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The Nexus Between Green Finance, Green Energy, Green Technology, and Fintech: A Pathway to Sustainable Development*

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ABSTRACT

Green finance, energy, technology, and fintech are essential drivers of a sustainable environment and the promotion of sustainable development. This study analyzes the causal relationships among green finance, green energy, green technology, and fintech indices. To ensure the reliability of our findings, we utilize daily data from reputable sources such as S&P Green Bond for green finance, S&P Global Clean Energy for green energy, Renewable Energy and Clean Technology for green technology, and S&P Kensho Future Payments for fintech indices. Following our objective, a Vector Autoregressive Regression (VAR) model is constructed first, followed by Granger causality and impulse response analysis. The causality results indicate bidirectional causal relationships between green finance and green energy and green technology, as well as one-way causal relationships from green finance to green technology and from green energy to green technology. Impulse response analysis shows that the green energy index is a significant shock transmitter to the green bond index. In contrast, the green technology index is a significant shock transmitter to the fintech index. The findings suggest that capital support for green finance is vital for promoting green energy and technology and supporting sustainable development.

Keywords: Green Finance, Fintech, Green Bond, Green Technology, Green Energy, Sustainable Development

Yeşil Finans, Yeşil Enerji, Yeşil Teknoloji ve Fintek Arasındaki Bağlantı: Sürdürülebilir Kalkınmaya Giden Yol

ÖZ

Yeşil finans, yeşil enerji, yeşil teknoloji ve Fintek sürdürülebilir çevreyi desteklemek ve sürdürülebilir kalkınmayı teşvik etmek için önemli itici güçler olarak görülmektedir. Bu kapsamda çalışmada yeşil finans, yeşil enerji, yeşil teknoloji ve fintek endeksleri arasındaki nedensel ilişkilerin 28/02/2014 – 06/03/2024 döneminde araştırılması amaçlanmaktadır. Çalışmada yeşil finans için S&P Green Bond, yeşil enerji için S&P Global Clean Energy, yeşil teknoloji için Renewable Energy and Clean Technology ve Fintek için S&P Kensho Future Payments endekslerine ait günlük veriler kullanılmıştır. Amaç doğrultusunda ilk olarak Vektör Otoregresif Regresyon (VAR) model oluşturulmuş, ardından Granger nedensellik ve etki-tepki analizi gerçekleştirilmiştir. Nedensellik bulgularına göre, yeşil finans ve yeşil enerji, yeşil teknoloji ve Fintek arasında çift yönlü nedensel ilişkiler olduğu ve yeşil finanstan yeşil teknolojiye doğru ve yeşil enerjiden yeşil teknolojiye doğru tek yönlü nedensel ilişkiler olduğu tespit edilmiştir. Etki-tepki analiz bulgularına göre ise, yeşil enerji endeksinin yeşil tahvil endeksine ve yeşil teknoloji endeksinin Fintek endeksine önemli bir şok aktarıcısı olduğu gözlemlenmiştir. Bulgular genel olarak yeşil finansa sağlanan sermaye desteğinin yeşil enerji ve yeşil teknolojiyi geliştirmek ve sürdürülebilir kalkınmayı desteklemek için önemli olduğunu göstermektedir.

Anahtar Kelimeler: Yeşil Finans, Fintek, Yeşil Tahvil, Yeşil Teknoloji, Yeşil Enerji, Sürdürülebilir Kalkınma

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1. Introduction

Environmental issues such as ecological imbalance, global warming, and inefficient resource use have become a growing concern for policymakers on a global scale. These issues directly impact social development and human survival. As consumption demands increase, ecosystems, climate change, environmental quality, and economic conditions come under pressure. To address these problems, a green economy has been introduced, aiming to promote low energy consumption, reduce pollution, and decrease emissions. Achieving sustainable development requires shifting investment models towards green technologies, particularly emphasizing low-carbon investments. To facilitate this, green finance needs to be encouraged. According to the United Nations, an annual investment of $1.5 trillion in green finance is necessary to meet the Paris Agreement's requirements. The financial sector is particularly vulnerable to climate change due to its direct impacts and the changing risk perceptions of customers and government policies aimed at reducing climate risks. (Liu et al., 2020; Madaleno et al., 2022; Balsalobre-Lorente et al., 2023; Nur et al., 2023).

Green finance is a term used by the United Nations Environment Programme (UNEP) to describe financial flows from public, private, and non-profit sectors directed towards sustainable development priorities. Its main aim is to create and distribute financial products and services that provide both investable returns and positive environmental outcomes (Lee, 2020). Green finance promotes sustainable development by directing social capital towards economic sectors that support the environment, such as renewable energy, green buildings, addressing the climate crisis, corporate governance, and environmental protection. Various types of green financial products exist, including green bonds, green investments, green insurance, and carbon finance, which can effectively channel investment capital into climate change mitigation and adaptation projects (Wang et al., 2022). Green bonds are critical for financing green projects such as renewable resources, water and energy efficiency, bioenergy, and low-carbon transportation. They are essential for sustainable development policies, as they provide an appropriate tool to finance a low-carbon economy and redistribute climate change mitigation costs across generations (Nur and Ege, 2022; Ege et al., 2023).

Green energy and technology are vital for reducing climate change, supporting environmental sustainability, and promoting sustainable development. To achieve this, it is necessary to identify environmentally friendly sources of growth, develop new eco-friendly industries, and create jobs and technology. Therefore, increasing investments and innovations that support sustainable development and create new economic opportunities are essential (Guo et al., 2020; Sharif et al., 2023). Green bonds provide a significant source of financing for renewable energy projects, enabling investors to balance their financial goals with their environmental sensitivities. Along with the growing interest in sustainable investment, these bonds accelerate the transition to a low-carbon future, contributing significantly to establishing and expanding clean energy facilities. In recent years, the global green bond market has grown rapidly and reached record highs, reflecting the increasing investor interest in sustainable energy projects (Wang and Wang, 2023). Madaleno et al. (2022) stated that green finance is vital for financing renewable and clean energy projects to reduce carbon emissions and ensure environmental sustainability. Therefore, green finance is expected to enhance environmental sustainability by financing energy and resource-efficient technologies. The energy sector requires financial support for both production and operation. Green finance is dedicated to funding green energy projects to promote the growth of the green energy industry. Consequently, the green finance market has become increasingly significant in securing financing for clean energy, primarily relying on advancing green technology (Li et al., 2022; Pang et al., 2022).

On the other hand, the lack of sufficient contracts, participants, and individuals with market knowledge creates an incomplete structure in financial markets, which stands out as one of the main challenges businesses face. In markets with insufficient competition, businesses have difficulty obtaining the capital they need, hindering their long-term growth. However, financial technologies (fintech) can revolutionize the financial services sector, significantly reducing barriers to access to finance for businesses (Chen, 2023). In addition, fintech is crucial in enabling green finance by utilizing big data analytics and artificial intelligence to promote green practices among consumers and small and medium-sized businesses (SMEs). Fintech can contribute to sustainable development by transforming resource management in several ways, such as increasing access to finance, enhancing transparency in supply chains, implementing eco-friendly financial services, and reducing carbon emissions and paperwork (Tan et al., 2023; Tiwari, 2024). Fintech development, however, has transformed the financing of renewable energy projects. Recently, innovative solutions such as crowdfunding, peer-to-peer lending systems, and digital investment platforms have become widespread. These approaches effectively overcome traditional barriers to financial support for sustainable energy projects. By enabling broader participation from individual and institutional investors, these platforms reduce the financing gap and support implementing sustainable energy programs (Sreenu, 2024).

Based on the above discussion, this study aims to examine the causal links between green finance, green energy, green technology, and fintech from February 28, 2014, to June 3, 2024. The study period was defined as the first and last time for which data on the index were accessible. This study contributes to the literature in several ways. Analyzing previous studies reveals that the findings differ depending on the method, period, and sample. Therefore, empirically revealing the relationships between these variables, which are theoretically assumed to influence each other, contributes to developing more effective strategies for sustainable development policies and environmentally friendly investments. Moreover, the study considers S&P Green Bond for green finance, S&P Global Clean Energy for green energy, Renewable Energy and Clean Technology for green technology, and S&P Kensho Future Payments for fintech indices (Assaf et al., 2024; Adekoya et al., 2025). Thus, it provides a new framework for understanding the interrelationships among these indices and draws new conclusions about the relationship between sustainable finance, energy, and technology. On the other hand, investigating the causal relationships among green finance, green energy, green technology, and fintech is closely linked to portfolio management and risk analysis. Therefore, the findings are critical for the strategic decisions of investors and portfolio managers.

The paper is structured as follows: Section 2 reviews the previous empirical literature; Section 3 details the dataset and methods used; Section 4 presents and discusses the empirical findings; and finally, Section 5 concludes the paper with conclusions and policy implications.

2. Literature Review

The growth of the green bond market has been shaped by factors such as increasing global awareness of the need to combat climate change, the development of green finance policies, and rising demand for sustainable investments. The 2015 Paris Agreement, which seeks to limit global warming below 2°C, has significantly influenced governments, companies, and investors, accelerating efforts in this area (Hu and Jin, 2023). On the other hand, digital technologies present numerous opportunities for developing innovative financing solutions. The energy sector considers fintech a game-changer due to its innovative nature and substantial impact. Promoting the allocation of funds towards energy efficiency yields significant social, environmental, and ecological benefits (Al-kasasbeh et al., 2024). In this context, numerous empirical studies have investigated the impact of green finance, green energy, green technology, and fintech on the sustainable environment and development. Meo and Karim (2022) find that green finance reduces environmental pollution in 10 countries that support it. Similarly, Sharif et al. (2022) find similar results in G7 countries, while Cao (2023) finds positive results in E7 countries and Zhang and Chen (2023) in China. Furthermore, many studies support the notion that green technology, green energy, and fintech contribute to a sustainable environment and development (Bilal et al., 2021; Lin and Ma, 2022; Udeagha and Ngepah, 2023; Usman, 2023; Chen et al., 2023).

On the other hand, some empirical studies have focused on the relationships between green finance, green energy, green technology, and Fintech indices. Chatziantoniou et al. (2022) examine the dynamic integration and return transmission between the S&P Green Bond Index, MSCI Global Environment, Dow Jones Sustainability Index World, and S&P Global Clean Energy indices. They find that the S&P Green Bond Index and the S&P Global Clean Energy Index emerge as net shock receivers. In contrast, the MSCI Global Environment and the Dow Jones Sustainability Index emerge as shock transmitters. Madaleno et al. (2022) find bidirectional causal relationships between green finance, clean energy, environmental responsibility, and environmental protection indices. Chatziantoniou et al. (2022) investigate the dynamic integration and return transmission between four well-known environmental financial indices: S&P Green Bond Index, MSCI Global Environment, Dow Jones Sustainability Index World, and S&P Global Clean Energy. The authors find that the S&P Green Bond Index and the S&P Global Clean Energy are both short-term and long-term shock receivers, while the MSCI Global Environment and Dow Jones Sustainability Index World stand out as both short-term and long-term shock transmitters. From a different perspective, Tiwari et al. (2023) find that price volatility in fintech markets contributes to the sensitivity of the price levels of renewable and fossil energy stocks, green bonds, environmentally focused stocks, and sustainable development projects. The authors argue that innovative green fintech can provide financial support to green projects and businesses, reducing asset-liability ratios and costs, alleviating liquidity problems, and increasing the financial strength of businesses. They also suggest that through equity financing, financial institutions can improve corporate governance by contributing to enterprises' management processes and supporting long-term sustainable growth.

Zhang and Umair (2023) find significant dynamic spillover effects between corporate bonds and renewable energy stocks, carbon markets, and renewable energy stocks. Focusing on the relationship between Fintech, green bonds, China's clean energy production and green investment risk dynamics, Wang and Wang (2023) emphasize that Fintech plays a critical role in facilitating the financing of sustainable energy initiatives in China. The authors argue that the proliferation of Fintech platforms and technologies has supported the growth of renewable energy projects, facilitated access to capital, and increased confidence in the viability of these projects. Dong and Huang (2024) find that positive fintech developments and reduced financial stress positively impact clean energy stocks in the global market from 2013 to 2022. The authors argue that fintech acts as a catalyst to encourage sustainable investments and restores investor confidence in the financial services sector. On the other hand, Liu and Wang (2024) find that fluctuations in the financial technology index contribute to the sensitivity of renewable energy stock prices in a global sample. Mohammed et al. (2024) investigate the market responses between AI, Fintech, non-greenwashing, and environmentally friendly markets in the US from 2017 to 2023. The authors identify significant volatility linkages between these groups and express the need for sustainable technology financing policies and real-time monitoring systems to address market volatility. Sheenan et al. (2024) examine the relationship between European sustainable bond markets and key financial markets, including corporate bonds, government bonds, renewable energy, equity, and volatility markets. They find bidirectional contagion between the sustainability-linked bond market and the green bond market, as well as contagion between other fixed income markets and the sustainable bond market.

Although an increasing number of studies examine the individual effects of green finance, green energy, green technology, and fintech on sustainable development, research on the causal relationships between these markets is limited. A review of the existing literature reveals that different indicators are used for green finance, green energy, green technology, and fintech, and the findings differ depending on the methodology and period used. Moreover, the role of fintech in the green transformation process is uncertain. Therefore, this paper aims to provide a more holistic perspective on the interconnected dynamics driving green transformation in financial markets by addressing these gaps to understand the evolution of these relationships, which are sensitive to market and policy changes.

3. Methodology

This section outlines the study's purpose, scope, dataset, and methodological framework, structured under relevant subheadings to ensure clarity and coherence.

3.1. Data

The study aims to determine the causal relationships among green finance, green energy, green technology, and fintech, covering the period from February 28, 2014, to June 3, 2024. It follows the existing literature and includes S&P Green Bond for green finance (Sinha et al., 2021; Zhang and Umair, 2023), S&P Global Clean Energy for green energy (Fuentes and Herrera, 2020; Dias and Silva, 2023; Rao et al., 2023), S&P Renewable Energy and Clean Technology (Rao et al., 2023) for green technology, and S&P Kensho Future Payments (Darehshiri, 2022; Ceron and Mengo, 2023; Liu, 2024) for fintech. The indices used in this study represent digital finance and green economy-based assets. The S&P Kensho

Future Payments Index includes companies developing next-generation payment solutions such as digital wallets, real-time payments, and biometric security. The S&P Green Bond Index is a selective indicator that tracks only green bonds that finance environmentally friendly projects. The S&P Global Clean Energy Transition Index measures the performance of global companies operating in clean energy. At the same time, the S&P/TSX Renewable Energy and Clean Technology Index includes TSX-listed companies developing green technology and sustainable infrastructure solutions (spglobal.com). These indices contribute to investment evaluations focusing on environmental sustainability and digital transformation. The study period was defined as the launch date of the S&P Green Bond index and the last date for which data on the index were accessible. The secondary data used in the study was obtained from spglobal.com.

3.2. Econometric Method

Determining the stationarity properties of the series is crucial for the statistically valid application of time series analysis methods and ensuring the reliability of the results. Accordingly, to assess the causality between green finance, energy, technology, and fintech markets, the stationarity of the series is first analyzed using the Dickey and Fuller ADF (1981), the Augmented Dickey-Fuller test (ADF), and the Phillips and Perron (1988) (PP) tests. Three different models have been developed for the ADF test, and the regression equation of the models is presented in Eq.

$$\Delta\gamma_t = \delta\gamma_{t-1} + \sum_{i=2}^{p} \beta_i \Delta\gamma_{t-i+1} + \varepsilon_t \tag{1}$$
$$\Delta\gamma_t = \mu + \delta\gamma_{t-1} + \sum_{i=2}^{p} \beta_i \Delta\gamma_{t-i+1} + \varepsilon_t \tag{2}$$
$$\Delta\gamma_t = \mu + \delta\gamma_{t-1} + \delta_2 \sum_{i=2}^{p} \beta_i \Delta\gamma_{t-i+1} + \varepsilon_t \tag{3}$$

Equation (1) above refers to the model without a constant and trend, equation (2) refers to the model with a constant and trend, and equation (3) also refers to the model with a constant and trend. The basic assumptions and hypotheses of the PP test are the same as those of the ADF test. However, the differences are that the PP test requires the series to follow a normal distribution, to be heterogeneous, and to have no autocorrelation among the error terms. Similarly, three different models are developed for the PP test, and the regression equations of the models are shown in Equations 4-6.

$$\gamma_t = \delta\gamma_{t-1} + \varepsilon_t \tag{4}$$
$$\gamma_t = \beta_1 + \delta\gamma_{t-1} + \varepsilon_t \tag{5}$$
$$\gamma_t = \beta_1 + \delta\gamma_{t-1} + \beta_2 \left(\mathrm{t} - \frac{\mathrm{T}}{2}\right) + \varepsilon_t \tag{6}$$

As in the ADF test, in the PP test, equation (4) refers to the model without a constant and trend, equation (5) refers to the model with a constant and trend, and equation (6) also refers to the model with a constant and trend. After testing the stationarity of the series, a Vector Autoregressive (VAR) model is constructed for causality and impulse response analysis. The VAR model is constructed using the standard VAR equation.

$$\mathrm{y_t} = \mathrm{a_1} + \sum_{\mathrm{i=1}}^{\mathrm{p}} \mathrm{b_{1i}y_{t-i}} + \sum_{\mathrm{i=1}}^{\mathrm{p}} \mathrm{b_{2i}x_{t-i}} + \mathrm{v_{1t}} \tag{7}$$

The VAR model is a statistical method that utilizes past values of dependent variables to make predictions. It does not distinguish between endogenous and exogenous variables. In this model, "p" represents the number of past values used for predictions, while "v" signifies the stochastic error terms. These error terms follow a normal distribution, have a constant variance, and have a zero mean. They also exhibit zero correlation with their past values. The VAR model can provide accurate predictions by leveraging past values of dependent variables. Furthermore, the VAR model helps investigate causality (Sims, 1980). The Granger (1969) causality test is a statistical assessment that examines whether the coefficients of past values of the explanatory variable are collectively zero. If they are, it suggests no causal relationship between the variables. The equation for the Granger (1969) causality test is expressed as follows.

$$\Delta x_t = \propto_0 + \sum_{j=i}^{k} \propto_{1j} \Delta x_{t-j} + \sum_{j=1}^{k} \propto_{2j} \Delta y_{t-j} + \varepsilon_{1t} \tag{3}$$

$$\Delta y_t = \beta_0 + \sum_{j=i}^{k} \beta_{1j} \Delta y_{t-j} + \sum_{j=1}^{k} \beta_{2j} \Delta x_{t-j} + \varepsilon_{2t} \tag{4}$$

The equation above contains two error terms, denoted as $\mathcal{E}_{1t}$ and $\mathcal{E}_{2t}$, which are uncorrelated. The variable k represents the number of lags for both variables. An impulse response analysis was conducted to determine the causal relationships between the variables. Impulse response analysis is a method used to investigate the impact of a random shock in one variable's error term within the VAR model on other variables in the system. It can also ascertain whether the variables can act as policy instruments. The VAR matrix form presents impulse response functions (Sims, 1980).

$$\begin{bmatrix} y_t \\ x_t \end{bmatrix} = \begin{bmatrix} a_{10} \\ a_{20} \end{bmatrix} + \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{bmatrix} y_{t-1} \\ x_{t-1} \end{bmatrix} + \begin{bmatrix} e_{1t} \\ e_{2t} \end{bmatrix} \tag{5}$$

For moving average ($\mathcal{E}_{yt}$) and ($\mathcal{E}_{xt}$) series,

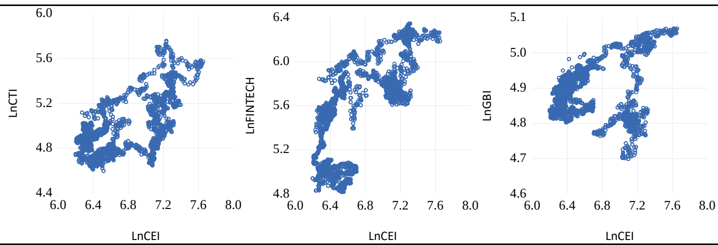
$$\begin{bmatrix} y_t \\ x_t \end{bmatrix} = \begin{bmatrix} \bar{y} \\ \bar{x} \end{bmatrix} + \sum_{i=0}^{\infty} \begin{pmatrix} \Phi_{11(i)} & \Phi_{12(i)} \\ \Phi_{21(i)} & \Phi_{22}(i) \end{pmatrix} \begin{bmatrix} \varepsilon_{yt-1} \\ \varepsilon_{xt-1} \end{bmatrix} \tag{6}$$

The coefficients of ϕ_i in equations (ε_{yt}) and (ε_{xt}) can be utilized to identify the effects of shocks on the entire time path of the y_t and x_t series.

4. Results

To analyze the linkages between green finance (S&P Green Bond Index - GBI), green energy (S&P Global Clean Energy Index - CEI), green technology (S&P Renewable Energy and Clean Technology Index - CTI) and fintech (S&P Kensho Future Payments Index), descriptive statistics are first presented (Table 1). All series used in the study were logarithmically transformed. The relationships between variables were observed by creating scatter plots in Table 1. Correlation coefficients were then calculated between the series. Subsequently, the findings of the unit root test, the Vector Autoregression (VAR) model, causality analysis, and impulse-response functions are systematically presented in the following.

Table 1. Descriptive Statistics

Stats.	GBI	CEI	CTI	FINTECH	LnGBI	LnCEI	LnCTI	LnFINTECH
Mean	135.034	865.665	149.319	274.932	4.902	6.688	4.976	5.529
Median	134.920	692.895	137.330	265.430	4.904	6.540	4.922	5.581
Maximum	158.990	2113.520	316.000	569.680	5.068	7.656	5.755	6.345
Minimum	109.800	492.810	99.120	123.200	4.698	6.200	4.596	4.813
Std. Dev.	10.479	357.059	39.228	114.184	0.077	0.374	0.232	0.421
Skewness	0.349	1.010	1.543	0.606	0.183	0.652	1.023	-0.032
Kurtosis	2.519	2.913	5.104	2.571	2.498	1.976	3.452	1.898
Jarque-Bera	75.243***	428.516***	1462.176***	173.519***	40.443***	288.218***	459.904***	127.472***
Observations	2514	2514	2514	2514	2514	2514	2514	2514
Scatter Plots								

Note: *, **, and *** denote the significance of the 10%, 5%, and 1% levels, respectively.

Upon analyzing Table 1, it was discovered that out of the variables- green finance (135.034), green energy (866.665), green technology (149.319), and fintech (274.932)- green energy has the highest mean, whereas green finance has the lowest mean. Additionally, green energy has the highest standard deviation (357.059). The LnFINTECH is negatively skewed to the right, while LnGBI, LnCEI, and LnCTI are positively skewed to the left. The LnFINTECH, LnGBI, LnCEI, and LnCT series exhibit positive kurtosis values, indicating that the data set has a pointed tail concerning the peaks. The J-B values for all variables are significant at the 1% significance level, suggesting that the variables do not adhere to a normal distribution. Logarithmic transformations of all variables were used to conduct the analyses. Moreover, a time graph illustrated in Figure 1 was created to observe the variables' changes over time.

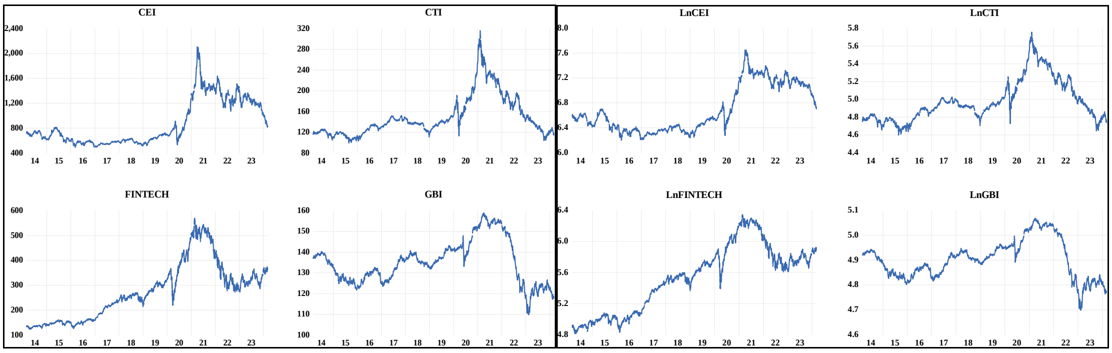


Figure 1. Indices Over Time

Figure 1 displays a decreasing trend in the variables during 2019, which can be attributed to the COVID-19 pandemic reducing interest in green investments. Taghizadeh-Hesary et al. (2021) argue that the COVID-19 pandemic and global recession have reduced investments in green projects worldwide, jeopardizing the achievement of climate-related goals. However, there was an increase in the performance of all indices during 2020-2021. This suggests that sustainable investments have significantly improved despite the pandemic. According to the results of descriptive statistics, the Spearman correlation test was applied because there was no normal distribution. The results of the correlation test are shown in Table 2.

Table 2. Spearman's Correlation Matrix

LnCEI	1.000	0.471***	0.655***	0.299***
LnCTI	0.471***	1.000	0.774***	0.636***
LnFINTECH	0.655***	0.774***	1.000	0.434***
LnGBI	0.299***	0.636***	0.434***	1.000
***p < 0.01, **p < 0.05, *p < 0.1.	LnCEI	LnCTI	LnFINTECH	LnGBI

The results of the Spearman correlation test indicate that all the indices have statistically significant relationships with one another. Consequently, the highest correlation is observed between LnFINTECH and LnCTI (0.774), while the lowest correlation is found between LnGBI and LnCEI (0.299). In the context of the impulse-response analysis applied within the VAR model, there is no high correlation between the series that would lead to a multicollinearity issue. Before examining the relationships among the indices, the stationarity of the variables was evaluated. The results of the unit root test are presented in Table 3.

Table 3. Unit Root Test Results

	ADF				PP			
Variables	t-stat	Prob.	t-stat	Prob.	t-stat	Prob.	t-stat	Prob.
LnGBI	-0.820	0.812	-0.735	0.969	-0.876	0.796	-0.789	0.965
ΔLnGBI	-44.840	0.000	-44.850	0.000	-45.059	0.000	45.045	0.000
LnCEI	-1.227	0.664	-1.747	0.729	-1.177	0.686	-1.609	0.789
ΔLnCEI	-17.390	0.000	-17.380	0.000	-44.382	0.000	-44.374	0.000
LnCTI	-1.405	0.581	-0.970	0.946	-1.440	0.563	-0.943	0.949
ΔLnCTI	-17.920	0.000	-17.950	0.000	-50.295	0.000	-50.308	0.000
LnFINTECH	-1.295	0.633	-1.719	0.742	-1.282	0.639	-1.608	0.789
ΔLnFINTECH	-33.960	0.000	-33.950	0.000	-52.626	0.000	-52.627	0.000
	Constant		Constant and Trend		Constant		Constant and Trend	

For the ADF and PP, the null hypothesis (H_0) suggests that a given time series contains a unit root, implying non-stationarity, while the alternative hypothesis (H_1) suggests that the series is stationary. According to the ADF and PP test results presented in Table 3, the null hypothesis is rejected for all variables in both the constant and trend specifications, implying that the series is non-stationary at levels. However, the null hypothesis cannot be rejected when first-order differences are taken, indicating that all variables become stationary at I(1). The PP unit root test was applied to consolidate the ADF test results. The PP test results show that all series are non-stationary at level values and become stationary when first differences are taken. Accordingly, the root results of the ADF and PP units are mutually supportive. After confirming stationarity, a Vector Autoregression (VAR) model is constructed. All series were stationarized and analyzed using the VAR model. The results of the lag length selection criteria for the VAR model are reported in Table 4.

Table 4. VAR Model Lag Length

Lag	LogL	AIC	SC	HQ
0	31585.77	-25.285	-25.276*	-25.282
1	31645.13	-25.320	-25.273	-25.303
2	31683.71	-25.338	-25.254	-25.307
3	31700.52	-25.339	-25.217	-25.295
4	31751.80	-25.367	-25.208	-25.309
5	31841.32	-25.426	-25.230	-25.355
6	31861.84	-25.429	-25.196	-25.345
7	31929.21	-25.470	-25.200	-25.372
8	31996.83	-25.512	-25.204	-25.400*
9	32022.24	-25.519*	-25.174	-25.394
10	32032.76	-25.515	-25.133	-25.376

The lag length for the VAR model is determined to be 9 using the LR, FPE, and AIC information criteria. Figure 2 displays the AR characteristic polynomial inverse roots for the VAR model constructed based on the specified lag length.

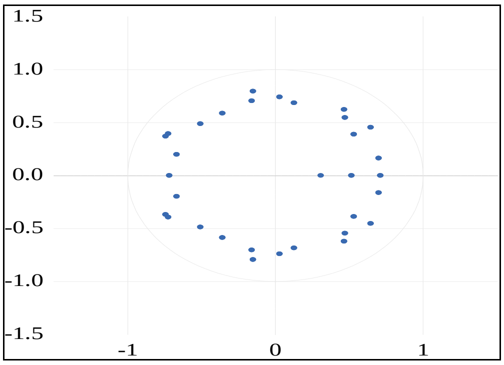


Figure 2. VAR Model Stationarity Graph

After analyzing the stationarity graph of the VAR model, it was observed that the inverse AR roots are within the unit circle, which indicates that the model is stationary. The autocorrelation issue in the model was further investigated, and the results of the LM tests are presented in Table 5.

Table 5. Autocorrelation LM Test Results

Lag	LRE*stat	df	Prob.	Rao F-stat	df	Prob.
10	21.020	16	0.177	1.314	(16, 7531.3)	0.177
20	20.705	16	0.190	1.294	(16, 7531.3)	0.190
30	14.213	16	0.582	0.888	(16, 7531.3)	0.582
40	19.021	16	0.267	1.189	(16, 7531.3)	0.267
50	13.931	16	0.603	0.870	(16, 7531.3)	0.603

Upon analyzing the LM test results, it was observed that the test probability values are higher than the critical value of 0.05, indicating no autocorrelation issue in the model. The model's assumptions were examined, and Granger causality analysis was performed. The results of the analysis are presented in Table 6.

Table 6. Granger Causality Test Results

Causality			Chi-sq	Prob
LnGBI	→	LnCEI	20.449	0.008
LnCEI	→	LnGBI	151.055	0.000
LnGBI	→	LnCTI	16.055	0.041
LnCTI	→	LnGBI	4.259	0.833
LnGBI	→	LnFINTECH	3.609	0.890
LnFINTECH	→	LnGBI	8.074	0.426
LnCEI	→	LnCTI	15.983	0.023
LnCTI	→	LnCEI	5.043	0.752
LnCEI	→	LnFINTECH	2.305	0.970
LnFINTECH	→	LnCEI	5.632	0.688
LnCTI	→	LnFINTECH	321.938	0.000
LnFINTECH	→	LnCTI	21.846	0.005

In Table 6, the causality test results indicate bidirectional causal relationships between green finance, green energy, green technology, and fintech. However, it has been confirmed that unidirectional causal relationships exist between green finance and green technology and between green energy and green technology. The study suggests that green bonds may play a significant role in financing clean energy and green technology. This is due to the substantial funding requirements of green investments, which often necessitate support from both the public and private sectors. Private capital is likely to complement public funding in promoting environmentally sustainable initiatives. Accordingly, it may benefit investors and companies to consider green bonds as a potential instrument for financing clean energy and technology in alignment with the Sustainable Development Goals. The findings indicate that capital support for green finance could be vital in fostering the growth of green energy and technology, thereby contributing to broader sustainability objectives (Madaleno et al., 2022). It has been observed that there is a two-way connection between fintech and green technologies, indicating that both significantly promote the green transition of businesses. Financial technologies aid in sustainable development by managing resources effectively. However, it has been found that there is no direct causal relationship between green finance and financial technologies. Therefore, investors and companies should concentrate on using green bonds to finance financial technologies and support sustainable development by promoting green technologies. Furthermore, an impulse response analysis was conducted following the causality analysis, and the results are illustrated in Figure 3.

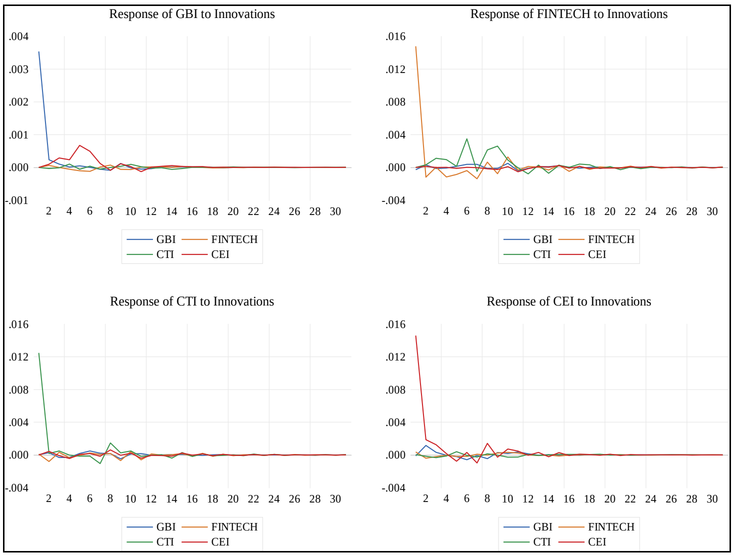


Figure 3. Impulse-Response Results

Based on the analysis of the impulse response, it can be inferred that a shock in fintech, green energy, and green technology results in a positive shock in the green finance series. Notably, the impact of the shock in green energy is significantly greater. These effects fade away and converge to zero after day 15. Thus, the green energy index is crucial for transmitting shocks to the green bond index and acts as a hedge against green energy investments. Moreover, a shock in green technology leads to a positive shock in the fintech series between days 5 and 10, and this effect disappears and converges to zero after day 20. Similarly, the green technology index serves as a significant shock transmitter to the fintech index and acts as a hedge against fintech investments. These results confirm the causality findings.

5. Conclusions and Recommendations

The study aims to analyze the relationships between green finance, green energy, green technology, and fintech indices from February 28, 2014, to June 3, 2024. To achieve this, the study employs a VAR model, Granger causality, and impulse response analysis. The results reveal bidirectional causal relationships between green finance and green energy, green technology, and fintech, as well as unidirectional causal relationships from green finance to green technology and from green energy to green technology. The impulse response analysis indicates that a shock in fintech, green energy, and green technology leads to a positive shock in the green finance series; however, this effect dissipates after the 15th day and converges to zero. Additionally, the study finds that the green energy index significantly affects the green bond index, while the green technology index impacts the fintech index. The findings align with studies by Chatziantoniou et al. (2022), Madaleno et al. (2022), Tiwari et al. (2023), Zhang and Umair (2023), Wang and Wang (2023), and Dong and Huang (2024), which confirm the relationship between green bonds, clean energy, sustainability, and fintech indices.

The findings of this study reveal that green bonds can be utilized as an effective instrument for financing both green energy and green technology investments. Green bonds are recognized as a reliable instrument for investors because they provide funds that adhere to the principles of transparency and accountability in financing projects that contribute to environmental sustainability goals. This is crucial for expanding green energy infrastructure and developing environmentally friendly technologies. The findings also indicate a bidirectional causal relationship between fintech and the advancement of green technologies. Fintech applications can enhance capital flows by enabling sustainable investments to reach a broader investor base, such as by facilitating investment in green projects through digital platforms, digitizing participation in carbon markets, or developing sustainability-based credit systems.

While green bonds support clean energy and green technology, no significant impact on fintech was identified during the analysis. Given the high financing needs associated with green investments, private sector engagement is essential for progress towards sustainability. Therefore, raising awareness among investors and companies about green finance, energy, technology, and financial mechanisms can be beneficial for advancing environmental and development goals. Consequently, promoting green finance as a strong and reliable financing mechanism, supporting it with policies to enhance environmental sensitivity in capital markets, and directing investors towards sustainability-based investments can contribute to achieving environmentally sound economic growth. Moreover, awareness campaigns, training programs, and the diversification of sustainable investment products can accelerate the green transformation of the financial system.

For future research, country-specific empirical analyses should be conducted using various country-specific indices. Additionally, asymmetric relationships (e.g., different responses to positive and negative shocks) and risk pass-through mechanisms should be investigated more deeply. Such studies would contribute to a better understanding of green financial integration at the global level.

Araştırmacıların Katkı Oran Beyanı / Contribution of Authors

Yazarların çalışmadaki katkı oranları Emre Esat TOPALOĞLU %35/ Tuğba NUR %35/ İlhan EGE %30 şeklindedir.
The authors' contribution rates in the study are Emre Esat TOPALOĞLU %35/ Tuğba NUR %35/ İlhan EGE %30 form.

Çıkar Çatışması Beyanı / Conflict of Interest

Çalışmada herhangi bir kurum veya kişi ile çıkar çatışması bulunmamaktadır.
There is no conflict of interest with any institution or person in the study.

İntihal Politikası Beyanı / Plagiarism Policy

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Bu çalışmada Yükseköğretim Kurumları Bilimsel Araştırma ve Yayın Etiği Yönergesi kapsamında belirtilen kurallara uyulmuştur.
In this study, the rules specified within the scope of the Higher Education Institutions Scientific Research and Publication Ethics Directive were followed.

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