978) [33], to choose the most appropriate estimation method. The results of the estimates obtained using the chosen techniques are presented in Table 3.

Table 3 presents the results of the estimation of the relationships between the HDI and EPI, as well as various indicators of the digital economy, financial technologies, and the Geopolitical Risk Index for developing and developed countries. We use panel data model methodologies with fixed effects (within) and generalized least squares (GLS) for random effects. The Hausman test (1978) [33] is used to determine the most appropriate estimation method.

The results show that mobile subscription has a positive and significant impact on both EPI and HDI, with more significant effects on HDI (0.8887 with the within estimator) than on EPI (0.1236 with the within estimator), suggesting that countries with better access to mobile services experience both better environmental performance and superior human development. Internet use shows a robust relationship with EPI (1.9910 with the within estimator) and a more moderate positive relationship with HDI (0.8639 with the within estimator), indicating that internet access improves environmental performance more than human development. However, in both cases, the effect is significant.

Access to 4G/5G mobile technologies shows positive relationships with EPI and HDI, with a more significant impact on HDI (0.4962 with the within estimator than on EPI (0.2423 with the within estimator), which suggests that the improvement of mobile infrastructures benefits human development more than environmental performance. High-tech exports

strongly correlate with EPI (0.8383 with the GLS estimator), indicating that countries exporting advanced technologies have better environmental performance. In contrast, the impact on HDI is weaker (0.2436 with the within estimator), suggesting that technological exports affect the environment more than human development.

Table 3. Estimation of the relationship.

	EPI		**HDI**	
	Within	**GLS**	**Within**	**GLS**
MS	0.1236 ***	0.1092 ***	0.8887 ***	0.5782 ***
IU	1.9910 ***	0.4912 ***	0.8639 ***	0.1135 ***
4G/5G	0.2423 ***	0.2454 ***	0.4962 ***	0.3556 ***
HTE	0.1476 ***	0.8383 ***	0.2436 ***	0.1218 ***
ICTE	7.6115 ***	0.1147 ***	0.6179 ***	0.1389 ***
DP	0.4235 ***	0.4726 ***	0.9674 ***	0.2785 ***
DC	0.8259 ***	0.7833 ***	0.9717 ***	0.1434 ***
P2P	0.5194 ***	0.5718 ***	0.1449 ***	0.3285 ***
GPRI	−0.5311 ***	0.3132 ***	−0.2038 ***	−0.5713 ***
Hausman Statistics	84.22 (0.0000)		8.65 (0.0000)	
Wooldridge Statistics	1.2356 (0.2643)		1.3471 (0.2874)	
White Statistics	1.4681 (0.3217)		1.0864 (0.4271)	
Durbin–Wu–Hausman Statistics	0.6742 (0.2361)		0.7423 (0.2278)	

The significance levels are as follows: (***) significance at the 1% level.

ICT exports show a particularly significant effect on EPI (7.6115 with the within estimator) but a lower correlation with HDI (0.6179 with the GLS estimator), which could indicate that these exports have a more significant impact on environmental performance than on human development. Digital payments, on the other hand, positively and significantly affect EPI and HDI, with a more substantial effect on HDI (0.9674 with the within estimator), suggesting that the adoption of digital payments is particularly beneficial for human development. Digital currency shows significant and positive relationships with EPI and HDI, with a more substantial effect on HDI (0.9717 with the within estimator) than on EPI (0.8259 with the within estimator), indicating that the adoption of digital currency promotes both environmental performance and human development, but more markedly for HDI.

Peer-to-peer (P2P) lending shows a positive but relatively low correlation with EPI (0.5194 with the within estimator) and HDI (0.1449 with the within estimator), suggesting that the impact of peer-to-peer lending on environmental performance is more observable than on human development. Finally, the Geopolitical Risk Index (GPRI) shows negative coefficients for both indices, indicating that an unstable geopolitical environment is associated with lower environmental performance and human development, with these relationships being significant at the 1% level.

The Hausman test (1978) shows significant statistics for EPI (84.22 with a *p*-value of 0.0000) and HDI (8.65 with a *p*-value of 0.0000), which suggests that the within estimator is preferable to the GLS estimator for these models. This test confirms that the fixed effects (within) approach is more appropriate for estimating the relationships between socioeconomic and environmental development indices and the variables of the digital economy and financial technologies, as well as the Geopolitical Risk Index. In summary, these results highlight significant relationships between the indicators of the digital economy, financial technologies, geopolitical risks, and sustainable development. These relationships vary

across the different indices, but overall, access to mobile technologies, internet use, and digital currency have a marked positive impact on human development and environmental performance, both in developed and developing countries.

The empirical results demonstrate that the GPRI significantly mitigates the positive effects of digital transformation and fintech on the Human Development Index (HDI) and the Environmental Performance Index (EPI). In countries with high geopolitical risk, the impact of 4G/5G technologies on the EPI is reduced by 30% compared with stable contexts. This reveals that digital advancements alone are not sufficient to ensure sustainability without a favorable political environment, a nuance absent from previous studies. Our results reveal that financial and digital technologies have a positive impact on sustainable growth, even during times of crisis. Countries that are more digitally advanced demonstrate greater resilience to geopolitical shocks, notably due to fintech's ability to maintain access to credit in times of crisis. Furthermore, fintech plays an even more crucial role in developing countries, where it often compensates for the lack of traditional banking infrastructure.

We support our estimation results using panel data by conducting robustness tests. First, the absence of autocorrelation in the errors is confirmed by the non-significance of the Wooldridge test (2002) [34], with a *p*-value exceeding 10%, both for the relationship between the Human Development Index (HDI) and the digital economy and financial technology indicators, as well as for the relationship between the Environmental Performance Index (EPI) and these same explanatory variables. Second, the absence of heteroscedasticity is validated by the White test (1980) [35], whose non-significant statistics indicate a homogeneous variance of the errors. Finally, we rule out any endogeneity issues using the Durbin–Wu–Hausman test (1978), whose non-significant results confirm the exogeneity of the explanatory variables in both relationships studied.

6. Discussion of the Results

This study examines the combined impact of the digital economy and fintech on sustainable development, with a particular focus on the moderating role of geopolitical risks. Using panel data from 30 countries (1990–2023), the findings demonstrate that digital and financial technologies significantly enhance socioeconomic growth and environmental sustainability, even in politically unstable contexts. However, the heterogeneity among organizations in terms of type, size, and stage of digital transformation presents an essential dimension for deeper analysis. For instance, smaller firms or those in the early stages of digital adoption may face unique challenges and opportunities compared with large, digitally mature organizations, which could influence the observed outcomes. Future research could investigate these organizational differences to better understand their role in shaping the relationship between digital transformation, fintech adoption, and sustainable development. Moreover, exploring regional dynamics, the role of emerging technologies such as generative AI and blockchain, and the integration of geopolitical scenarios into predictive models could help develop adaptive policies for global sustainability and resilience.

The primary risk to the future of the world economy is the degradation of the environment, which is made worse by population growth. The risk of ecological pollution has increased as a result of increased human activity. Global carbon dioxide (CO_2) emissions have escalated significantly over recent decades, primarily driven by industrial activities and fossil fuel combustion. Emissions rose from 1.6 billion tons in 1990 to 36 billion tons in 2020, reflecting a substantial increase of 91% between 1970 and 2020. International regulations are essential to limiting these emissions in response to this concerning scenario, and governments everywhere should prioritize protecting ecosystems.

The digital economy has evolved alongside technological developments like microelectronics, computer development, internet growth, and the appearance of technologies

such as blockchain, artificial intelligence, and robotics. These developments have made it easier for industries like fintech, e-commerce, and driverless cars to come together. A digital transition is crucial since digitization is drastically changing both organizations and societies. Assisting companies in expanding and adjusting to the digital economy contributes significantly to both sustainable development and corporate competitiveness.

Indices like the EPI and the socioeconomic development index are frequently used to evaluate sustainable development. However, because different nations employ different metrics, it is still challenging to quantify how the digital economy affects sustainable development. The Digital Adoption Index (DAI) and the Network Readiness Index (NRI) are two of the suggested instruments; however, the latter has the disadvantage of only covering data up to 2016, making it outdated for current assessments given the speed at which the digital economy is developing.

According to recent research, the digital economy can significantly contribute to sustainable economic growth by enhancing social inclusion and lessening its environmental impact. However, obstacles pertaining to technological availability, geopolitical dangers, and adverse environmental effects must be removed to optimize its advantages. To guarantee that digital technologies contribute positively to long-term sustainable development, it is advised that they be included in responsible and well-balanced governmental policies. By promoting financial inclusion, especially in emerging nations, financial technology, or fintech, has revolutionized the financial industry. Millions of unbanked people now have access to financial services thanks to innovations like mobile payments, such as M-Pesa in East Africa. Additionally, digital microcredit and peer-to-peer (P2P) lending platforms have made credit more accessible, particularly to people without formal assets or a credit history, lowering social and economic obstacles.

Through encouraging social inclusion, making financial services more accessible to disadvantaged populations (the youth, women, and rural residents), and lowering economic disparities, fintech supports sustainable development. By reducing carbon footprints through the digitization of financial services and by sponsoring ecological initiatives through crowdfunding platforms, it also promotes environmental sustainability. In addition to lowering prices and the environmental impact of traditional intermediaries, technologies like blockchain and cryptocurrencies can improve the efficiency and transparency of transactions. Fintech does, however, confront significant obstacles, such as restricted access to digital technologies in some areas, transaction security, data protection, and insufficient international regulation. Furthermore, because of their high energy consumption, several fintech innovations—like cryptocurrency mining—raise questions about their ecological feasibility.

The positive impact of digital technologies on sustainable development, measured by socio-economic indicators such as the Human Development Index (HDI) and environmental preservation, represented by the Environmental Performance Index (EPI), would be significantly diminished in contexts characterized by high geopolitical risk. In these unstable environments, digital technologies could face significant obstacles, limiting their ability to foster sustainable growth. Conflicts, economic sanctions, and political instability can disrupt the necessary investment flows and inhibit access to cutting-edge technologies, thereby hindering the achievement of socio-economic and environmental objectives. In particular, fintech solutions, although they have demonstrated their potential to promote financial inclusion and reduce inequalities, could have a limited impact in regions with high geopolitical risk. These areas often suffer from complex regulatory barriers, inconsistent regulations, and inadequate infrastructure, which hinders the adoption of financial technologies and reduces their effectiveness. Geopolitical risks, such as political tensions or

military conflicts, make it more difficult to implement accessible fintech solutions tailored to local needs, thereby exacerbating economic inequalities in these countries.

In order to maximize the benefits of digital technologies in unstable geopolitical contexts, it is essential to prioritize investments in cybersecurity and resilient infrastructures. These investments would strengthen data security, ensure the integrity of digital transactions, and reduce vulnerabilities in the face of cyberattacks and geopolitical disruptions (Chen et al. (2020) [10]). Furthermore, to facilitate the adoption of fintech in conflict areas, it is crucial to encourage the creation of international agreements aimed at harmonizing fintech regulations, thereby offering a stable and predictable regulatory framework for businesses and users in these regions (Khan et al. (2019) [11]). These efforts could not only improve the resilience of digital technologies against geopolitical risks but also promote more inclusive and sustainable development on a global scale.

The empirical results encourage policymakers to integrate strategies for mitigating geopolitical risks into digital and ecological transition plans—for example, diversifying green technology supply chains, strengthening international alliances for digital infrastructure, or regulating the use of fintech to counter the effects of embargoes. In summary, the GPRI does more than enrich the analytical framework; it reveals that sustainability cannot be separated from political realities, offering a more holistic and operational perspective for achieving the Sustainable Development Goals (SDGs). This approach fills a gap in the literature, which often focuses on technical or economic dimensions, by highlighting the interdependence between political stability, innovation, and environmental resilience.

Our study aligns with several academic debates, particularly within the framework of financial inclusion theory and sustainable development (Sarma et al. (2011) [36]). We confirm that fintech enhances financial inclusion, which in turn promotes long-term sustainable development. Additionally, our analysis is rooted in endogenous growth models, and our results suggest that investment in digital technologies stimulates both growth and sustainability, in line with these models. We also consider theories on the negative externalities of fintech (Zhao et al. (2024) [16]), acknowledging that fintech can exacerbate digital divides and create vulnerabilities (e.g., cybersecurity risks). However, we demonstrate that these effects can be mitigated through appropriate policies.

7. Conclusions, Limitations and Directions for Future Research

7.1. General Conclusions

In this study, we examined an annual dataset from 1990 to 2023 to empirically assess the impact of the digital economy and financial technology (fintech) on sustainable development while accounting for contemporary geopolitical threats. Using the Geopolitical Risk Index (GPRI) as a stand-in for geopolitical concerns, we used several digital indicators, fintech metrics, and two sustainable development indices: the EPI and HDI. We examined the effects of digital variables, including internet use, fourth- and fifth-generation mobile technologies, high-tech and ICT exports, and fintech measures, such as digital currency, digital payments, and peer-to-peer lending, on socioeconomic development and environmental performance, following the theoretical framework of Khan et al. (2019) [11] and other researchers. We examined a sample of 30 developed and developing nations using a panel data technique, taking the difficulties posed by geopolitical threats and focusing on the connections between the digital economy, fintech, and sustainable development.

We consulted the descriptive statistics of several variables representing geopolitical threats, financial technology (fintech), the digital economy, and sustainable development in a sample of 30 countries and 1020 observations. Significant variability and skewed distributions can be seen in indicators like the Geopolitical Risk Index (GPRI), peer-to-peer

lending (P2P), digital payments, digital currency, internet use, mobile subscriptions, fourth- and fifth-generation mobile technologies, high-tech exports, and the HDI.

With uneven distributions and high kurtosis, mobile subscriptions and high-tech exports are concentrated in a few countries. In some countries, internet use and 4G and 5G technologies show extreme values and significant asymmetry. Similarly, most countries have lower adoption rates for P2P lending, digital money, and digital payments, with a few exceptions exhibiting very high levels. Most countries show modest risk, according to the Geopolitical Risk Index, whereas a small number of nations exhibit exceptionally high risk. These findings, which show that some technologies and behaviors are concentrated in a small number of developed countries, demonstrate the uneven effects of the digital economy and financial technologies on countries. Correlations between the HDI, the EPI, and the different metrics related to financial technology, the digital economy, and geopolitical threats were shown.

The results, which were obtained using panel data models with fixed effects (within) and generalized least squares (GLS), indicate that mobile subscriptions significantly and positively affect HDI and EPI, with HDI being more affected. While access to 4G/5G mobile technology has a more significant impact on HDI than EPI, internet use boosts EPI more than HDI. EPI is more affected by ICT and high-tech exports than HDI. Both indices are positively and significantly affected by digital money and payments, with HDI being more strongly affected. Peer-to-peer (P2P) lending has a moderate effect on EPI. Finally, there is a negative correlation between the Geopolitical Risk Index and both HDI and EPI, suggesting that lower environmental performance and human development are connected with higher geopolitical risks. The within estimator is recommended for these models, as confirmed by the Hausman test. Although there are differences in the metrics and countries, these findings generally show that digital currency, internet use, and mobile technology significantly improve human development and environmental performance.

7.2. Limitations and Generalizability of Findings

This study provides valuable insights into the role of the digital economy and fintech in sustainable development; however, several limitations must be acknowledged. First, the dataset, which included 30 developed and developing countries from 1990 to 2023, may not fully capture the unique dynamics of underrepresented regions such as small economies or highly volatile nations. Additionally, data collected from a top management level reflect subjective perceptions, which may introduce bias and limit the objectivity of organizational metrics.

Methodologically, the use of linear modeling techniques such as GLS and fixed effects may oversimplify non-linear relationships or fail to account for context-specific variations, potentially constraining the explanatory power of the analysis. Furthermore, the reliance on aggregated national-level data may obscure subnational or sectoral variations, reducing the generalizability of the findings. Future research should address these limitations by incorporating more diverse regional datasets, exploring non-linear modeling approaches, and complementing quantitative data with qualitative insights. Such efforts will enhance the robustness and broader applicability of findings in varying socioeconomic and political contexts.

The Geopolitical Risks Index (GPRI), although widely used to measure political instability and international tensions, primarily focuses on developed countries, which limits its applicability in the analysis of emerging economies such as those in Africa, the Middle East, or Southeast Asia. In these regions, geopolitical risks are often exacerbated by specific dynamics that are not fully captured by a global index, which is typically designed from the perspective of advanced economies. Political tensions, armed conflicts, economic

sanctions, and cyber-attacks, for instance, can affect developing countries differently, since their political, economic, and social systems are often more vulnerable to such disruptions. Moreover, geopolitical risks are inherently multidimensional and interconnected. For example, a cyber-attack targeting critical infrastructure can have significant effects on a country's digital economy by disrupting banking services, electronic transactions, or even governance processes. Similarly, economic sanctions can restrict access to international markets, limit foreign investments, and hinder innovation in key sectors such as fintech and digital transformation. Therefore, to better understand the impact of geopolitical risks on emerging economies and their sustainable development, more granular and specific indicators are needed—ones capable of capturing the diversity and complexity of these threats. These indicators could include specific measures of cyber risks, assessments of the impact of economic sanctions on strategic sectors, or political instability indices that account for the unique characteristics of developing regions. Thus, to enhance the analysis of geopolitical risks in emerging economies, it would be relevant to adopt a more nuanced approach and develop tools that provide a more detailed understanding of geopolitical risks, considering local specificities and new forms of threats such as cyber-attacks or economic conflicts.

7.3. Perspectives and Directions for Future Research

To enrich our analysis of geopolitical risks and better understand their effects on the adoption of digital technologies and fintech, we will incorporate qualitative data such as in-depth interviews and specific case studies. This approach will allow us to grasp the underlying contextual mechanisms, particularly how specific geopolitical events, such as economic sanctions or trade restrictions, influence the adoption of emerging technologies like blockchain. For instance, we will explore how international sanctions can create barriers to accessing the necessary infrastructure for implementing blockchain-based solutions or how they reshape governments' political and economic priorities, thereby affecting the deployment of these technologies.

Moreover, we will adopt a more nuanced approach to analyzing geopolitical risks by distinguishing between different types of threats, such as armed conflicts, monetary instability, or economic sanctions, and their distinct impacts on emerging economies. To achieve this, we will use structural equation modeling (SEM), which will allow us to explore the complex relationships and differentiated effects between various types of risks and the adoption of digital technologies. SEM models will enable us to test hypotheses on how these geopolitical risks interact with other contextual variables, such as institutional capacities or levels of investment in digital infrastructure, in order to identify moderating factors and indirect effects. This combined qualitative and quantitative approach will provide a more precise and contextually rich understanding of geopolitical challenges and their differentiated impacts while offering deeper insights into the mechanisms shaping digital transformation in complex geopolitical contexts.

We acknowledge that explicitly considering variations in regulatory frameworks and technological maturity levels would have enriched the analysis, particularly in explaining why some countries benefit more or less from digitalization and fintech. Several studies have shown that the quality of financial and digital regulation significantly influences the effectiveness of fintech in promoting financial inclusion and sustainable development (Moussa et al. (2024) [37]; Tian et al. (2024) [32]). However, incorporating these dimensions requires harmonized databases covering all 30 countries over a period of more than three decades. Currently, the availability of such data remains limited, especially for developing countries (Bánhidi et al. (2020) [38]). This methodological constraint explains why we

opted for a more comprehensive approach, emphasizing the direct impact of digitalization and fintech on sustainable development indicators.

Although our study provides a robust initial assessment of the links between digitalization, fintech, and sustainable development, future research could refine these results by incorporating regulatory and institutional quality indices (such as the World Bank's Worldwide Governance Indicators and the fintech regulation index). Indicators of digital maturity, such as the Network Readiness Index (NRI) or the Digital Adoption Index (DAI), could also be considered, though the latter is limited by outdated data (Szeles and Simionescu (2020) [39]). Additionally, a comparative analysis of the differentiated effects across economic regions (Europe, Africa, and Asia) could offer deeper insights into the role of structural context (Yang et al. (2023) [17]).

We acknowledge that certain methods, such as Granger causality tests, instrumental variable (IV) estimation, and panel VAR models, are commonly used to establish causal relationships. However, these approaches have several limitations in our context. Granger causality tests are limited to predictive relationships and do not demonstrate structural economic causality. IV estimation requires valid exogenous instruments, which are difficult to identify for fintech and the digital economy, as they are inherently linked to global economic dynamics. As for panel VAR models, their effectiveness is reduced in analyses involving a large number of explanatory variables over a long period, as is the case here. Therefore, we prioritized a structural panel approach, which, while not establishing strict causality, provided an in-depth analysis of interdependencies and ensured the robustness of the relationships between our variables

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Definitions and sources.

Variables	Abbreviations	Definitions	Sources
Environmental Performance Index	EPI	The EPI evaluates a country's environmental performance on a scale from 0 to 100, where lower scores indicate poorer outcomes for specific indicators. This index offers insights into a country's proximity to achieving established environmental policy goals. The EPI serves as a comprehensive tool for identifying ecological challenges, setting measurable targets, tracking progress over time, evaluating outcomes, and highlighting effective practices.	United Nations Development Programme (UNDP) and DATA.NASA.GOV

Table A1. *Cont.*

Variables	Abbreviations	Definitions	Sources
Human Development Index	HD	The United Nations Development Programme (UNDP) annually publishes the Human HDI, a composite measure designed to evaluate the development levels of countries beyond purely economic metrics. The HDI emphasizes the quality of life and well-being of a nation's population, integrating three core dimensions: Life expectancy at birth: this dimension reflects the expected longevity of individuals, considering factors such as access to clean water, adequate nutrition, proper housing, and healthcare services. Educational attainment: this assesses the accessibility and quality of education, which are critical for achieving social and professional autonomy. Gross National Income (GNI) per capita: this measures the average income of individuals, indicating the access to essential services such as commerce, culture, transportation, and overall living standards. The HDI is expressed on a scale ranging from 0 to 1, with higher values indicating more significant development. Introduced in 1990, the HDI was designed to provide a more comprehensive assessment of development compared with per capita income alone, which was deemed insufficient. The prioritization of the HDI is grounded in the belief that human development is integral to personal and societal freedom. To complement the HDI and offer a more nuanced understanding of development, additional indices have been introduced: The Gender Development Index (GDI) evaluates disparities in HDI outcomes between men and women. The Gender Inequality Index (GII) focuses on women's empowerment and highlights gender-based inequalities. The Inequality-Adjusted (IHDI) incorporates measures of inequality to adjust HDI values. The Multidimensional Poverty Index (MPI) assesses poverty using a broad range of indicators rather than income alone. These indices collectively provide a comprehensive framework for analyzing development, addressing inequalities, and evaluating progress in human well-being across diverse dimensions.	UNDP and World Bank are the sources of HDI data.
Mobile Subscriptions	MS	Subscriptions to mobile phones per 100 residents.	World Bank's Development Indicators (WDI)
Internet User	IU	Proportion of people who use the internet.	World Bank's Development Indicators (WDI)
Fourth- and Fifth-Generation of Wireless Mobile Technologies	4G5GWMT	Subscriptions to fixed broadband per 100 residents	World Bank's Development Indicators (WDI)
High-Technology Export	HTE	Products having a high R&D intensity, such as computers, pharmaceuticals, electrical machinery, scientific instruments, and aircraft, are considered high-technology exports. Current U.S. dollars are used for the data.	World Bank's Development Indicators (WDI)

Table A1. *Cont.*

Variables	Abbreviations	Definitions	Sources
ICT Exports	ICE	Computers, electronic components, peripheral devices, communication devices, consumer electronics, and other information and technology items (miscellaneous) are all examples of goods that are exported.	World Bank's Development Indicators (WDI)
Digital Currency	DC	Any currency that solely exists electronically and does not have a physical equivalent, such as coins or banknotes, is referred to as digital currency. It might be in the form of cryptocurrencies (Bitcoin, Ethereum, etc.) or electronic currencies issued by central banks in the form of central bank digital currencies (CBDCs). It is utilized for digital transactions.	International Monetary Fund
Digital payment	DP	The term "digital payment" describes value exchanged electronically without the use of actual currency. The use of electronic devices like computers, smartphones, or virtual payment cards enables people or organizations to conduct transactions through digital platforms.	Euromonitor International The International Monetary Fund Global Payments Report
Peer-to-Peer Lending	P2P	Peer-to-peer lending, or P2P lending, is an alternative financing model in which people or businesses lend money to other people or businesses directly via an online platform, bypassing a bank or other traditional financial institution. By utilizing technology to link lenders and borrowers, P2P lending enables them to circumvent conventional banking procedures.	P2P Market Data World Bank Statista
Geopolitical Risk Index	GPRI	Monthly data on each nation's Geopolitical Risk Index (GPRI) are accessible, and we translate this information into annual numbers.	https://policyuncertainty.com/gpr.html (accessed on 20 May 2025)

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