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Article

Assessing the Nexus Between Green Finance, Green Bonds and Environmental Sustainability in Selected Countries

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Abstract

This study examines the nexus between green finance, green bonds, and environmental sustainability in five countries Nigeria, Denmark, France, Spain, and the Netherlands over the period 2017-2025. Environmental sustainability is proxied by the ecological footprint per capita, while green finance flows, green bond issuance, and renewable-energy financing are expressed as ratios to real GDP to permit comparison across countries with different reporting currencies (USD and EUR). Using the Fixed Effects estimator with Driscoll-Kraay standard errors an estimator that is robust to heteroscedasticity, serial correlation, and cross-sectional dependence in panels with a moderate time dimension the results show that green finance and green bond issuance both significantly reduce the ecological footprint in the entity fixed-effects specifications, confirming their effectiveness in advancing environmental sustainability. Renewable-energy financing, by contrast, is associated with a significant increase in the ecological footprint in the short run, a pattern consistent with the early, infrastructure-intensive phase of the energy transition. Inflation exerts a small but statistically significant positive effect on the ecological footprint. The direction and significance of green bonds, renewable-energy financing, and inflation are consistent across pooled OLS, two-way fixed effects, and entity-clustered specifications, while the sign of green finance is sensitive to model choice and reverses under pooled OLS, a finding discussed in detail as part of the study's robustness analysis rather than presented as uniform robustness across all variables. The study recommends deepening green bond markets, particularly in emerging economies such as Nigeria, and pairing renewable-energy financing with efficiency and circular-economy measures to shorten the transition lag before environmental gains materialise.

Keywords

Green finance, Green bonds, Ecological footprint, Environmental sustainability, Panel data

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1. Introduction

Environmental degradation, driven by carbon-intensive growth models, has placed the mobilization of climate-aligned capital at the centre of global economic policy [1,2]. Green finance the channelling of capital toward projects that generate environmental benefits, including renewable energy, clean transportation, and sustainable water management has emerged as a principal instrument through which governments and financial systems seek to reconcile economic growth with ecological limits [3]. Within this broader architecture, green bonds have become one of the fastest-growing debt instruments globally, transitioning from niche vehicles to mainstream financial mechanisms that signal authentic corporate environmental commitment and actively drive long-term corporate carbon mitigation [4,5].

Both advanced and emerging economies have expanded their green finance architecture in recent years. Denmark, France, Spain, and the Netherlands all signatories to the European Green Deal have developed mature green bond markets underpinned by well-established regulatory taxonomies [6,7]. Nigeria, by contrast, represents an instructive emerging-market case; it became the first African country to issue a sovereign green bond in December 2017, worth ₦10.69 billion, financing renewable energy, rural electrification, and afforestation projects [8,9]. Nigeria has since issued a third sovereign green bond of ₦50 billion in June 2025, alongside expanding subnational and corporate green bond activity led by Lagos State's maiden subnational issuance and domestic commercial banks [10,11]. Despite this expansion, Nigeria's cumulative green bond issuance remains a small fraction of global totals, raising the question of whether green finance instruments are yet delivering measurable environmental dividends in emerging markets relative to their more mature European counterparts [12,13].

A growing empirical literature associates green finance development with reductions in the ecological footprint a composite measure of the biologically productive land and water area required to support a population's consumption and absorb its waste [14,15]. However, most existing studies concentrate on large cross-country panels of either exclusively developed or exclusively developing economies, and few explicitly disentangle the distinct operational channels of green finance flows, green bond issuance, and renewable-energy financing within a single, integrated empirical model [16]. Moreover, comparative evidence that positions an emerging sovereign green bond pioneer such as Nigeria alongside mature European green bond markets within a unified econometric framework remains scarce, limiting the generalizability of current macroeconomic policy prescriptions across asymmetric financial systems.

This study addresses this gap by assessing the nexus between green finance, green bonds, and environmental sustainability in Nigeria, Denmark, France, Spain, and the Netherlands over 2017-2025. Specifically, the study investigates: (i) the effect of green finance flows on the ecological footprint; (ii) the effect of green bond issuance on the ecological footprint; and (iii) the effect of renewable-energy financing on the ecological footprint, while controlling for inflation. The remainder of the paper is organised as follows: Section II reviews the theoretical and empirical literature; Section III presents the data and methodology; Section IV reports and discusses the results; Section V presents robustness checks; Section VI discusses the study's theoretical and practical contributions and limitations; and Section VII concludes with policy recommendations.

2. Literature Review

Green finance refers to financial investment channelled toward projects and initiatives that generate environmental benefits, including renewable energy, energy efficiency, pollution prevention, and sustainable resource management [17]. Green bonds constitute a specific fixed-income instrument whose proceeds are earmarked exclusively for environmentally beneficial projects, distinguishing them from conventional bonds through their use-of-proceeds restriction, project eligibility criteria, and impact-reporting obligations [18]. Environmental sustainability, in turn, is most commonly proxied in the empirical literature by the ecological footprint, which captures the aggregate demand that consumption and production place on ecosystems, and is preferred over carbon emissions alone because it incorporates cropland, grazing land, forest, fishing grounds, and built-up land [19].

2.1 Theoretical Framework

Ecological modernisation theory provides the principal theoretical anchor for this literature. The theory holds that environmental degradation is not an inevitable consequence of economic growth but can be decoupled from it through technological innovation, institutional reform, and the redirection of capital toward cleaner production processes [20]. Within this framework, green finance operates as a transmission channel by lowering the cost of capital for clean technologies and raising the cost of capital for polluting activities, it reallocates investment toward less resource-intensive production, thereby reducing the ecological footprint over time.

2.2 Empirical Review

Empirically, a study of thirteen countries with the highest levels of green financial development over 1992-2020 found that green finance and green growth reduce the ecological footprint, using Augmented Mean Group (AMG), FMOLS, and DOLS estimators alongside Dumitrescu-Hurlin causality tests [14]. Shah et al. [15] found that green bonds significantly improve environmental sustainability by reducing ecological pressures and strengthening resource capacities. Their findings provide empirical evidence that green bond financing is an effective mechanism for supporting sustainable development and environmental protection. A separate cross-regional study spanning South Asia, South-East Asia, China, the Middle East, and Europe over a fifteen-year period similarly found that green finance development substantially improves environmental sustainability outcomes and specifically recommended the expansion of green bonds at municipal, provincial, and national levels [16].

Complementing these findings, Horn et al. [21] utilised a panel dataset of 29 OECD economies over 2014-2020 to examine the determinants and environmental effects of green bond issuance, reporting that higher environmental awareness, GDP per capita, and renewable-energy capacity are associated with a higher volume of issued green bonds, and that green bond volume in turn improves the ecological budget and biodiversity while reducing the ecological footprint.

However, the assumption of a universally linear, positive environmental dividend has been challenged by recent global comparative frameworks. Gul et al. [22] examined the effects of green finance and green innovation on sustainable economic development across 82 developed and developing economies. Using advanced panel estimation techniques and machine learning models, the study assessed the long-run relationships among these variables. The findings revealed that both green finance and green innovation significantly promote sustainable economic development by reducing environmental emissions. The study further showed that these positive effects are stronger in developed economies than in developing countries, highlighting the need for greater support for green financial instruments and innovation in developing nations.

This structural heterogeneity is further corroborated by Chang et al. [23], whose asymmetric quantile-on-quantile evaluation of the top ten green-finance-supporting economies finds that green finance improves environmental quality measured by the ecological footprint in eight of the ten sampled countries at particular quantiles of the data distribution, with two countries yielding mixed results, indicating that the elasticity between green finance and ecological footprint mitigation is highly contingent on a country's specific quantile of financial development and its position in the distribution of green-finance intensity.

On green bonds specifically, evidence regarding empirical additionality whether these instruments drive novel environmental improvements or simply refinance existing assets remains highly mixed. A study of green bond determinants across twenty-nine OECD countries over 2014-2020 found that environmental awareness, GDP per capita, and renewable energy capacity are associated with higher green bond issuance, and that green bond volume is in turn linked with improved environmental performance indicators [21]. Similarly, an evaluation of key European issuers (including France, the Netherlands, and Spain) over 2013-2023 established that economic growth, energy prices, R&D spending, regulatory quality, and renewable energy consumption positively influence green bond market depth [7].

The role of renewable energy in this nexus is similarly debated. A global study of fifty-four countries using panel least squares and generalized method of moments methods found that non-renewable energy consumption significantly raises the ecological footprint across all regions, while renewable energy reduces ecological impact most notably in developed countries implying that the environmental payoff to renewable-energy financing may depend on the stage of a country’s energy transition and its existing infrastructure base [24]. This distinction is particularly relevant for a sample combining an early-stage issuer such as Nigeria with mature European markets, since renewable-energy financing directed at grid expansion and infrastructure build-out in the earlier phase of a transition can coincide with elevated resource use before efficiency gains and the displacement of fossil generation materialize.

2.3 Recent Literature (2024-2026) and the Emerging Regional and Technological Dimensions of Green Finance

This subsection incorporates recent (2024-2026) studies that extend the green finance-sustainability literature into regional and technological dimensions not covered in the original review. On the regional dimension, Zin Lin et al. [25] assesses global best-practice green finance and carbon-market architectures including the EU Emissions Trading System, the Carbon Border Adjustment Mechanism, and green bond standards for their applicability to ASEAN economies, and finds that fragmented regulation and underdeveloped carbon markets constrain the region's clean-energy transition, recommending harmonised green finance taxonomies and coordinated regional carbon pricing. This regional evidence reinforces the present study's premise that the maturity of a green finance architecture, rather than green finance activity alone, conditions the environmental payoff of green capital, a theme directly relevant to the Nigeria-versus-Europe comparison undertaken here.

A second emerging strand examines the interaction between artificial intelligence and green finance. BinSaddig, Awwad, and Zakaria [26] conduct a bibliometric and thematic review of 78 Scopus-indexed studies (2016-2025) and find that AI-driven financial technology is reshaping green finance and sustainability-oriented financial systems, although the literature remains fragmented across technological, financial, environmental, and governance dimensions. Related contributions extend this theme to green governance in Gulf Cooperation Council industrial firms [27], to innovation-oriented sustainability strategy more broadly [28], and to bibliometric mapping of artificial intelligence and corporate environmental sustainability [29]. Awwad [30] traces the evolution of climate finance and sustainability scholarship through the Journal of Cleaner Production, situating green bonds and green finance instruments within a wider climate-finance research agenda. On governance and institutional quality in fragile and emerging markets, BinSaddig et al. [31] and BinSaddig et al. [32] examine digital transformation, institutional governance, and corporate social responsibility in Palestine, while Khoffash and Awwad [33] provide bank-level evidence on the challenges and opportunities of green financing in an emerging, capital-constrained economy evidence that parallels, and lends external validity to, the Nigerian case examined in this study.

Taken together, this recent literature underscores two gaps that the present study speaks to directly: first, that the environmental payoff of green finance instruments is conditional on regional and institutional maturity rather than uniform across countries, consistent with the mixed evidence in Chang et al. [23] and Adam [25]; and second, that emerging-market evidence on green financing including from Nigeria and other capital-constrained economies remains comparatively scarce relative to the growing OECD- and Europe-focused literature, a gap this study's five-country design, spanning one emerging and four mature markets, is intended to help close.

Taken together, the literature establishes a broadly favourable relationship between green finance and environmental sustainability, while leaving open questions regarding: (i) the distinct contribution of green bonds relative to broader green finance flows; (ii) the short-run environmental cost of renewable-energy infrastructure build-out; and (iii) how these relationships hold when an emerging sovereign green bond issuer is analysed alongside mature European markets within a single panel. Table 1 summarises several of the studies most closely related to this one. This study contributes to closing these gaps.

Table 1. Summary of selected recent studies on green finance, green bonds, and environmental sustainability.

Sample	Methodology	Main Findings	Research Gap Addressed	Ref.
13 leading green-finance economies, 1992-2020	AMG, FMOLS, DOLS; Dumitrescu-Hurlin causality	Green finance and green growth reduce the ecological footprint	Establishes GF-EFP link but not the GF/GB/REF decomposition	[14]
Global green-bond-issuing economies	Panel estimation	Green bonds improve environmental sustainability by reducing ecological pressure	Confirms GB effect in isolation, not alongside GF and REF	[15]
29 OECD countries, 2014-2020	Two-stage panel model	GB volume linked to higher ecological budget/biodiversity and lower ecological footprint	OECD-only; no emerging-market comparator	[21]
Top 10 green-finance economies	Asymmetric quantile-on-quantile	GF improves environmental quality in 8 of 10 countries; effects are quantile-dependent	Shows cross-country heterogeneity this study tests directly for Nigeria vs. Europe	[23]
ASEAN (Indonesia, Singapore, Thailand)	Comparative policy analysis	Fragmented regulation and shallow carbon markets constrain green finance uptake	Extends the maturity/heterogeneity theme to a second emerging region	[25]
78 Scopus studies, 2016-2025	Bibliometric/thematic review	AI-driven fintech is reshaping green finance but research remains fragmented	Flags an emerging technological dimension for future extensions of this study	[26]
Nigeria, Denmark, France, Spain, Netherlands, 2017-2025	Fixed Effects, Driscoll-Kraay SE	GF and GB reduce EFP under entity FE; REF raises EFP short-run; inflation raises EFP	Integrates GF, GB, and REF as distinct channels in one emerging + four mature markets	This study (2026)

Source: Authors' compilation, 2026.

3. Methodology

3.1 Nature and Sources of Data

The study uses secondary annual data spanning 2017-2025 for five countries Nigeria, Denmark, France, Spain, and the Netherlands constituting a balanced panel of 45 country-year observations. The sample was purposively selected to combine an emerging sovereign green bond issuer (Nigeria) with mature European green bond markets operating under the EU taxonomy and Green Deal framework, allowing the study to assess whether the green finance-sustainability nexus holds across differing stages of market development. Table 2 defines and describes the study variables, and Table 3 sets out the exact database, indicator, and reporting source used for each country and variable, to provide clear documentation of data provenance. Because Nigerian monetary series are recorded in United States dollars while the four European series are recorded in euros, all monetary flow variables (green finance, green bonds, and renewable-energy financing) are re-expressed as ratios to each country's own real GDP before estimation, so that coefficients reflect scale-free shares of economic output rather than raw currency levels that would otherwise not be directly comparable across the dollar- and euro-denominated series.

Table 2. Description, measurement, and sources of variables.

Variable	Definition	Measurement
Ecological Footprint (EFP)	Biologically productive land and water area required to support consumption and absorb waste; the study's environmental sustainability proxy.	Global hectares per capita (gha/capita)
Green Finance (GF)	Total green/climate finance flows directed to environmentally beneficial projects.	Green finance as % of real GDP
Green Bonds (GB)	Value of green bonds issued in a given year (sovereign, subnational, and corporate).	Green bond issuance as % of real GDP
Renewable Energy Financing (REF)	Financing directed specifically at renewable energy generation and infrastructure.	REF as % of real GDP
Real GDP (RGDP)	Gross domestic product at constant prices, used as the scaling denominator for GF, GB, and REF.	National currency, constant prices
Inflation (INF)	Annual percentage change in the consumer price index; included as a macroeconomic control.	Annual percentage

Source: Authors' compilation, 2026.

Table 3. Data sources by country and variable.

Variable	Nigeria	Denmark, France, Spain, Netherlands	Notes
Ecological Footprint (EFP)	Global Footprint Network, National Footprint and Biocapacity Accounts (NFA), gha/capita series	Global Footprint Network NFA, gha/capita series, cross-checked against Eurostat resource-use indicators	GFN publishes with an approximate two-to-three-year reporting lag; 2024 and 2025 country-year values were derived by trend extrapolation from the 2017-2022/23 GFN series using each country's average annual growth rate, cross-checked against the trajectory of national energy- and material-consumption indicators. These extrapolated points are flagged as an explicit data limitation (see Section VI).
Green Finance (GF)	Central Bank of Nigeria (CBN) Statistical Bulletin;	National central bank and finance-ministry green/sustainable finance disclosures; European Commission Green Deal Investment Plan monitoring data; OECD green finance statistics	Expressed as a ratio to real GDP (see Model Specification) to permit comparison across USD- and EUR-denominated series.
Green Bonds (GB)	DMO sovereign green bond prospectuses (2017, 2025)	National green bond registries; Climate Bonds Initiative country databases; EU taxonomy-aligned issuance records	Zero-issuance years for Nigeria (2018, 2021, 2022) are retained and handled via the inverse hyperbolic sine transformation (Equation 2).
Renewable Energy Financing (REF)	World Bank World Development Indicators (WDI)	IEA World Energy Investment database, country series	IEA investment series is harmonised to constant-price, GDP-ratio terms for comparability.
Real GDP (RGDP)	World Bank World Development Indicators (WDI), constant-price GDP series	World Bank WDI;	Used solely as the scaling denominator for GF, GB, and REF.
Inflation (INF)	World Bank WDI CPI inflation series	World Bank WDI; Eurostat HICP-based inflation series	Retained in levels because Spain recorded a negative value in 2020.

Source: Authors' compilation, 2026.

3.2 Model Specification

Anchored in ecological modernisation theory, the study treats the ecological footprint as a function of green finance, green bonds, renewable-energy financing, and inflation. The baseline model is specified as:

$$EFP_{it} = \beta_0 + \beta_1 GF_{it} + \beta_2 GB_{it} + \beta_3 REF_{it} + \beta_4 INF_{it} + \mu_i + \varepsilon_{it} \quad \text{..............................(1)}$$

where EFP is the ecological footprint per capita, GF is green finance as a share of GDP, GB is green bond issuance as a share of GDP, REF is renewable-energy financing as a share of GDP, INF is the inflation rate, μ_i captures unobserved, time-invariant country characteristics, and ε_{it} is the idiosyncratic error term for country i in year t. To stabilise variance and permit an elasticity interpretation, green finance, renewable-energy financing, and the ecological footprint are transformed into natural logarithms. Because green bond issuance takes a value of zero in years with no new issuance (as observed for Nigeria in 2018, 2021, and 2022), the standard log transformation is undefined; the inverse hyperbolic sine (IHS) transformation, $\text{arcsinh}(x) = \ln(x + \sqrt{x^2+1})$, is applied instead, since it behaves like a logarithm for larger values while remaining defined at zero a widely used solution for zero-heavy financial flow variables. Inflation is retained in levels because it takes negative values (Spain, 2020). The estimated model is therefore:

$$lnEFPit = \beta 0 + \beta 1lnGFit + \beta 2IHS(GBit) + \beta 3lnREFit + \beta 4INFit + \mu i + \varepsilon it \quad \text{......................(2)}$$

3.3 Estimation Technique

The panel comprises five entities observed over nine years (N = 5, T = 9), a dimension too small for second-generation panel unit root and cointegration techniques such as the cross-sectionally augmented Dickey-Fuller (CADF) or Westerlund tests, which require a considerably larger cross-sectional dimension to deliver reliable inference. A small N is common in comparative country-panel studies that purposively combine a small number of structurally distinct economies rather than drawing a large random sample the design used, for example, by Chang et al. [23] in their ten-country asymmetric analysis and by Zin Lin et al. [25] in a three-country ASEAN comparison and the trade-off is made explicit here: the design sacrifices the large-N asymptotics needed for second-generation panel techniques in order to hold institutional and taxonomy heterogeneity between an emerging and four mature green bond markets fixed and observable, which a larger, more homogeneous sample would not permit. The Fixed Effects (FE) estimator is adopted a priori over Random Effects, since the five sampled countries were purposively selected (not randomly drawn from a larger population) and are likely to differ systematically in time-invariant respects such as regulatory taxonomy, industrial structure, and baseline resource endowment conditions under which the Random Effects orthogonality assumption is difficult to sustain. An F-test for poolability is used to confirm the presence of significant entity fixed effects.

Three additional diagnostics were carried out on the full country-year panel: a Hausman specification test formally comparing the Fixed Effects and Random Effects estimators; a Dumitrescu-Hurlin (2012) panel Granger non-causality test on each financing variable and the ecological footprint, in both directions, to probe reverse causality; and an attempted System/Difference GMM re-estimation as a dynamic robustness check. Results and their interpretation are reported in Table 4 and discussed immediately below; full estimation code is provided in the accompanying Stata 17 do-file.

Table 4. Additional diagnostics: Hausman test and Panel Granger Causality.

Test	Statistic	df / N	p-value
Hausman test (FE vs. RE)	$\chi 2 = 3.367$	df = 4	0.498
Panel Granger: GF → EFP	$\bar{W} = 1.570$, $\bar{Z} = 0.902$	N = 5	0.367
Panel Granger: EFP → GF (reverse)	$\bar{W} = 1.973$, $\bar{Z} = 1.539$	N = 5	0.124
Panel Granger: GB → EFP	$\bar{W} = 1.941$, $\bar{Z} = 1.489$	N = 5	0.137
Panel Granger: EFP → GB (reverse)	$\bar{W} = 2.694$, $\bar{Z} = 2.678$	N = 5	0.007
Panel Granger: REF → EFP	$\bar{W} = 1.403$, $\bar{Z} = 0.638$	N = 5	0.524
Panel Granger: EFP → REF (reverse)	$\bar{W} = 0.850$, $\bar{Z} = -0.237$	N = 5	0.812

Notes: Hausman test computed with a Nerlove (between-entity) variance-component Random Effects estimator, since the Swamy-Arora estimator is not identified when the number of entities equals the number of estimated parameters (N = 5, k = 5). Panel Granger causality is the Dumitrescu-Hurlin (2012) test, lag = 1, based on five per-country OLS regressions of each variable on its own first lag and the first lag of the counterpart variable; $\bar{W}$ is the cross-sectional average Wald statistic and $\bar{Z}$ its standardised form. Source: Authors' computation using Python (linearmodels, statsmodels), 2026; replication do-file provided separately for Stata 17.

The Hausman test does not reject the null hypothesis that the Random Effects estimator is consistent ($\chi 2 = 3.367$, df = 4, p = 0.498), which on its face appears to favour Random Effects over Fixed Effects. This result should, however, be interpreted with caution rather than taken as overturning the a priori case for Fixed Effects set out above. Because N = 5 exactly equals the number of estimated slope parameters plus the constant, the conventional Swamy-Arora between-entity variance component cannot be identified (the estimator divides by N − k = 0); the Random Effects estimates reported here instead use a Nerlove-type variance component computed from the dispersion of the five estimated country fixed effects. Because the five countries in this panel differ enormously in baseline ecological footprint (from 1.09-1.15 gha/capita in Nigeria to 6.48-7.28 in Denmark), the between-entity variance so computed is very large relative to the within-country residual variance, so the quasi-demeaning weight is $\theta = 0.997$ that is, the Random Effects transformation is numerically almost identical to full within-entity demeaning. The Fixed Effects and Random Effects coefficient vectors are consequently nearly identical by construction (for example, lnGF: −0.0375 under FE versus −0.0378 under RE), which mechanically produces a small Hausman statistic regardless of whether the Random Effects orthogonality assumption genuinely holds. In this small-N setting the Hausman test is therefore under-powered and its failure to reject should not be read as evidence that Random Effects is preferred; the theoretical case for Fixed Effects that the five countries were purposively selected and differ systematically in time-invariant respects such as green finance taxonomy and industrial structure remains the study's primary justification, consistent with the guidance that Hausman tests are unreliable in panels with very few cross-sectional units.

The Dumitrescu-Hurlin panel Granger causality tests find no significant causality, in either direction, between green finance and the ecological footprint (p = 0.367 and p = 0.124) or between renewable-energy financing and the ecological footprint (p = 0.524 and p = 0.812) at conventional significance levels. For green bonds, however, the test finds no significant evidence that green bonds Granger-cause the ecological footprint (p = 0.137) but does find that the ecological footprint Granger-causes green bond issuance in the reverse direction (p = 0.007). This is a genuine and important qualification to the study's green bond findings: it raises the possibility that countries with an already-lower or improving ecological footprint find it easier, or more attractive, to issue green bonds for example, because a smaller resource footprint may correlate with the institutional and market-development characteristics that also support green bond market depth rather than green bond issuance being the sole driver of ecological footprint reduction implied by the Table 8 and Table 9 coefficients. Given the short time dimension (T = 9, or 8 usable observations per country after first-differencing for a single lag), these panel causality results should be treated as indicative rather than definitive; the Dumitrescu-Hurlin test's standardised $\bar{Z}$ statistic is derived under asymptotics in the number of cross-sectional units, and N = 5 is far smaller than the sample sizes for which the test's asymptotic properties are established. Subject to that caveat, the reverse-causality signal for green bonds is reported transparently here, and the study's green bond coefficient should accordingly be interpreted as a robust within-country association rather than as unambiguous evidence of a unidirectional causal effect running from green bonds to the ecological footprint.

A System/Difference GMM re-estimation (Arellano-Bond/Blundell-Bond) was also attempted, using both Python (pydynpd) and by preparing the equivalent Stata 17 specification (see the accompanying do-file, which uses the community-contributed xtabond2 command). Both implementations returned an explicit diagnostic warning that difference and system GMM "do not work well on long ($T \geq N$) panel data" before estimation could proceed reliably. This is not a software artefact but a substantive econometric constraint: Arellano-Bond-type GMM estimators derive their consistency from asymptotics in the number of cross-sectional units (N) with the time dimension (T) fixed and small, and are well known to suffer from instrument proliferation and unreliable, imprecisely estimated coefficients once the number of potential instruments approaches or exceeds N a risk that is especially acute here because N = 5 is smaller than T = 9, the reverse of the configuration GMM is designed for. Rather than report GMM coefficients that the estimator's own diagnostics flag as unreliable in this setting, the study does not include a GMM specification among its preferred estimates. This is recorded as an explicit limitation in Section VI: a longer-panel or larger-N extension of this dataset would be required before System or Difference GMM could be applied with confidence.

To guard against heteroscedasticity, serial correlation, and cross-sectional dependence the three violations of classical OLS assumptions most common in macro panels combining countries of very different scale the study estimates the Fixed Effects model with Driscoll-Kraay [34] standard errors. The Driscoll-Kraay estimator produces a heteroscedasticity- and autocorrelation-consistent (HAC) covariance matrix that remains valid under general forms of spatial and cross-sectional correlation, and is well suited to panels, such as this one, with a small-to-moderate number of cross-sectional units and a longer time dimension. Prior to estimation, the study conducts a Modified Wald test for groupwise heteroscedasticity, a first-differenced autocorrelation test, and Pesaran's Cross-Sectional Dependence (CD) test on the Fixed Effects residuals, in order to characterise the error structure that Driscoll-Kraay standard errors are designed to accommodate. Variance inflation factors (VIFs) are also computed to assess multicollinearity among the green finance, green bond, and renewable-energy financing regressors, which are conceptually related components of a country's broader green finance architecture.

4. Results

Table 5 presents the descriptive statistics for the study variables. Green finance averages 2.808% of GDP across the panel, ranging from 1.016% to 6.120%, while green bond issuance averages 1.134% of GDP but exhibits a minimum of zero, reflecting years in which Nigeria recorded no new green bond issuance. The ecological footprint averages 4.084 global hectares per capita, ranging from 1.090 to 7.280, consistent with the substantially higher per-capita resource consumption of the sampled European economies relative to Nigeria. Inflation shows the widest dispersion (standard deviation of 6.754), driven by episodes of elevated inflation across all five countries following 2021-22. The Jarque-Bera statistics indicate that GF, GB, REF, and EFP do not significantly depart from normality at the 5% level, while inflation is significantly non-normal, reflecting the extreme values recorded during the post-pandemic inflationary period; this non-normality does not compromise the Driscoll-Kraay estimates, which do not rely on a normality assumption for valid inference.

Table 5. Descriptive statistics.

Statistic	GF (%GDP)	GB (%GDP)	REF (%GDP)	EFP (gha/cap)	INF (%)
Mean	2.808	1.134	1.088	4.084	5.686
Median	2.678	1.002	1.029	4.200	2.600
Maximum	6.120	3.333	2.787	7.280	28.920
Minimum	1.016	0.000	0.042	1.090	-0.300
Std. Dev.	1.234	0.897	0.784	1.847	6.754
Skewness	0.622	0.647	0.377	-0.459	1.735
Kurtosis	2.402	2.719	1.906	2.043	6.514
Jarque-Bera	5.796	3.382	1.408	0.718	29.456
Probability	0.055	0.184	0.495	0.698	0.000
Observations	45	45	45	45	45

Source: Author's computation using Stata 17.

Table 6 reports variance inflation factors below the conventional threshold of 10, indicating that multicollinearity while non-trivial, as expected given that green finance, green bonds, and renewable-energy financing are overlapping components of the same green finance architecture does not rise to a level that would invalidate the regression estimates.

The elevated but acceptable VIFs for GF and GB (8.96 and 8.61, respectively) motivate the sequential model-building strategy adopted in the analysis that follows, which introduces the regressors incrementally to assess the stability of each coefficient.

Table 6. Variance inflation factor (VIF) test.

Variable	VIF
lnGF	8.96
I(GB)	8.61
lnREF	6.96
INF	3.15
Mean VIF	6.92

Source: Authors' computation, 2026.

Table 7 reports the diagnostic tests conducted on the Fixed Effects residuals. The F-test for poolability strongly rejects the null hypothesis of no entity effects, confirming that country-specific fixed effects are appropriate. The Modified Wald test does not reject the null of constant variance across countries ($p = 0.348$), the first-differenced autocorrelation test provides no strong evidence of serial correlation ($p = 0.127$), and Pesaran's CD test does not detect significant cross-sectional dependence among the residuals ($p = 0.939$). While these results suggest that the classical Fixed Effects standard errors are reasonably well behaved, the Driscoll-Kraay estimator is retained as the reporting standard because it nests the classical case, imposes no cost in efficiency when the underlying assumptions hold, and provides a conservative safeguard against the small-sample heteroscedasticity and dependence risks inherent in a panel that combines economies of markedly different scale.

Table 7. Panel diagnostic test results.

Diagnostic Test	Statistic	p-value	Implication
F-test for Poolability	12,020.0	0.000	Significant entity fixed effects; pooled OLS rejected
Modified Wald (Heteroscedasticity)	5.590	0.348	Groupwise heteroscedasticity not significant
First-Differenced AR(1) Test	-0.173	0.127	No strong evidence of serial correlation
Pesaran CD Test	0.077	0.939	No significant cross-sectional dependence

Source: Authors' computation using Stata, 2026.

Table 8 presents the Fixed Effects estimates with Driscoll-Kraay standard errors, introducing the regressors sequentially. The explanatory power rises substantially across specifications, from a within-R^2 of 0.505 in the green-finance-only Model I to 0.975 in the fully specified Model IV, indicating that green finance, green bonds, renewable-energy financing, and inflation jointly account for the overwhelming majority of within-country variation in the ecological footprint over the sample period. However, the sign of the green finance coefficient is not stable across the sequential specifications: it is negative in Model I (−0.071), turns positive in Model II once green bonds are added (+0.062), and reverts to negative in Models III and IV (−0.038 and −0.037) once renewable-energy financing and inflation are included. The study does not, therefore, characterise the green finance coefficient as stable across all four models; rather, the sign reversal in Model II is most plausibly a symptom of the elevated variance inflation factors reported in Table 6 for lnGF and I(GB) (8.96 and 8.61 respectively), which indicates meaningful overlap between green finance flows and green bond issuance both are components of the same broader green finance architecture, so a bivariate specification that omits renewable-energy financing (Model II) is more exposed to this overlap than the fully specified Model IV. Once all three financing variables and inflation are included jointly (Model IV), green finance and green bonds are both negative and highly significant, and it is this fully specified, multicollinearity-adjusted result that the study treats as its preferred estimate; the Model I-II sign reversal is reported transparently as evidence of the shared variance among the green finance regressors rather than omitted or downplayed.

Table 8. Fixed effects with driscoll-kraay standard errors.

Variable	Model I	Model II	Model III	Model IV (Full)
lnGF	-0.071*** (0.000)	0.062*** (0.000)	-0.038*** (0.000)	-0.037*** (0.000)
I(GB)		-0.137*** (0.000)	-0.105*** (0.000)	-0.105*** (0.000)
lnREF			0.045*** (0.000)	0.042*** (0.000)
INF				0.001** (0.024)
Constant	1.326*** (0.000)	1.319*** (0.000)	1.399*** (0.000)	1.393*** (0.000)
R^2 (within)	0.505	0.914	0.971	0.975
Entity Effects	Yes	Yes	Yes	Yes
Observations	45	45	45	45

Note: Dependent variable: Log ecological footprint (sequential models). Driscoll-Kraay standard errors (Bartlett kernel, bandwidth = 4) reported. P-values in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Source: Authors' computation using Stata, 2026.

5. Discussion

The effect of green finance on environmental sustainability: the results in Model IV show that green finance exerts a negative and statistically significant effect on the ecological footprint, confirming that a larger green finance share of GDP is systematically associated with a smaller ecological footprint, ceteris paribus. Because a lower ecological footprint denotes improved environmental sustainability, this finding indicates that green finance meaningfully reduces environmental degradation across the sampled countries. The economic logic underlying this result is best understood through the lens of ecological modernisation theory: green finance repositions the relative cost of capital, cheapening credit for low-impact, resource-efficient activities while raising the implicit cost of capital for polluting ones, thereby nudging the composition of investment toward less resource-intensive production [20]. This mirrors a wider strand of the finance-environment literature showing that a deeper, better-functioning financial system does not merely finance more activity but changes what gets financed, easing firms' access to the capital needed for research, development, and the adoption of cleaner technologies [35]. The Porter Hypothesis offers a complementary, firm-level rationale where environmentally oriented capital is available and competitively priced, firms that innovate toward resource efficiency and lower-footprint processes can gain a competitive advantage rather than simply bear a compliance cost, so that the reallocation of finance and the reallocation of production reinforce one another [36]. This result is consistent with evidence from thirteen leading green-finance economies and a forty-four-country OECD panel, both of which report that green finance reduces the ecological footprint by redirecting capital toward lower-impact production processes [14,37].

However, the effect of green bonds on environmental sustainability: green bond issuance exerts a negative and highly significant effect on the ecological footprint, the largest elasticity among the three financing variables. Economically, this larger effect is intuitive: unlike broader green finance flows, green bonds are a contractually earmarked instrument use-of-proceeds restrictions, project eligibility criteria, and independent impact-reporting obligations bind the issuer to a specific environmental project for the life of the instrument, sharply narrowing the scope for capital to be diverted to unrelated or less environmentally beneficial uses [18]. This earmarking also has a market-pricing dimension: because investors can verify environmental intent more readily for a labelled green bond than for an undifferentiated pool of green finance, green bonds have been shown to command a modest yield discount, often termed the "greenium," reflecting non-pecuniary investor demand for verified environmental impact and effectively lowering the cost of environmentally earmarked capital relative to conventional financing [38]. In Nigeria specifically, this earmarking is codified in the SEC Green Bond Rules of 2018 and the Federal Government's Sustainable Bond Framework of 2025, which limit the diversion of proceeds to non-environmental purposes [18,39,40]. This finding tempers the more cautious evidence from a difference-in-differences study of global green and conventional bond issuers, which found no significant post-net-zero relationship between green bond issuance and emissions specifically [41]; the present result suggests that, at least within this five-country panel spanning both mature and emerging markets, green bond proceeds are associated with measurable reductions in the broader ecological footprint even where the emissions-specific channel may be weaker.

Thus, the effect of renewable-energy financing on environmental sustainability: the results show a positive and statistically significant relationship between renewable-energy financing and the ecological footprint, the opposite sign to green finance and green bonds. While counterintuitive at first glance, this pattern has a straightforward economic explanation rooted in the physical, rather than purely financial, nature of renewable-energy investment. Building solar, wind, and grid-expansion capacity requires land conversion, mineral extraction, concrete and steel, and construction-phase energy use before a single unit of clean electricity displaces fossil generation; the ecological footprint captures exactly this upstream resource draw, so a rising REF-to-GDP ratio can raise the footprint mechanically during the build-out phase even as it lays the foundation for later environmental gains.

This is consistent with global evidence that the ecological payoff of renewable energy is most pronounced in developed countries with mature grids, while economies still constructing their renewable infrastructure can see rising resource use during the construction and installation phase before the displacement of fossil generation and efficiency gains materialise [24]. This build-out interpretation is further supported by more recent OECD evidence: Hon et al. [21] similarly find that green bond volume raises the ecological budget and reduces the ecological footprint only once environmental awareness and renewable-energy capacity are already established, suggesting a maturation lag between renewable-energy financing and its eventual environmental payoff that is broadly consistent with the transitional interpretation offered here. Within this panel, renewable-energy financing rises sharply and simultaneously with real GDP and overall green finance activity across all five countries over the sample period (Table 5), so the positive coefficient most plausibly reflects this transitional infrastructure-build effect land conversion, material use, and construction-phase resource demand associated with solar, wind, and grid-expansion projects rather than a genuine adverse effect of clean energy investment itself. The short sample window limits the ability to observe the longer-run displacement effect that would be expected to eventually dominate as installed renewable capacity matures and begins substituting for fossil generation.

Finally, inflation exerts a small but statistically significant positive effect on the ecological footprint. Economically, this is consistent with the view that inflationary episodes, such as those recorded across all five countries in 2022-23, raise the relative price of energy and other inputs, prompting short-run substitution toward less efficient, more carbon- and resource-intensive production and consumption choices as households and firms economise on capital outlays that would otherwise improve efficiency. Rising prices can also compress the fiscal space and household disposable income available for environmental and energy-efficiency investment, so that inflation acts less as a direct driver of ecological degradation than as a macroeconomic headwind that slows the pace of the very green investment this study identifies as beneficial.

6. Robustness Checks

To assess whether the Model IV findings are sensitive to the choice of estimator, the study re-estimates the full specification using three alternative approaches: (i) Pooled OLS with Driscoll-Kraay standard errors, which removes the entity fixed effects; (ii) Fixed Effects with both entity and time effects under Driscoll-Kraay standard errors, which additionally absorbs common annual shocks such as global inflationary or energy-price cycles; and (iii) Fixed Effects with standard errors clustered at the country level, a conventional alternative to Driscoll-Kraay for panels with a small number of clusters.

Table 9 shows that the direction and significance of the coefficients are not uniformly robust across all four specifications, and the discussion below reports these differences explicitly rather than characterising the full set of results as robust. Renewable-energy financing is the only variable that retains the same sign (positive) and significance across all four specifications, making it the most robust result in the study. Green bonds are negative and significant under the entity-fixed-effects specifications the two-way effects model, the clustered-SE model, and the Table 8 baseline but positive and significant under Pooled OLS (+0.604), a sign reversal the study attributes to the absence of entity fixed effects in the pooled specification, which leaves the coefficient exposed to time-invariant cross-country differences (such as taxonomy maturity) that are correlated with both green bond issuance and the ecological footprint. Inflation follows the same pattern in reverse: it is negative and significant under Pooled OLS (−0.023) but positive and significant under all three fixed-effects specifications (+0.001 in each case), so the sign of the inflation coefficient, like that of green bonds, depends on whether entity effects are included, and the fixed-effects sign is the one the study treats as its preferred estimate given the a priori case for Fixed Effects over pooled estimation set out in Section III. Green finance is negative and significant in the entity-fixed-effects baseline (−0.037) and under clustered standard errors (−0.037), but turns positive under the two-way entity-and-time fixed-effects specification (+0.051), indicating that once common annual shocks (such as the 2022 global energy-price and inflation surge) are absorbed by time effects, the residual within-country variation in green finance no longer moves inversely with the ecological footprint; this instability is reported here as a genuine limitation of the green finance result rather than resolved by asserting robustness. Taken together, the robustness analysis supports three conclusions with differing degrees of confidence: renewable-energy financing's positive, short-run association with the ecological footprint is the most robust finding in the study; green bonds' negative association is robust to the inclusion of entity fixed effects but not to their exclusion; and the sign of green finance is the least robust of the three financing variables, being sensitive to whether time effects are included, a result the study attributes to the shared variance between green finance and green bonds identified via the VIF diagnostics in Table 6 and discussed further in Section VI.

Table 9. Robustness checks dependent variable: Log ecological footprint.

Variable	Pooled OLS-DK	FE (Entity+Time)-DK	FE Clustered SE	FE-DK Baseline (Table 8)
lnGF	-1.050*** (0.000)	0.051*** (0.001)	-0.037*** (0.001)	-0.037*** (0.000)
I(GB)	0.604*** (0.007)	-0.097*** (0.000)	-0.105*** (0.000)	-0.105*** (0.000)
lnREF	0.419*** (0.000)	0.036*** (0.000)	0.042*** (0.000)	0.042*** (0.000)
INF	-0.023*** (0.002)	0.001*** (0.001)	0.001*** (0.000)	0.001** (0.024)
Constant	1.982*** (0.000)	1.301*** (0.000)	1.393*** (0.000)	1.393*** (0.000)
Entity Effects	No	Yes	Yes	Yes
Time Effects	No	Yes	No	No
R^2	0.902	0.968	0.975	0.975
Observations	45	45	45	45

Note: p-values in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Source: Authors' computation using Stata, 2026.

On the High Within-R^2 in the Full Specification: The within-R^2 of 0.975 reported for Model IV in Table 8 is unusually high for cross-country panel data, and the study addresses directly, rather than passes over, the concern this raises regarding possible overfitting or multicollinearity. Two features of the panel's structure are relevant. First, with $N = 5$ entities and $T = 9$ years, the full model estimates five country fixed effects plus four slope coefficients and a constant against only 45 observations, so the ratio of estimated parameters to observations is high by the standards of larger macro panels; a high within-R^2 in this setting partly reflects the model's flexibility relative to the sample size rather than exceptional out-of-sample predictive power, and the coefficients reported here should be read as describing the estimation sample rather than as validated out-of-sample forecasts. Second, the elevated but sub-threshold variance inflation factors reported in Table 6 (8.96 for lnGF and 8.61 for I(GB)) confirm that green finance and green bond issuance share substantial common variation; because within-R^2 rises mechanically as correlated regressors are added even when individual coefficients become less precisely identified, part of the increase from 0.914 in Model II to 0.975 in Model IV is attributable to this shared variance rather than to genuinely independent explanatory contributions from each variable. The study therefore treats the high within-R^2 as an indication that the fully specified model fits the observed within-country variation closely over a short, purposively selected panel, and not as evidence that the estimated elasticities would generalise to a larger or more heterogeneous sample of countries; this caveat is reflected in the Limitations subsection below.

7. Theoretical and Practical Contributions, and Study Limitations

This section sets out a clearer articulation of the study's theoretical contribution and a dedicated discussion of its limitations.

7.1 Theoretical and Practical Contributions

Theoretically, this study contributes to ecological modernisation theory by disaggregating the single, composite "green finance" construct used in most prior cross-country studies [14,16,37] into three conceptually distinct channels broad green finance flows, contractually earmarked green bond issuance, and renewable-energy financing specifically and estimating their separate, and in the case of renewable-energy financing opposing, effects on the ecological footprint within a single empirical model. Prior studies have generally treated green finance as a unitary channel operating in one direction on environmental outcomes; by showing that renewable-energy financing carries the opposite sign to green finance and green bonds over 2017-2025, this study provides evidence that ecological modernisation's decoupling mechanism operates on a lag, with an initial, resource-intensive infrastructure-build phase preceding the anticipated later-stage environmental dividend, a refinement of the theory's implicit assumption of a immediate and uniformly negative relationship between green capital allocation and ecological pressure.

The rationale for combining Nigeria with four European economies, specifically, is that it allows the theoretical decoupling mechanism to be tested under two structurally different green finance regimes within the same empirical framework: a codified, taxonomy-governed regime (Denmark, France, Spain, and the Netherlands, operating under the EU Green Deal and taxonomy) and an emerging, still-maturing regime (Nigeria, operating under the SEC Green Bond Rules of 2018 and the 2025 Sustainable Bond Framework). Because the Fixed Effects specification nets out time-invariant differences between these regimes, the resulting within-country coefficients isolate the association between year-to-year changes in green finance instruments and the ecological footprint net of each country's baseline institutional maturity a design choice that directly targets the comparative gap identified in Section II, namely that comparative evidence positioning an emerging sovereign green bond pioneer alongside mature European markets within a single econometric framework remains scarce [12,13].

Practically, the study offers policymakers in emerging green bond markets and Nigerian authorities specifically evidence that, of the three financing channels examined, green bond issuance carries the most consistent and largest environmental payoff once entity effects are accounted for, supporting continued deepening of the sovereign and subnational green bond programme rather than reliance on undifferentiated green finance flows alone. For practitioners overseeing renewable-energy financing, the results caution against interpreting a rising ecological footprint during a renewable-energy build-out phase as evidence that the investment is environmentally counterproductive, and instead support pairing such financing with complementary efficiency and land-use measures, discussed further in the policy recommendations in Section VII.

7.2 Limitations

The study has five main limitations, acknowledged here. First, the sample size ($N = 5$ countries, $T = 9$ years, 45 country-year observations) is small; while the countries were purposively selected to combine an emerging and four mature green bond markets rather than randomly sampled, the small N limits the statistical power available to detect smaller effects and precludes the use of second-generation panel techniques that require a larger cross-sectional dimension, as noted in Section III. Second, the study period (2017-2025) is short relative to the multi-decade horizons over which infrastructure-driven environmental effects, such as the renewable-energy build-out effect identified in Section IV, are expected to fully unwind; the positive REF coefficient reported here should accordingly be read as a short-run, transitional estimate rather than a statement about the long-run environmental payoff of renewable-energy investment. Third, green bond data availability is uneven across the panel: Nigeria's green bond market is comparatively young, with issuance concentrated in three discrete years (2017, 2025, plus subnational and corporate issuance), while the four European markets issue more continuously, so the panel's green bond variable captures a more volatile, lumpier series for Nigeria than for its European comparators. Fourth, as reported in Section III (Table 4), the Hausman test is under-powered in this $N = 5$ panel and does not, by itself, discriminate between Fixed and Random Effects, so the theoretical case for Fixed Effects remains the primary justification; the Dumitrescu-Hurlin panel Granger causality tests find no significant causality for green finance or renewable-energy financing in either direction, but do find that the ecological footprint Granger-causes green bond issuance ($p = 0.007$) rather than the reverse, indicating a genuine reverse-causality risk specific to the green bond coefficient that qualifies, without overturning, the study's conclusion regarding green bonds; and System/Difference GMM could not be reliably estimated because the panel's dimensions ($T = 9 \geq N = 5$) fall outside the regime for which Arellano-Bond/Blundell-Bond estimators are asymptotically valid, a constraint confirmed by explicit software diagnostics reported in Section III rather than assumed. Fifth, the model's set of controls is limited to inflation; GDP per capita, trade openness, energy consumption, institutional quality, and CO_2 emissions are all plausible omitted determinants of the ecological footprint that the current 45-observation panel does not have the degrees of freedom to accommodate without compromising estimation precision, and their omission means the reported elasticities may partly reflect these omitted correlates. Extending the panel's time dimension and incorporating this fuller set of controls, together with the Hausman, Granger, and GMM diagnostics noted above, is identified as the principal direction for follow-up research building on this study, and the authors intend to pursue this extension using the existing CBN, World Bank WDI, IEA, and Global Footprint Network data infrastructure described in Table 3.

8. Conclusion and Recommendations

This study assessed the nexus between green finance, green bonds, and environmental sustainability in Nigeria, Denmark, France, Spain, and the Netherlands over 2017-2025, using the ecological footprint per capita as the sustainability proxy and the Fixed Effects estimator with Driscoll-Kraay standard errors to accommodate the small-N, moderate-T structure of the panel and the possibility of cross-sectional dependence across economies linked by global climate finance markets.

The findings show that green finance and green bond issuance both significantly reduce the ecological footprint under the preferred entity-fixed-effects specification, with green bonds exerting the larger and most consistent effect across the entity-fixed-effects specifications specifically (though not under Pooled OLS, as discussed in Section V) evidence that earmarked, independently verified financing instruments translate more forcefully into environmental gains than broader green finance flows. Renewable-energy financing, by contrast, is associated with a significant increase in the ecological footprint over the sample period and is the study's most robust result across all specifications, attributed to the resource demands of infrastructure build-out during an early phase of energy transition rather than to any inherent adverse effect of clean energy investment. Inflation exerts a small positive effect on the ecological footprint under the fixed-effects specifications, consistent with short-run substitution toward less efficient production and consumption during periods of rising prices.

Based on these findings, the study offers the following policy recommendations:

(i) Governments, particularly in emerging markets such as Nigeria, should deepen sovereign and subnational green bond programmes and strengthen use-of-proceeds verification and impact-reporting frameworks, since green bonds show the strongest and most consistent association with reduced ecological footprint in this study.

(ii) Renewable-energy financing should be paired with energy-efficiency, land-use planning, and circular-economy measures during the infrastructure build-out phase, to shorten the lag between renewable-energy investment and its eventual reduction of the ecological footprint.

(iii) Macroeconomic stabilisation policies that contain inflation should be viewed as complementary to environmental policy, given the positive association between inflation and the ecological footprint identified in this study.

(iv) Regulators in emerging green bond markets should study the eligibility, verification, and impact-reporting standards of mature markets such as Denmark, France, Spain, and the Netherlands, to accelerate the maturation of domestic green bond frameworks.

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Ethics Statement

Not applicable. This study relies exclusively on secondary, publicly available macroeconomic and financial data at the country level; it does not involve human participants, human data, or animal subjects, and therefore did not require ethics committee or institutional review board approval.

Informed Consent

Not applicable. This study did not involve human participants.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Underlying sources include the Central Bank of Nigeria Statistical Bulletin, the World Bank World Development Indicators, the International Energy Agency World Energy Investment database, the Global Footprint Network National Footprint and Biocapacity Accounts, and national debt management office and green bond registry disclosures, as detailed in Table 3.

Author Contributions

Toryila Raphael Orshio: conceptualization, methodology, formal analysis, data curation, and writing – original draft. Adofu Ilemona, Obadiah Jonathan Gimba, and Abubakar Saad Bahuli: supervision, validation, and writing – review and editing. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Generative AI Statement

A generative artificial intelligence tool (Claude, Anthropic) was used solely for language polishing and editing of the manuscript text, including grammar, phrasing, and formatting. It was not used to generate the manuscript's content, arguments, data analysis, or original scholarly contribution. All conceptualisation, econometric modelling, data analysis, interpretation of results, citation selection and verification, and the substantive conclusions and policy recommendations are the authors' own; the corresponding author reviewed all AI-assisted language edits and takes full responsibility for the final text.

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