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S.I. : GREENWASHING

Can multifarious types of green bonds be accused of greenwashing with a durative analysis? Insights from a permanent causality vs. temporary causality phenomenon

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Abstract
Green bonds are useful monetary tools that can finance sustainable endeavors to bolster an eco-friendly economy. This research inspects the frequency-domain causal relationship between diverse green bond types and the green economy from June 30, 2014 to August 3, 2023. The goal is to understand both permanent and temporary causal phenomena between them. The findings reveal that only pioneering green bonds display a robust bidirectional causal link with an eco-efficient economy. Meanwhile, other green bond types, like conventional, municipal, and currency-dominated green bonds, may be susceptible to greenwashing due to the absence of a thorough permanent causal tie with an ecologically sustainable economy. Additionally, enhancing pioneering green bonds by integrating ESG (Environmental, Social, and Governance) stocks can transform the cause-and-effect dynamic between specific green bonds and the green economy. It shifts from a bilateral cause to a unilateral one stemming from the environmentally friendly economy and extending to distinguished green bonds. This phenomenon persists whether the 5% annual fee for sustaining and managing the index combining green bonds and ESG equities is considered or not. Interestingly, an environmentally conscious economy, in both persistent and transient associations, consistently affects ecological bonds with diverse traits. This highlights the importance of the overall state of an environmentally responsible economy in enhancing green bonds. These discoveries provide novel perspectives for green market regulators and policymakers to design improved standards for green assets.

Keywords Green bonds · Municipal green bonds · Greenwashing · Frequency-domain causality approach · Permanent causality

1 Introduction

Green bonds exemplify an ingenious financial instrument that redirects private capital to ecologically sustainable undertakings. The funds garnered through such debt issuances are expressly allocated to finance green initiatives, as delineated by pre-established

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parameters. Transparency is imperative, with issuers obligated to report on the application of capital to uphold accountability. In essence, green bonds empower issuers to bankroll environmentally conscious endeavors like renewable energy, energy efficiency, and sustainable water management, while furnishing investors fixed-income returns for championing such virtuous causes. The appeal is multifaceted—investors can align investments with personal values while still reaping yields, and issuers may even dangle tax incentives that further sweeten the proposition. In the process, communities and the environment also stand to benefit from the positive effects of the projects funded by green bonds. It is a win–win solution for everyone involved. Green bonds enable a win–win solution—investors earn returns while projects funded catalyze environmental and social progress. The projects financed can reduce pollution, restore environments, improve efficiency, and enhance community climate resilience. Thus, green bonds align financial outcomes with ethical values, channeling finance sustainably. This symbiosis makes green bonds an innovative instrument that advances conscientious capitalism and more livable communities (García-Lamarca & Ullström, 2022; Key et al., 2021; Nel & Hill, 2014). Green bonds undergo meticulous verification processes to ensure proceeds strictly finance eco-conscious ventures. The International Capital Market Association's Green Bond Principles offer best practices guiding issuers to augment transparency, disclosure, and integrity, thus safeguarding green bonds' legitimacy in financing sustainable development. Although voluntary, compliance is encouraged to amplify credibility in capital markets. The principles advocate clear communication of environmental aims, oversight of funds, and consistent reporting on allocation and impact. Overall, rigorous certification per esteemed standards like the GBP engenders trust in green bonds fulfilling sustainability commitments. By maintaining stringent oversight and transparency, green bonds can validate their role as a credible vehicle for investors to bankroll environmental progress (Ehlers & Packer, 2016; Shishlov et al., 2016).

Critically, issuers are encumbered with ensuring projects satisfy all applicable environmental standards. Of course, one must be wary of potential greenwashing, where sustainability claims are hyperbolic or outright duplicitous. Prudence dictates meticulous due diligence into both the project and issuer credentials and assertions. Additionally, investors should evaluate risks like interest rate fluctuations and inflation, as with any fixed-income vehicle. Overall, green bonds proffer an ingenious win–win value proposition of financing environmental progress while providing investors attractive yields, provided measures are taken to validate issuer credibility and claims (Lu, 2021; Mejía-Escobar et al., 2021; Shishlov et al., 2016).

There exist several variants of green bonds, each with distinct attributes and aims. Use of Proceeds (UoP) Green Bonds represent the most common type of green bonds. The bond issuer accumulates capital through the bond issuance and later directs the accrued revenue to finance or refinance green projects. Such endeavors can include renewable energy deployments, energy efficiency upgrades, sustainable water management, green building construction, and more. UoP green bonds are structured to ensure the mobilized funds are utilized solely for environmentally beneficial purposes (Fatica & Panzica, 2021; Tuhkanen & Vulturius, 2022). Furthermore, Green Project Bonds, similar to Use of Proceeds bonds, are issued to fund distinct green projects. The primary divergence is that green project bonds are often linked to a particular project's cash flows and income generation, providing investors with exposure to the financial performance of the endeavor (Cicchiello et al., 2022; Horsch & Richter, 2017). Moreover, Green Securitized Bonds are backed by an aggregation of assets that generate green cash flows. For example, a portfolio of renewable energy installations' cash flows could underpin a green securitized bond. This bond variety aids in diffusing the risk across various projects and enhances the scalability of green finance (Tang & Zhang, 2020; Yunita et al., 2023).

The multiplicity of green bond varieties caters to the multifaceted dimensions of sustainable development. Collectively, these instruments contour the green sector through financing, forming project implementation, instigating policy reforms, encouraging collaboration, and addressing ecological and social challenges. By furnishing capital for green initiatives, these bonds augment the supply of sustainable investments, invigorating the green industry. The diverse green bond types provide tailored incentives for varied efforts, promoting cooperation among stakeholders and coaxing policy changes that advance sustainability objectives. In unity, these impacts engender a more sustainable and resilient future. Green bonds supply the capital to construct green infrastructure and operations (Adhikari & Taylor, 2012; Gregory, 2023). They shape the real-world execution of environmental and social projects. They motivate public and private sector coordination on sustainability. And they advocate for reforms that ingrain sustainability in economic systems. The symbiotic effects of the green bond ecosystem drive systemic transitions toward ecological resilience and social equity. Green bonds thus epitomize a potent lever in mobilizing finance to accelerate sustainable development. However, if a type of green bond does not meaningfully contribute to the green economy and is employed primarily for marketing or perception purposes without conferring substantial environmental benefits, it may be deemed a form of greenwashing (Badenhoop, 2022). This is because greenwashing is a deceptive form of marketing that deliberately distorts the environmental benefits of a product, service, or organization. By issuing green bonds that do not actually contribute to a green economy, companies are obscuring their environmental impact and giving a false impression of their commitment to sustainability. This can be detrimental to the public perception of sustainability initiatives and may even diminish trust in companies and organizations. As such, it is imperative for companies to be transparent in their environmental commitments and to accurately report the impacts of their initiatives (Shi et al., 2023).

In this research study, we closely inspected the causal connections between a diverse set of independent green bonds and ESG (Environmental, Social, and Governance) equity-integrated green bond market indices and the wider green economy. Our primary intention was to introduce these types of relational associations as a helpful metric for thoroughly exploring the concerning issue of greenwashing, considering both the enduring and long-lasting nature as well as the transient and short-term nature of this phenomenon. Our current study makes several novel contributions to the existing literature and knowledge base in this domain. First, the green bonds we examined can be categorized into three distinct groups of green bond market indices, specifically global green bond market indices, municipal green bond market indices, and currency-denominated green bond market indices. While these various indices seem to represent more targeted and niche segments of the overall and comprehensive green bond market, they could still be collectively grouped together under the broad umbrella category of general green bond market indices given their common unifying theme of tracking the performance of the green bond asset class as a whole. The key differentiators between these groups relate primarily to geographic focus, bond type specificity, and currency denomination parameters. As the second key contribution, we divided the global green bond market indices into two main types of differentiated green bonds, namely the S&P Green Bond Index which maintains very stringent standards and criteria in order to only include those specific bonds whose proceeds are definitively used to finance certified environmentally friendly projects, and the S&P Green Bond Select Index that seeks to accurately measure the performance of all globally issued green-labeled bonds, subject to very stringent financial eligibility criteria as well as comprehensive extra-financial eligibility criteria. Thirdly, we thoroughly evaluated the precise effect and impact of ESG-screened equities penetration into the core relationship between standardized green bonds and the advancement of a regenerative economy model. In fact, in an alternative scenario, we first integrated ESG equities with selectively chosen green bonds in order to enhance them in a balanced manner and optimize opportunities for capital growth, and then after establishing this integration, we subsequently inspected the exact shape and nature of the causal links between these ESG equities-modified preferred green bonds and the ideals of a circular economy. We used two distinct versions of ESG equities modification, first by accounting for the 5% annual fee typically charged by the index provider or manager for maintaining and comprehensively administering the ESG stocks-green bonds merged index, and second by completely ignoring this annual index administration fee. Lastly, we thoroughly differentiated between enduring and everlasting causalities versus momentary and transient causalities by using a sophisticated spectral Granger causality analytical approach which helped us to very precisely investigate the intricate relationships from short-term, medium-term, and long-term perspectives.

Our in-depth empirical results and findings definitively demonstrate that only those global green bonds rated and designated as excellence-level securities have a truly comprehensive, holistic, and ironclad permanent two-way causality interaction with the wider eco-economy across all measured timescales and angular frequencies, which could unequivocally refute accusations of greenwashing for this highest caliber and grade of global green bond type. In stark contrast, non-excellent and lower-tier global green bonds cannot consistently play the definitive role of cause in the specific case of catalyzing growth in the green economy at some critical short-term and long-term time intervals related to both transient and enduring timescale analysis perspectives, and it is in fact the sustainable green economy itself which distinctly plays the primary role of cause in more extended and comprehensive short-term and long-term frequency ranges when it comes to these non-excellent global green bonds. Moreover, the intricate two-way causality relationship between locally issued municipal green bonds and a climate change stabilization focused green economy has considerable and non-trivial exceptions in both causal directions, and we could distinctly observe that their mix of perennial and ephemeral back-and-forth causalities are not fully valid or accurately applicable for all of the empirically examined time frequencies. The main substantive difference between municipal green bonds and non-excellence global green bonds that emerges from the data is that the supportive and reinforcing cause character of the environmental sustainability focused economy in catalyzing the municipal green bonds is markedly less pronounced and prominent compared to the case of lower-grade non-excellence global green bonds. However, for the specific cases of currency-denominated green bonds as well as both types of ESG stocks-linked preferred green bonds, there is no evidence of permanent or temporary causality relationships stemming from the eco-bonds themselves to the sustainable green economy, and only currency-denominated green bonds demonstrate even a minimal degree of temporary causality in the direction of the low-carbon green economy. These nuanced findings are strongly reinforce the work of Dill (2023) which claimed that green bonds as an asset class are also significantly heterogeneous in terms of amount issued, currency denomination, type of environmental or climate project financed, and overall development level of the country's domestic capital market. Therefore, this work brings valuable new insights and perspectives for green securities designers and clean economy focused market policy makers so that they can more appropriately distinguish between the different segments of green bonds currently trading in global financial markets. In particular, our rigorous study makes novel contributions to the evolving regulatory and oversight viewpoints of the diverse range of actively engaged governmental, independent, and civil society organizations which are working to foster more honest and accurate environmental claims and impact reporting in the rapidly expanding area of sustainable finance.

The paper will progress as follows: Section 2 reviews relevant literature. Sections 3 and 4 delineate the methodologies and materials used. Section 5 presents the analysis results. Finally, Sect. 6 discusses policy implications and conclusions.

2 Literature review

The utilization of green bonds has garnered substantial recognition as a prominent financial instrument over recent years, showcasing remarkable global growth since their inception in 2013. Despite its relative novelty, the extant corpus of scholarly literature pertaining to green bonds remains somewhat limited. In this context, Ge and Liu (2015) conducted an empirical investigation aimed at discerning the nexus between a firm's Corporate Social Responsibility (CSR) performance and the expenses associated with the issuance of new bonds within the US market. Their findings illuminate that companies demonstrating stronger CSR performance enjoy cost advantages when issuing bonds. Consistent findings in this vein have been corroborated by Oikonomou et al. (2014). Expanding upon this research landscape, Bauer and Hann (2010) conducted a comprehensive analysis encompassing a diverse sample of publicly traded US corporations across various industries. Their study unveiled a positive correlation between environmental concerns and heightened costs of debt financing, coupled with a negative association between proactive environmental policies and debt costs. Moreover, the study identified environmental concerns as a contributing factor to diminished credit ratings. Similarly, Menz (2010) scrutinized the European corporate bond market and found that socially responsible firms, under analogous circumstances, exhibited a slightly greater risk premium compared to their non-socially responsible counterparts, albeit with minimal statistical significance. Furthermore, Zerbib (2019) conducted an extensive examination of 135 green bonds possessing investment-grade ratings issued on a global scale. His findings indicated that investors displayed a discernible inclination to accept an additional eight basis points of yield in order to invest in green bonds post-issuance. Notably, considerable attention has been devoted to issuers beyond corporate entities. Karpf and Mandel (2017) investigated the performance of green bonds vis-à-vis conventional bonds within the US municipal bonds market and unearthed indications of a market penalty for green bonds.

With few notable exceptions, the fundamental structural characteristics of green bonds closely mirror those of traditional bonds within the fixed-income market. Green bond offerings manifest a risk-return profile consistent with conventional bond issuances. The price dynamics and yield to maturity (YTM) of green bonds bear notable resemblance to those of their conventional counterparts. Empirical research in recent times has underscored a strong association between YTM in green bonds and conventional bonds, as exemplified by Wanke (2017). A conventional utilization of profits within the realm of green bonds pertains to a financial liability vehicle that bestows liability upon the issuer in cases of default concerning interest payments or principal repayment. Vigilant oversight of the capital raised through such bonds typically entails the creation of a dedicated sub-account or the implementation of an internal protocol within the issuing entity. Conversely, green revenue bonds can be characterized as non-recourse financial instruments, where credit risk is contingent upon assured cash flows stemming from revenue streams, fees, and taxes, as delineated by the International Capital Market Association (ICMA) in 2017. Funds derived from these bonds possess the potential to be allocated toward environmentally sustainable initiatives, irrespective of their direct thematic alignment. In a different vein, a green project bond denotes a bond issuance exclusively earmarked for funding one or more green projects. The underwriter assumes full risk, irrespective of issuer involvement, in alignment with guidelines articulated by Ceres (2014) and ICMA (2017). Green securitized bonds constitute financial instruments backed by specific green endeavors and may take diverse forms, including covered bonds and asset-backed securities, as explicated by ICMA (2017). In cases of payment default, these bonds typically offer recourse solely to the underlying assets, with their repayment contingent on the cash flows generated by these assets, an illustration provided by Kaminker and Stewart (2012).

The G20 Green Finance Study Group (GFSG) recently conducted a survey that unearthed a notable impediment impeding the advancement of the green bond market, particularly in developing nations. The study findings underscore that a significant majority, up to 74% of respondents, identified a substantial challenge in the form of a limited understanding of established global protocols governing green bond transactions (GFSG, 2016). This lack of awareness assumes particular significance in developing countries, where it may be exacerbated by the failure of policymakers, bond issuers, and investors to recognize the merits of green bonds. Furthermore, the absence of universally recognized standards governing green bonds, as posited by the Organization for Economic Co-operation and Development (OECD, 2017), in conjunction with the nascent emergence of this financial instrument, contributes to the existing knowledge gap. Moreover, the presence of inadequate institutional frameworks in select developing nations constitutes an additional obstacle to the widespread adoption of green bonds. It is not uncommon for distinct government departments, each possessing unique mandates and expertise, to pursue divergent and potentially conflicting objectives when implementing governmental programs. Consequently, in regions lacking robust public support for climate policies, initiatives promoting environmental sustainability may find themselves relegated to lower priority (Obradovich & Zimmerman, 2016). In his seminal research in 2015, Mark Carney elucidates the likely repercussions of climate change on the economy, coining the term “tragedy of the horizon.” Temporal myopia encapsulates the tendency of investors and stakeholders to inadequately consider environmental concerns, primarily due to the gradual unfolding of these perils over extended timeframes. This phenomenon, where investors often fail to fully integrate environmental hazards into their assessments, finds support in academic scholarship (Hong et al., 2019). This enduring trend persists despite the existence of substantial empirical evidence highlighting the significant financial consequences associated with both physical risks, such as climate-related droughts and floods, and transition risks, denoting the potential for profound changes in environmental regulations (Caldecott et al., 2014). A noteworthy manifestation of this transformative dynamic is observable in credit rating agencies’ commitment to incorporate the financial risks stemming from the shift toward more stringent carbon emission regulations, as mandated by the Paris Agreement, into their assessments of credit risks for issuers operating in environmentally detrimental industries (Moody’s Investors Service, 2016b).

The existing body of literature has made notable progress in elucidating the intricate nexus between corporate sustainability performance, bond issuance costs, and stakeholder investment behavior in the realm of green bonds. However, there are conspicuous gaps in research that necessitate further investigation. Firstly, there is a dearth of studies that comprehensively explore the nuanced dynamics of green bond performance across diverse market segments and geographies. Although some studies have examined the green bond market in the USA, an extended cross-country analysis is imperative to gain a comprehensive understanding of how environmental, social, and governance (ESG) considerations influence the costs of bond issuance and investor preferences in varied financial landscapes. Conducting cross-sectional investigations of this nature would facilitate the identification of whether the observed cost advantages for socially responsible firms, as documented in the US context, hold true in other regions or if variations arise due to disparate market conditions, regulatory frameworks, or investor behaviors. Secondly, when considering the evolving role of green bonds in emerging economies and their impact on sustainable development, it becomes evident that the research gap is pronounced. Existing studies predominantly focus on developed markets, potentially neglecting the unique characteristics and challenges associated with green bond issuance in emerging economies. An imperative research agenda should thus scrutinize the drivers and barriers of green bond adoption in developing countries and examine the influence of these instruments on environmental sustainability and economic growth. The understanding of how green bonds can act as catalysts for sustainable development in emerging markets and how they interact with the distinctive socio-economic contexts therein would yield valuable insights into the global expansion of green finance and contribute to the resolution of pressing environmental and developmental challenges.

3 Methodology

In divergence from conventional Granger causality analyses, the estimation procedure employed in this research facilitates prognostication of outcome variables at distinct time frequencies (Breitung & Candelon, 2006). This intimates the methodology enables the discernment of historical fluctuations, wherein policy interventions could potentially be implemented. However, it is prudent to note this approach has a delimited time horizon and cannot presage infinite time models. The causal framework utilized herein, operating within the frequency domain, strictly adheres to the specifications delineated in Hosoya's erudite work (Hosoya, 1991). While furnishing perspicacity into causal relationships at precise frequencies, acknowledging the constraints of a finite time scope is judicious. Additional scholarly inquiry employing alternative frameworks could enable more extensive prognostication of long-term patterns. Nevertheless, the frequency-based analysis undertaken in this study rigorously complies with established academic conventions and protocols.

We begin by representing the time series as two-dimensional vectors $\left[x_{\mathrm{t}}, y_{\mathrm{t}}\right]'$, consisting of the elements x_{t} and y_{t} at discrete time points t = 1, …, T. It is hypothesized that yt follows a finite-order vector autoregressive model denoted as $\theta(L)d_{\mathrm{t}} = \varepsilon_{\mathrm{t}}$, where $\theta(L)$ takes the form $I - \theta_1 L - \ldots - \theta_{\mathrm{p}} L^{\mathrm{p}}(L^{\mathrm{k}} d_{\mathrm{t-k}}$ being a lag polynomial) and ε_t denotes the residual term. This formulation, framed within a moving average context, assumes stationarity of the process. Notably, the positive definite error term ε_{t} is expressed via Cholesky decomposition, elegantly capturing the underlying structure of the phenomenon under study. In this work, the matrix of coefficients is artfully encapsulated by the symbol ψ, while the symbolic representation of white noise is embodied in the appellation η. It is within this conceptual framework that the following proposition is expounded:

$$d_t = \begin{bmatrix} \psi_{11}(L) & \psi_{12}(L) \\ \psi_{21}(L) & \psi_{22}(L) \end{bmatrix} \begin{bmatrix} \eta_{1t} & \eta_{2t} \end{bmatrix} \tag{1}$$

The revelation of the spectral density linked to the variable designated as x_t is articulated in the subsequent manner:

$$f_x(\omega) = \frac{1}{2\pi}\left\{ \left|\psi_{11}\left(e^{-i\omega}\right)\right|^2 + \left|\psi_{12}\left(e^{-i\omega}\right)\right|^2 \right\} \tag{2}$$

In the ensuing discourse, the configuration of the causal estimation as posited by Hosoya (1991) is expounded upon in the subsequent manner:

$$M_{y\to x}(\omega) = \log\left[\frac{2\pi f_x(\omega)}{\left|\psi_{11}\left(e^{-i\omega}\right)\right|^2}\right] = 1 + \log\left[\frac{\left|\psi_{12}\left(e^{-i\omega}\right)\right|^2}{\left|\psi_{11}\left(e^{-i\omega}\right)\right|^2}\right] \tag{3}$$

Here, ω symbolizes the frequency, and y does not exert causal influence upon $x(\mathrm{y} \to \mathrm{x})$ at the specific ω frequency when the magnitude of $\left|\psi_{12}\left(e^{-i\omega}\right)\right|$ equals zero. Should $d_t = \left[x_t, y_t\right]$ demonstrate cointegration, the vector autoregressive representation of finite order, expressed as $\theta(L)d_t = \varepsilon_t$, takes form:

$$\Delta d_t = \left(\theta_1 - I\right)d_{t-1} + \theta_2 d_{t-2} + \ldots + \theta_p d_{t-p} + \varepsilon_t = \tilde{\theta}(L)d_{t-1} + \varepsilon_t \tag{4}$$

The assessment of causality within a frequency domain for elements that exhibit cointegration ($\left[x_t, y_t\right]$) can be formulated as follows:

$$\Delta d_t = \tilde{\phi}(L)\varepsilon_t = \tilde{\xi}(L)\eta_t \tag{5}$$

In this context, let $\tilde{\phi}(L) = \tilde{\phi}(L)G^{-1}, \eta_t = G\varepsilon_t$, and the matrix G, which is lower triangular, is characterized by $E\left(\eta_t \dot{\eta}_t\right) = I$. Consequently, the expression denoting cointegration between the elements $\left(\left[x_t, y_t\right]\right)$ is succinctly rendered as $\dot{\beta}\tilde{\phi}(1) = 0$, wherein the cointegration vector β is established as stationary $\dot{\beta} z_t$. Notably, the computation of causality for the series that maintain stationarity continues in the tradition set by Hosoya (1991) in Eq. (3), articulating:

$$M_{y\to x}(\omega) = 1 + \log\left[\frac{\left|\psi_{12}\left(e^{-i\omega}\right)\right|^2}{\left|\psi_{11}\left(e^{-i\omega}\right)\right|^2}\right] \tag{6}$$

Consequently, the formulation of the null hypothesis, postulating that y does not exert causal influence or predictive power on x at a specific frequency (ω) within the context of bivariate framework estimation $\left(M_{y\to x}\right)$, is presented as follows:

$$M_{y\to x}(\omega) = 0 \tag{7}$$

To be succinct, the null hypothesis concerning the cause-and-effect relationship between two variables ($x_t|y_t$, both utilized as both target and predictor variables) can be evaluated using an F-test statistic through a generalized model specification. The equation representing the vector autoregression (VAR) of x_t can be succinctly articulated as follows, as proposed by Breitung and Candelon (2006):

$$x_t = \alpha_1 x_{t-1} + \dots + \alpha_p x_{t-p} + \beta_1 y_{t-1} + \dots + \beta_p y_{t-p} + \varepsilon_{1t} \quad (8)$$

In the context of Eq. (8), the linear constraint is analogous to the null hypothesis $M_{y\rightarrow x}(\omega) = 0$. Here, α and β represent the estimated parameters at time t and lag p, accompanied by an error term ε_t.

4 Data specification

In our research, we have chosen the NASDAQ OMX Green Economy Index as a guide for understanding the Green Economy. This index helps us track how different companies in various industries contribute to sustainable development. Our main data source for this index is https://www.capitaliq.com/.

When looking at green bond indices, we have considered four important ones. The S&P Green Bond Index gives us insights into the global green bond market by focusing on bonds that support eco-friendly projects. The S&P Green Bond Select Index, part of the S&P Green Bond Index, helps us understand how globally issued green-labeled bonds perform, following strict financial and other criteria. Similarly, the S&P US Municipal Green Bond Index helps us explore the US green municipal bond market by picking out bonds that fund environmentally friendly initiatives. Additionally, the S&P Green Bond US Dollar Select Index lets us see the performance of US dollar-denominated green-labeled bonds from the S&P Green Bond Index. Turning to ESG equities-integrated green bond indices, we are looking at two different ones. The S&P Global ESG Equity & Green Bond Balanced Index helps us understand the balance between stocks and bonds. It combines the S&P Global 50 ESG Select Equal Weight Index and the S&P Green Bond Select Index to show us growth and risk management. On the other hand, the S&P Global ESG Equity & Green Bond Balanced 5% Decrement Index shows us the performance of the previous index after deducting a fixed fee of 5% per year.

We have collected data for both green bond and ESG equities-integrated green bond indices from spglobal.com. Our research spans from June 30, 2014, when the S&P US Municipal Green Bond Index started, to August 3, 2023. To help with references, you can find abbreviations and full names of these indices in Table 1. The analysis utilized the returns of each variable, which were computed using natural logarithms.

Table 2 provides an exhaustive overview of descriptive statistics for the variables under consideration. The mean values, spanning a range from 0.032 for GECO to -0.008 for ESGB5, offer insights into the average magnitudes within the dataset. Meanwhile, the medians, varying between 0.096 for GECO and 0.011 for ESGB5, afford a glimpse into the central tendencies of the distributions, with a particularly notable distinction observed in the case of GECO. Evidencing a wide spectrum, the dataset showcases the interval between the highest and lowest values. GECO commands the highest maximum value, scaling to 9.253, whereas ESGB5 presents the lowest at 3.316. Similarly, the lowest minimum, observed at -12.238 for GECO, stands in contrast with the highest minimum, recorded at -6.033 for ESGB5. The standard deviations (Std. Dev.), serving as markers of the degree of dispersion from the mean, take center stage. Remarkably, ESGB and ESGB5 emerge with elevated standard deviations (0.537), signaling more pronounced variability in comparison to other variables. An

Table 1 Full names and abbreviations

Full names	Abbreviations
NASDAQ OMX Green Economy Index	GECO
S&P Green Bond Index	GRB
S&P Green Bond Select Index	GBS
S&P US Municipal Green Bond Index	MGB
S&P Green Bond US Dollar Select Index	DGB
S&P Global ESG Equity & Green Bond Balanced Index	ESGB
S&P Global ESG Equity & Green Bond Balanced 5% Decrement Index	ESGB5

Table 2 Descriptive statistics

	GECO	GRB	GBS	MGB	DGB	ESGB	ESGB5
Mean	0.032	−0.006	−0.007	0.009	0.004	0.012	−0.008
Median	0.096	0.000	0.000	0.018	0.010	0.031	0.011
Maximum	9.253	2.272	2.516	4.133	1.105	3.329	3.316
Minimum	−12.238	−2.410	−2.962	−3.384	−1.564	−6.019	−6.033
Std. Dev	1.167	0.377	0.429	0.269	0.214	0.537	0.537
Skewness	-0.806	−0.202	−0.194	−1.069	−0.632	−0.988	−0.989
Kurtosis	14.564	7.294	7.309	70.318	8.421	16.042	16.015
Jarque–Bera	12,906.2***	1761.0***	1772.1***	429,431.7***	2932.6***	16,471.5***	16,406.5***
KPSS	0.08643	0.21151	0.22008	0.16995	0.26009	0.07178	0.07185
ADF	−14.417***	−29.874***	−43.144***	−17.242***	−40.947***	−28.104***	−28.134***
PP	−47.583***	−42.844***	−43.353***	−27.390***	−41.845***	−41.988***	−42.020***

*** shows 1% significance level

investigation into skewness, an indicator of distribution asymmetry, uncovers variations among variables. While GECO and ESGB5 display negative skewness, indicative of a leftward tail, the remaining variables showcase a blend of negative and positive skewness, albeit leaning toward a state of equilibrium. Kurtosis, the barometer of tail thickness, accentuates the differences observed across distributions. Particularly arresting is the kurtosis of MGB at 70.318, underscoring substantial tails and potential outliers. Other variables similarly exhibit elevated kurtosis in contrast to the reference of a normal distribution. Shifting the focus to assessments of normality and stationarity, the Jarque–Bera test divulges the non-normality across all variables, affirmed by the substantial test statistics. Interestingly, the tests for unit roots (KPSS, ADF, and PP) divulge a consistent state of stationarity across all variables. This is supported by the perpetually negative test statistics for ADF and PP, as well as the absence of stationarity null hypothesis rejection for KPSS, even within the stringent confines of the 1% significance level. In consequence, it can be deduced that the variables are devoid of stochastic trends. Figure 1 illustrates the plot of returns.

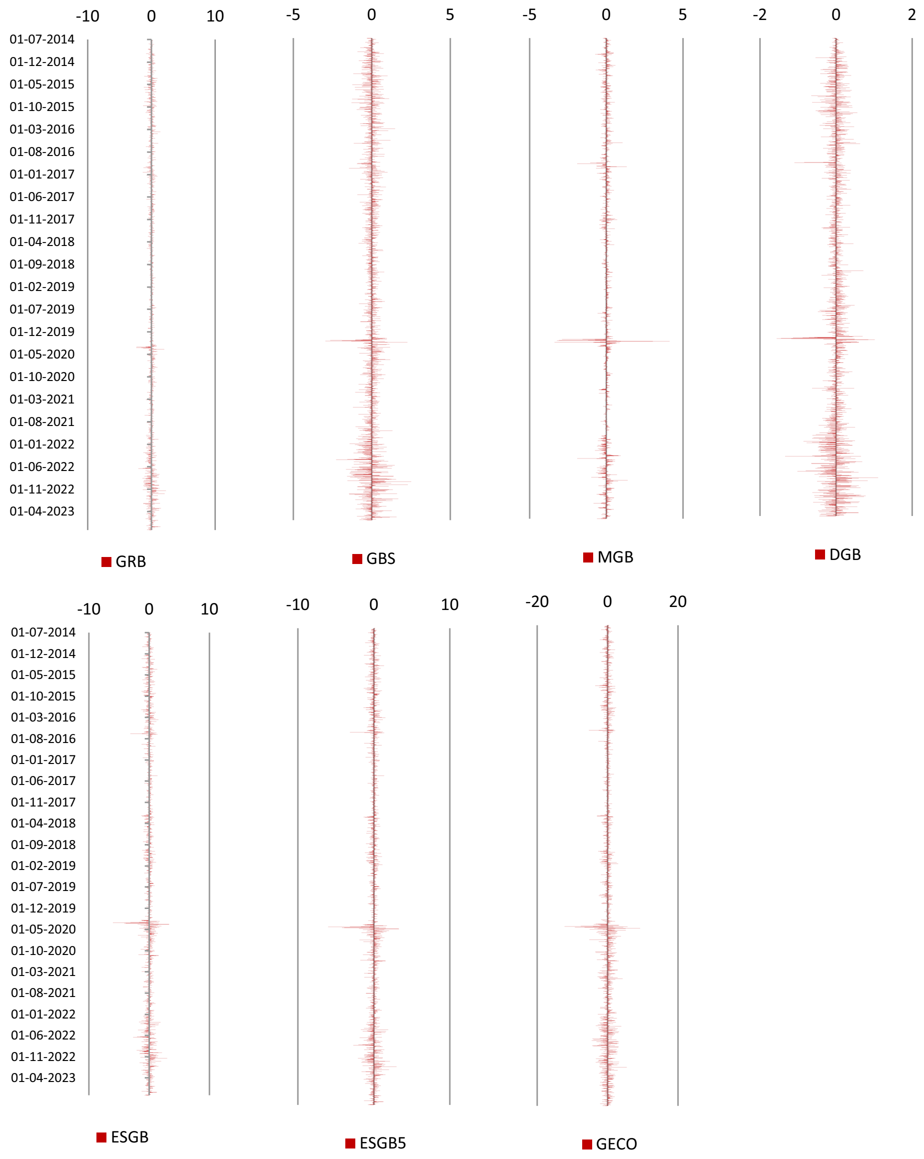

Fig. 1 Time series for the returns

5 Results

5.1 Static Granger causality test results

At the onset of our inquiry, we undertook an examination into the static Granger causality interrelations between unfiltered green bond indices and ESG-integrated green bond indices, alongside the overarching notion of a climate-conscious economy. The outcomes of this meticulous inspection have been thoughtfully presented in Tables 3 and 4. Our empirical analysis has yielded noteworthy results, warranting comprehensive appraisal. In essence, we found ourselves well-positioned to reject the null hypothesis of no Granger causality at conventional significance levels for both causal directions, albeit with some nuanced variations contingent on the chosen lag intervals. This complexity highlights that our conclusions regarding null hypothesis dismissal are distinctly sensitive to the precise lag configuration utilized. Consequently, the static Granger causality evaluation implies that historical information from either return variable does contribute to predictive accuracy for the other series, provided due consideration is given to the lag parameter, which introduces heightened sensitivity, ultimately influencing our definitive assessment of the causality nexus.

For instance, we discern a salient bidirectional causal association between the Green Economy Composite Index (GECO) and the Green Bond Return Index (GRB) across lags 5, 6, 11, 12, 13, 14, 19, and 20, achieving a robust 90% confidence interval. This reciprocal interaction transitions into a unidirectional causality, specifically from GECO to GRB, across the remaining lags. This intriguing dynamic indicates a potential lack of interaction between the sustainable economy and green bond markets during certain lag periods. However, it merits noting that select existing studies, including the works of Ning et al. (2023), Pham (2021), and Mensi et al. (2022), advocate substantial interplay within these realms of environmental stewardship economies.

In this particular context, it is of fundamental import to acknowledge that exclusively relying on linear Granger causality test outcomes engenders susceptibility to misinterpretation. When conventional Granger causality findings exhibit marked shifts consequent to the modification of lag order selection, it strongly portends that the causal relationship under examination is substantially influenced by the specific temporal intervals subsumed within the analysis. This scenario gives rise to the distinct and intriguing possibility that the underlying causal connections are inherently intertwined with certain frequencies or periodicities intrinsic to the time series data. In cases where such frequency-specific causal linkages exist, traditional static linear Granger causality tests are inherently limited in their capacity to elucidate said nuanced dependencies. This limitation stems from their formulation, oriented principally toward assessing causality across the aggregate span of the time series. Consequently, these static tests may fail to identify or entirely overlook these intricate frequency-dependent causal relationships bound to particular periodic components within the data. Herein, frequency-domain Granger causality tests emerge as indispensable analytical instruments, equipped with the unique capacity to delineate and elucidate these frequency-specific causal connections that would otherwise escape detection. Employing these frequency-based tests enhances the comprehensiveness of the causal inference, furnishing crucial insights into the generative mechanisms driving the observed causal associations. Furthermore, when the objective encompasses conducting comparative analyses, aimed specifically at ascertaining the relative magnitude and strength of causality across distinct frequency ranges, the frequency-domain approach constitutes an indispensable methodological framework. Not only does this approach enable more granular understanding of the intricate data dynamics, but also provides enhanced perspicacity into the elemental periodic constituents undergirding the causal relationships. In essence, the frequency-based analysis augments analytical rigor, conferring an enriched characterization of the causal structures within the complex temporal phenomena.

Table 3 Static Granger causality test (part 1)

	F-stat	*P*-value	*F*-stat	*P*-value	F-stat	*P*-value	F-stat	*P*-value	*F*-stat	*P*-value
Lag	1		2		3		4		5	
GRB does not Granger Cause GECO	2.10E+00	1.47E−01	1.89E+00	1.51E−01	1.51E+00	2.11E−01	1.28E+00	2.75E−01	2.03E+00	7.13E−02
GECO does not Granger Cause GRB	5.27E+01	5.44E−13	3.07E+01	7.07E−14	2.14E+01	1.20E−13	1.65E+01	2.34E−13	1.44E+01	7.00E−14
GBS does not Granger Cause GECO	2.62E+01	3.29E−07	9.97E+00	4.89E−05	1.07E+01	5.23E−07	8.90E+00	4.00E−07	7.72E+00	3.28E−07
GECO does not Granger Cause GBS	3.62E+01	2.11E−09	2.22E+01	2.73E−10	1.51E+01	1.02E−09	1.13E+01	4.49E−09	9.17E+00	1.18E−08
MGB does not Granger Cause GECO	2.49E+01	6.61E−07	9.57E+00	7.29E−05	9.21E+00	4.70E−06	7.11E+00	1.10E−05	5.83E+00	2.35E−05
GECO does not Granger Cause MGB	1.50E+01	1.11E−04	8.65E+00	1.80E−04	7.03E+00	1.06E−04	5.41E+00	2.48E−04	4.18E+00	8.70E−04
DGB does not Granger Cause GECO	7.46E+00	6.36E−03	1.54E+00	2.15E−01	1.43E+00	2.33E−01	1.60E+00	1.72E−01	1.49E+00	1.88E−01
GECO does not Granger Cause DGB	1.01E+02	2.59E−23	5.34E+01	2.11E−23	3.69E+01	2.71E−23	2.74E+01	3.21E−22	2.37E+01	2.70E−23
ESGB does not Granger Cause GECO	1.73E−05	9.97E−01	2.47E+00	8.48E−02	1.85E+00	1.36E−01	1.70E+00	1.47E−01	1.83E+00	1.03E−01
GECO does not Granger Cause ESGB	1.85E+01	1.75E−05	1.55E+01	2.13E−07	1.03E+01	9.32E−07	9.54E+00	1.21E−07	9.04E+00	1.60E−08
ESGB5 does not Granger Cause GECO	7.59E−04	9.78E−01	2.46E+00	8.56E−02	1.84E+00	1.38E−01	1.69E+00	1.50E−01	1.81E+00	1.07E−01
GECO does not Granger Cause ESGB5	1.87E+01	1.63E−05	1.56E+01	1.79E−07	1.04E+01	8.24E−07	9.65E+00	9.78E−08	9.00E+00	1.75E−08
Lag	6		7		8		9		10	
GRB does not Granger Cause GECO	2.04E+00	5.69E−02	1.71E+00	1.03E−01	1.39E+00	1.94E−01	1.44E+00	1.67E−01	1.22E+00	2.75E−01
GECO does not Granger Cause GRB	1.28E+01	3.23E−14	1.22E+01	2.29E−15	1.07E+01	6.70E−15	9.58E+00	1.88E−14	9.38E+00	2.07E−15
GBS does not Granger Cause GECO	5.95E+00	3.50E−06	5.45E+00	3.25E−06	4.82E+00	6.61E−06	4.32E+00	1.37E−05	3.82E+00	3.95E−05
GECO does not Granger Cause GBS	7.46E+00	6.21E−08	6.99E+00	2.87E−08	6.24E+00	5.21E−08	5.66E+00	8.85E−08	5.49E+00	4.18E−08
MGB does not Granger Cause GECO	4.80E+00	7.12E−05	3.96E+00	2.62E−04	3.55E+00	4.31E−04	3.07E+00	1.17E−03	2.89E+00	1.37E−03
GECO does not Granger Cause MGB	4.03E+00	5.06E−04	3.53E+00	9.03E−04	4.05E+00	8.40E−05	3.83E+00	7.94E−05	3.93E+00	2.48E−05
DGB does not Granger Cause GECO	1.39E+00	2.14E−01	1.53E+00	1.53E−01	1.63E+00	1.10E−01	1.58E+00	1.14E−01	1.41E+00	1.69E−01
GECO does not Granger Cause DGB	2.01E+01	5.55E−23	1.78E+01	3.80E−23	1.62E+01	1.88E−23	1.44E+01	6.38E−23	1.32E+01	7.93E−23
ESGB does not Granger Cause GECO	1.59E+00	1.47E−01	9.90E−01	4.36E−01	7.39E−01	6.57E−01	7.84E−01	6.32E−01	7.12E−01	7.14E−01
GECO does not Granger Cause ESGB	9.74E+00	1.28E−10	1.07E+01	2.41E−13	9.73E+00	2.31E−13	8.91E+00	2.62E−13	8.26E+00	2.87E−13
ESGB5 does not Granger Cause GECO	1.55E+00	1.56E−01	9.84E−01	4.41E−01	7.31E−01	6.64E−01	7.73E−01	6.42E−01	7.06E−01	7.20E−01
GECO does not Granger Cause ESGB5	9.68E+00	1.52E−10	1.08E+01	2.05E−13	9.74E+00	2.26E−13	8.86E+00	3.22E−13	8.25E+00	2.97E−13

5.2 Frequency-domain Granger causality test results: green bond indices

The emergence of the interconnection between the examined variables manifests across frequencies designated as 2–3, 1–2, and 0–1. In alignment with the approach put forth by Guan et al. (2020), these discrete frequencies substantiate a linkage encompassing short-, medium-, and long-term time horizons. It is noteworthy that the interval 0–1 harbors a connotation of permanent causality, whereas the interval 2–3 signifies a depiction of transitory causality.

The results illuminated in Fig. 2 provide invaluable revelations into the intricate causal linkages among various green bond indices, meticulously scrutinized through frequency-domain Granger causality techniques. To enhance lucidity, we have segmented the complex statistical computations, dedicating distinct graphical representations to each index (see Figs. 3, 4, 5, 6).

A discerning analysis of Fig. 3 unveils a fascinating panorama of two-way causal affiliations between the Global Green Bond Index (GRB) and NASDAQ OMX Green Economy Index (GECO), spanning short- and long-term windows. However, a conspicuous asymmetry exists in the magnitude and scope of influence. Notably, GECO emerges as a dominant causal agent, overshadowing GRB, especially within permanent causality, prominently observed in the 0 to 1 frequency spectrum. These deductions resonate strongly with the pioneering work of Ghaemi Asl et al. (2023), who posit avant-garde green bonds as exerting substantially greater causal sway over sustainability, effectively spanning a comprehensive frequency range, compared to conventional green bonds.

Of paramount intrigue is the enduring, considerable long-run imprint of the green economy on the benchmark GBS, despite a relatively minor, yet noticeable, lasting impact on sustainable production. In contrast, Fig. 4 adeptly delineates an all-encompassing bilateral linkage, cementing an enduring reciprocal association between GBS and GECO, beautifully underscoring their evolving interplay. Intriguingly, within short-term GECO interactions, GRB and GBS exhibit remarkable uniformity, devoid of meaningful divergence. These illuminating revelations find robust validation in the research of Zhao et al. (2022), whose work emphasizes green bonds as pivotal financing conduits for energy efficiency, generating substantial 4.9% economic expansion, while nurturing robust green economic renewal, potentially rising annually by approximately 17%.

The revelations in Fig. 5 unveil a fascinating panorama, illuminating the intricate, multifaceted interplay between the MSCI Global Green Bond Index (MGB) and Global Green Economy Index (GECO). A captivating finding emerges, with evidence showcasing mutual causal influences resonating across short- and long-term horizons. Yet a notable nuance materializes during the transition from extreme short- or long-term frequencies toward mid-term boundaries and the junction between short- and long-run domains. Within this spectral progression, GECO's causal prowess gradually wanes, while MGB's causality role steps into the spotlight, portraying exquisite temporal sensitivity and subtle modulation in their interconnectedness.

Shifting focus to Fig. 6 reveals a distinct, intriguing pattern specifically within dollar-denominated green bonds (DGB). Remarkably, DGB uniquely lacks any enduring causal imprint on the eco-centric economy. In contrast, GECO persistently fosters causal links to DGB across all frequencies, with robust manifestations in the long-run. Curiously, this sustained influence is not reciprocated by DGB, unveiling a unidirectional association. Plausible explanations for DGB's non-contributive behavior include nuances of exchange rate fluctuations, potential regional constraints, and inherent

Table 4 Static Granger causality test (part 2)

	F-Stat	*P*-value	F-Stat	*P*-value	F-stat	*P*-value	F-stat	*P*-value	F-stat	*P*-value
Lag	11		12		13		14		15	
GRB does not Granger Cause GECO	1.58E+00	9.85E−02	1.61E+00	8.28E−02	1.56E+00	8.82E−02	1.56E+00	8.35E−02	1.47E+00	1.08E−01
GECO does not Granger Cause GRB	8.57E+00	5.43E−15	7.84E+00	1.70E−14	7.25E+00	4.43E−14	7.09E+00	1.53E−14	6.80E+00	1.33E−14
GBS does not Granger Cause GECO	3.49E+00	7.44E−05	3.56E+00	2.80E−05	3.31E+00	4.96E−05	3.14E+00	6.88E−05	2.97E+00	1.03E−04
GECO does not Granger Cause GBS	5.06E+00	7.48E−08	4.70E+00	1.26E−07	4.66E+00	5.52E−08	4.65E+00	2.03E−08	4.35E+00	4.28E−08
MGB does not Granger Cause GECO	2.69E+00	1.90E−03	2.58E+00	2.08E−03	2.42E+00	3.02E−03	2.48E+00	1.74E−03	2.35E+00	2.34E−03
GECO does not Granger Cause MGB	3.83E+00	1.77E−05	3.53E+00	3.20E−05	3.50E+00	2.00E−05	3.61E+00	5.79E−06	3.79E+00	1.10E−06
DGB does not Granger Cause GECO	1.30E+00	2.16E−01	1.23E+00	2.58E−01	1.16E+00	3.03E−01	1.13E+00	3.28E−01	1.10E+00	3.52E−01
GECO does not Granger Cause DGB	1.22E+01	1.32E−22	1.12E+01	5.04E−22	1.04E+01	9.09E−22	9.84E+00	1.10E−21	9.25E+00	2.26E−21
ESGB does not Granger Cause GECO	8.04E−01	6.36E−01	8.09E−01	6.42E−01	7.95E−01	6.66E−01	7.50E−01	7.25E−01	6.76E−01	8.10E−01
GECO does not Granger Cause ESGB	7.47E+00	9.97E−13	6.89E+00	2.24E−12	6.50E+00	2.80E−12	5.91E+00	1.48E−11	5.50E+00	4.06E−11
ESGB5 does not Granger Cause GECO	7.91E−01	6.50E−01	7.99E−01	6.52E−01	7.88E−01	6.74E−01	7.42E−01	7.33E−01	6.69E−01	8.17E−01
GECO does not Granger Cause ESGB5	7.46E+00	1.03E−12	6.89E+00	2.28E−12	6.50E+00	2.88E−12	5.90E+00	1.62E−11	5.49E+00	4.48E−11
Lag	16		17		18		19		20	
GRB does not Granger Cause GECO	1.45E+00	1.08E−01	1.37E+00	1.40E−01	1.34E+00	1.55E−01	1.52E+00	6.82E−02	1.47E+00	8.13E−02
GECO does not Granger Cause GRB	6.36E+00	3.72E−14	6.16E+00	2.86E−14	5.92E+00	3.32E−14	5.66E+00	5.38E−14	5.48E+00	5.61E−14
GBS does not Granger Cause GECO	2.82E+00	1.49E−04	2.68E+00	2.24E−04	2.57E+00	3.05E−04	2.56E+00	2.34E−04	2.43E+00	3.90E−04
GECO does not Granger Cause GBS	4.23E+00	3.53E−08	4.00E+00	6.58E−08	3.90E+00	5.94E−08	3.83E+00	4.38E−08	3.66E+00	7.76E−08
MGB does not Granger Cause GECO	2.23E+00	3.35E−03	2.26E+00	2.27E−03	2.18E+00	2.77E−03	2.09E+00	3.90E−03	2.00E+00	5.37E−03
GECO does not Granger Cause MGB	3.62E+00	1.43E−06	3.92E+00	1.09E−07	3.79E+00	1.22E−07	3.79E+00	6.09E−08	3.92E+00	1.08E−08
DGB does not Granger Cause GECO	1.10E+00	3.45E−01	1.03E+00	4.20E−01	1.03E+00	4.23E−01	1.16E+00	2.87E−01	1.17E+00	2.70E−01
GECO does not Granger Cause DGB	8.79E+00	2.96E−21	8.43E+00	3.03E−21	7.95E+00	9.42E−21	7.53E+00	2.53E−20	7.19E+00	5.55E−20
ESGB does not Granger Cause GECO	6.57E−01	8.38E−01	6.75E−01	8.30E−01	7.51E−01	7.59E−01	8.89E−01	5.98E−01	8.92E−01	5.98E−01
GECO does not Granger Cause ESGB	5.21E+00	6.85E−11	4.93E+00	1.31E−10	4.74E+00	1.68E−10	4.48E+00	3.97E−10	4.28E+00	7.00E−10
ESGB5 does not Granger Cause GECO	6.54E−01	8.40E−01	6.76E−01	8.30E−01	7.45E−01	7.66E−01	8.79E−01	6.10E−01	8.88E−01	6.04E−01
GECO does not Granger Cause ESGB5	5.19E+00	7.88E−11	4.91E+00	1.56E−10	4.73E+00	1.85E−10	4.47E+00	4.25E−10	4.28E+00	7.38E−10

parallels with conventional bonds. These profound revelations find further validation in Zhenbin (2020)'s illuminating 5-year analysis comparing the S&P Green Bond US Dollar Select Index and S&P US Aggregate Bond Index. This comparison reveals a compelling narrative of convergence, with the Green Bond Index gradually mirroring the Aggregate Bond trajectory over time, indicating remarkable alignment. Moreover, a focused 1-year analysis accentuates this parallelism, with consistent Green Bond Index outperformance, underscoring the persistence of aligned tendencies within this intricate interplay.

Our research illuminates a richly diverse and interactive landscape across various green bond categories, aligning with previous studies underscoring the heterogeneous behaviors within green bonds (Monasterolo & Raberto, 2018). The existence of discrete green premiums further highlights this inherent heterogeneity, as noted by Chiesa and Barua (2019)

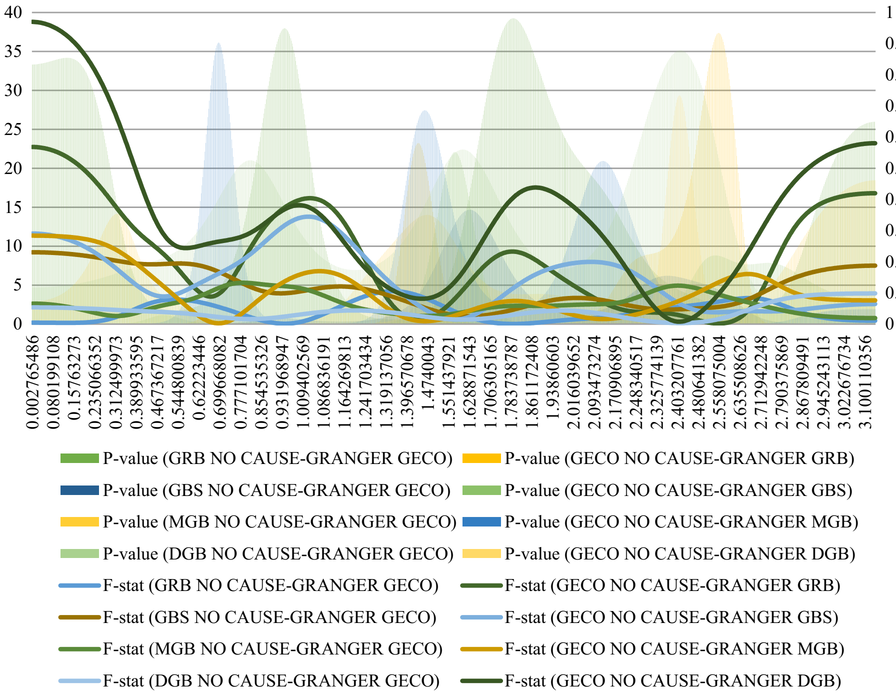

Fig. 2 Frequency-domain Granger causality test results; case of green bond indices. (Note: The vertical axis situated on the right-hand side is purposed for the presentation of P-value plots, while the vertical axis positioned on the left-hand side is intended for the illustration of F-statistic diagrams. Across the horizontal axis, a skillfully constructed spectrum of frequencies elegantly unfurls, spanning from the minute magnitude of 0.002765486 to the expansive domain of 3.138827167. This meticulous range adroitly encapsulates the sweeping landscape of diverse temporal contexts, revealing a nuanced tapestry of time horizons. Within this aesthetic arrangement, the frequency intervals are ingeniously arrayed as 2–3, 1–2, and 0–1, each deliberately unveiling a triad of distinct temporal trajectories, each possessing its own temporal attributes and profound implications. Notably, the interval designated as 0–1 assumes an unmistakable import, portending a realm wherein causal bonds acquire the quality of permanence. Within this temporal span, causality adopts an enduring aspect, alluding to sustained connections and persistent influence. In vivid contrast, the interval 2–3 evokes an aura of ephemerality, epitomizing a domain of transient causal links, intricately bound by the fleeting lifespans of momentary interactions)

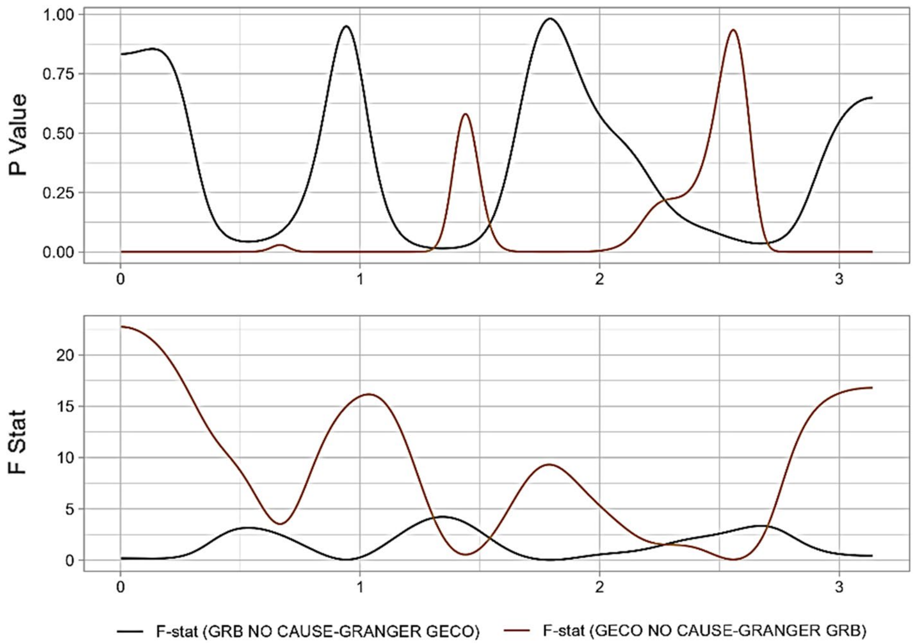

Fig. 3 Frequency-domain Granger causality test results; case of GRB indices (Note: Please see the explanatory note that provides additional context for Fig. 2)

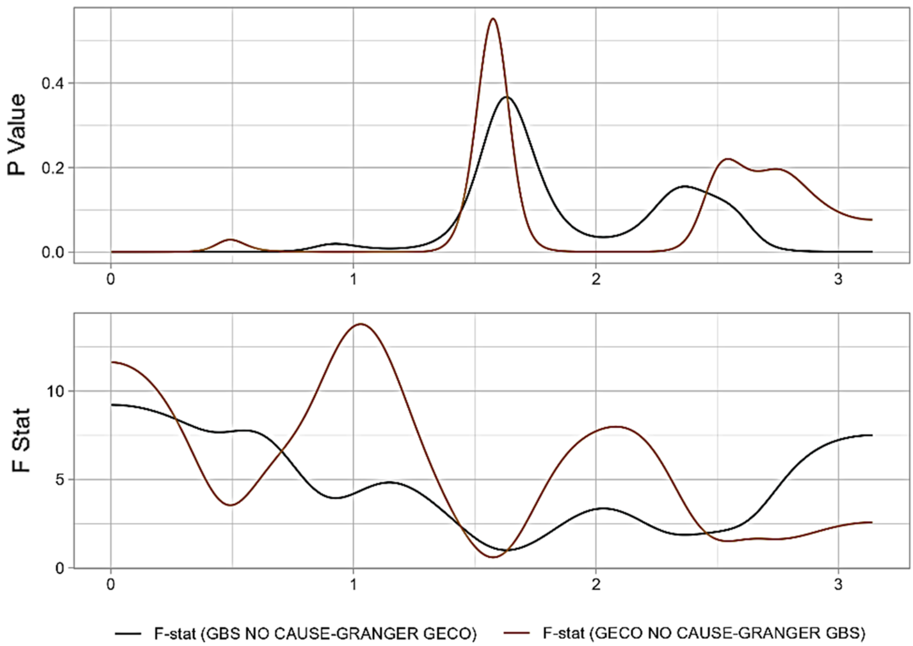

Fig. 4 Frequency-domain Granger causality test results; case of GBS indices (Note: Please see the explanatory note that provides additional context for Fig. 2)

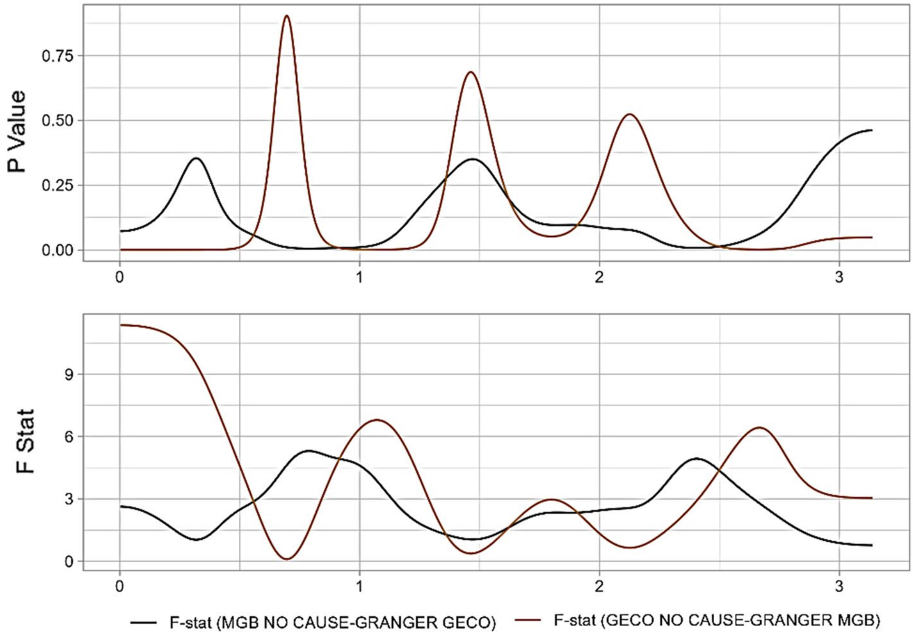

Fig. 5 Frequency-domain Granger causality test results; case of MGB indices (Note: Please see the explanatory note that provides additional context for Fig. 2)

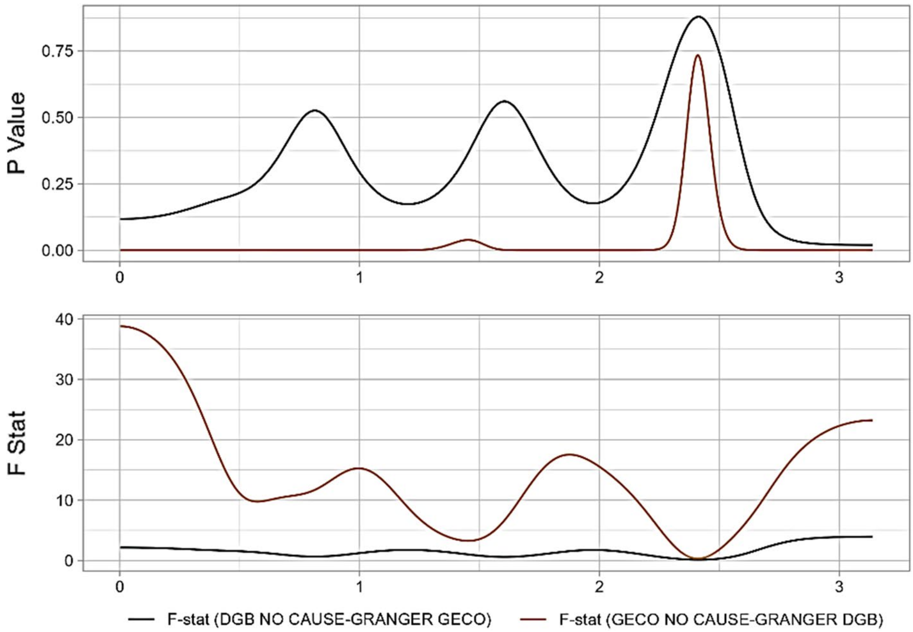

Fig. 6 Frequency-domain Granger causality test results; case of DGB indices (Note: Please see the explanatory note that provides additional context for Fig. 2)

who validate such diversity across bond markets, rooted in factors including issue size, coupon rate, credit rating, collateral availability, and issuer attributes.

Based on our comprehensive analysis, we can reasonably conclude the S&P Green Bond Index (GBS), S&P Green Bond Select Index (GRB), and S&P US Municipal Green Bond Index (MGB) present no credible evidence of greenwashing. Our work elucidates meaningful, supportive connections between these indices and the green economy across short- and long-term horizons. This aligns with research by Antoniuk and Leirvik (2021), demonstrating the sensitivity of municipal and select green bond indices to climate-friendly economic trends and pivotal climate policy events.

To sum up, our study dispels concerns of greenwashing, as the actions of these indices strongly align with broader green economy objectives of environmental sustainability and decarbonization. This synthesis of evidence elevates their credibility as pivotal drivers of sustainable finance, promoting a climate-conscious investment approach harmonious with collective aspirations for an eco-friendly, resilient economic landscape. Our nuanced analysis provides invaluable insights into the intricate, multifaceted green bond ecosystem, reinforcing the credibility of key indices as agents of meaningful impact rather than instruments of greenwashing.

5.3 Frequency-domain Granger causality test results: ESG equities-integrated green bond indices

The displays in Figs. 7, 8, 9 thoughtfully illustrate the outcomes from our frequency-domain Granger causality evaluation of ESG-integrated green bond indices. They highlight the lack of significant divergence in behavior between the ESG enhanced green bond indices (i.e., ESGB and ESGB5) regarding causal interactions with the Global Green Economy Index (GECO). This implies including or excluding an annual fixed fee does not meaningfully alter the inherent nature of ESG-inclusive green bond indices. Additionally, our findings show integrating ESG stocks into the S&P Green Bond Select Index fails to improve the efficacy of selected green bonds or influence the green economy over short or long timescales. In contrast, GECO consistently maintains its significant role as a causal factor for ESGB and ESGB5, both temporarily and permanently. This aligns with Yang et al. (2022), who illuminated the constructive role of green economic growth across environmental, social, and governance pillars when analyzed separately.

Interestingly, our findings highlight a potential shortcoming within the environmental aspect of the ESG framework. This aspect not only falls short in effectively promoting sustainable equities within the green economy, but appears to potentially undermine the efficacy of green bonds on a climate-conscious economy. This echoes Senadheera et al. (2021), amplifying concerns around factors like limited comparability, biased scoring metrics, combining diverse environmental factors, varying rating provider methodologies, and limited robust datasets, which collectively erode the utility of environmental scoring as a tool to advance financial sector greening. Consequently, we advocate reimagining the environmental aspect to incorporate comprehensive metrics addressing the diverse facets of the environment, preventing unforeseen ecological crises.

It is critical to address the primary drawbacks around inconsistent metric scope and evaluation criteria to enable the environmental aspect to become an effective instrument facilitating sustainable finance and development. Aligning with our findings on the limited promotional impact of ESG equities on green bonds, Trahan and Jantz (2023) emphasize the persistent criticism and frustration stemming from the ambiguity around ESG meaning

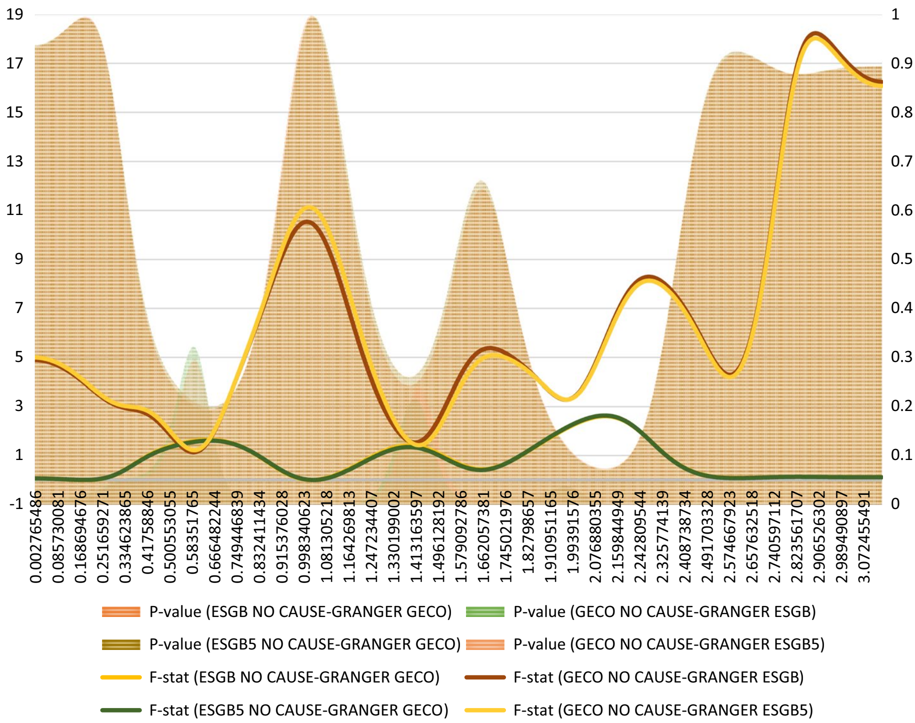

Fig. 7 Frequency-domain Granger causality test results; case of green bond indices (Note: Please see the explanatory note that provides additional context for Fig. 2)

and objectives. These challenges introduce risks like potential sudden capital outflow with ensuing environmental impacts if momentum falters. Their discourse underscores quantifying the environmental aspect while highlighting its theoretical underdevelopment in key areas, mirrored in emissions rating regimes often characterized by loosely defined parameters and misleading precision. In contrast to the enriching potential of sustainable investments proposed by Roy (2023), who presented a structured ESG-based credit rating model for green financing, our results present a divergent perspective. While Roy (2023) introduced this framework to validate green economy viability, our findings suggest the need for a more comprehensive approach. Finally, it should be noted that our study underscores the complex support between ESG equities and green bonds, revealing potential limitations and emphasizing the need for refined metrics and a more nuanced understanding of the intricate dynamics underpinning sustainable finance.

6 Conclusion

In this study, we employed an intricately crafted research methodology to systematically elucidate the causal mechanisms linking a diverse array of green bond indices, the broader ecosystem of the green economy, and the integration of environmental, social, and governance (ESG) equities. Our analytical efforts were buttressed by a meticulously curated

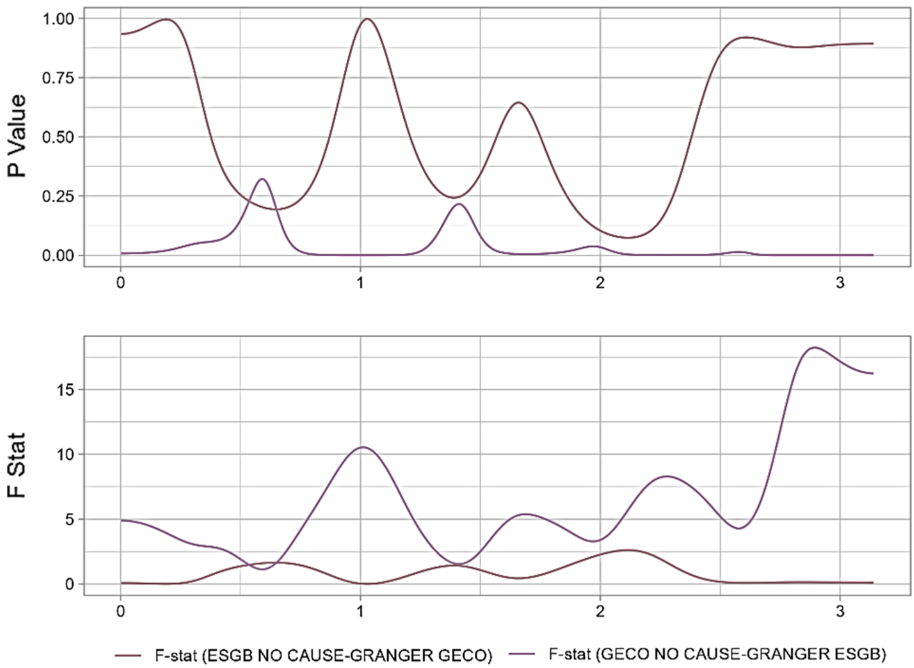

Fig. 8 Frequency-domain Granger causality test results; case of DGB indices (Note: Please see the explanatory note that provides additional context for Fig. 2)

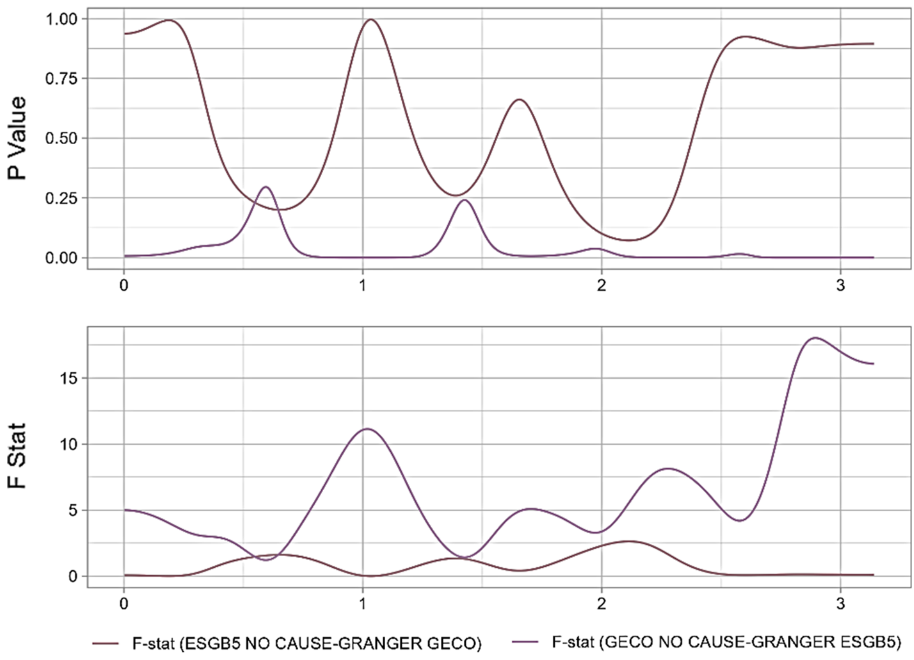

Fig. 9 Frequency-domain Granger causality test results; case of DGB indices (Note: Please see the explanatory note that provides additional context for Fig. 2)

dataset spotlighting seminal green bond indices including S&P Green Bond Index, S&P Green Bond Select Index, S&P US Municipal Green Bond Index, S&P Green Bond US Dollar Select Index, S&P Global ESG Equity & Green Bond Balanced Index, and S&P Global ESG Equity & Green Bond Balanced 5% Decrement Index. Complementing this, the NASDAQ OMX Green Economy Index provided a panoramic perspective on the broader canvas of sustainable development. Guided by sophisticated frequency-domain Granger causality techniques, we undertook a meticulous elucidation of the complex interrelationships between these variables across diverse time horizons, thereby generating nuanced comprehension of their multifaceted interconnectivity. Drawing from established academic conventions and protocols, our methodological scaffolding enabled discernment of temporal patterns spanning the continuum from short-term to medium-term and long-term dimensions, engendering holistic exploration of the intricate causal networks.

The implications of our scholarly study reverberate expansively across the landscape of green finance. Our meticulous examination of diverse green bond indices reveals an enduring causal nexus interlinking select indices with the dynamism of the green economy. This strongly underscores the credibility and efficacy of these instruments as catalytic drivers of affirmative environmental and social impacts. Notably, our study reveals subtle divergences in the causal mechanisms across various green bond genres, highlighting the importance of assimilating their distinct attributes and aspirations. Our study also delved into the intricate ecosystem of ESG equity integration within green bond indices. While this assimilation did not profoundly transform the essence of ESG-inclusive indices, it did surface potential limitations in the ecological facet of ESG frameworks. This underscores the urgency of redefining environmental assessment approaches to encompass a broader scope that enables holistic appraisal harmonious with sustainable finance objectives. By closely interrogating the causal interdependencies between green bonds, the green economy, and ESG integration, our study generates invaluable insights for policymakers, market participants, and researchers alike. We emphatically underscore the critical import of transparency, integrity, and stringent benchmarks in green bond issuance as bulwarks against the specter of greenwashing, given the synergistic ties between green bonds and sustainable growth as beacons for conscientious capitalism and societal enhancement.

In the evolving landscape of green finance, our study serves as an impassioned call for ceaseless collaboration, innovation, and refinement of green bond initiatives. By cultivating unflagging governance, transparency, and accountability, we can solidify the role of green bonds as the lodestar for catalyzing sustainable development, conferring enduring environmental and societal benefits. The burgeoning green bond domain represents an auspicious avenue for channeling private capital into environmentally sustainable ventures. However, to consecrate this domain and mitigate greenwashing risks, policymakers must implement a multifaceted blueprint. Foremost, a standardized reporting framework mandating transparent insights into green bond proceeds utilization, impacts, and sustainability alignment is imperative. Such standardization amplifies transparency, enables comparability, and guarantees channeling of funds toward eco-friendly projects. Additionally, robust third-party verification and certification of green bonds is essential. Independent verification substantiates the authenticity of financed projects, preempting misleading assertions, while reputable certifications amplify credibility. Policymakers should also promote green bond diversification, incentivizing specialized instruments tailored to particular objectives, thereby financing a diverse array of environmentally transformative undertakings. Within this maze of efforts, catalyzing excellence-level green bonds via ancillary benefits tantalizes issuers toward high-impact initiatives, engendering ascending cycles of confidence and alignment with green economy objectives. Finally, integrating ESG metrics into green bond assessments provides holistic appraisal of issuers' sustainability performance. Mandating long-term impact evaluations requiring robust evidence of funded projects' actual environmental dividends is imperative. By implementing these multifaceted policies, the green bond market can flourish as a steadfast conduit for sustainable investment, nourishing a verdant economy that resonates with nature's harmony and radiates beneficence for all stakeholders.

Data Availability All data analyzed during this study are available from first author.

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