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Assessing environmental sustainability under risk and governance pressures: new insights from Canada

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Environmental sustainability is a central concern in environmental economics, yet the effects of institutional quality and macroeconomic risks on sustainability outcomes remain underexplored, particularly in developed economies. This study examines how economic policy uncertainty (EPU), political risk (PRI), and governance quality (GOV) influence environmental sustainability in Canada, using the load capacity factor as a proxy. Utilizing quarterly data from 1990 to 2022, we apply the quantile-on-quantile regression method to capture heterogeneous and nonlinear relationships across different levels of environmental performance. Robustness is ensured through wavelet coherence analysis. The results reveal that EPU positively affects sustainability at higher quantiles, possibly due to precautionary shifts in policy or investment behavior. PRI also contributes positively in high-risk settings, reflecting the role of political institutions in environmental governance. Strong governance exhibits a consistently favorable impact across quantiles. Moreover, environmental innovation strengthens the positive effects of all three variables. These findings underscore the importance of adaptive institutions, risk-aware policymaking, and innovation-driven strategies for advancing environmental sustainability.

KEYWORDS

political risk, economic policy uncertainty, governance, environmental sustainability, quantile-on-quantile regression

1 Introduction

Climate change has emerged as one of the most pressing global challenges, with regions worldwide experiencing unprecedented temperature increases, prolonged droughts, and declining precipitation levels (Zhang L. et al., 2024; Kim et al., 2025; Yang et al., 2025). These climatic changes significantly affect human well-being and economic activities, reinforcing the urgent call for sustainable environmental policies (Hsu et al., 2024; Hu et al., 2025; Xu et al., 2025). International agreements such as the Paris Agreement and commitments reaffirmed at COP26 and COP28 highlight the global consensus on adopting sustainable growth strategies. Yet, despite these pledges, achieving environmental sustainability remains complex, influenced by a mix of economic, political, and institutional dynamics (Chen et al., 2021; Mohiuddin et al., 2025; Talema and Nigusie, 2024).

Previous research has typically examined environmental sustainability using proxies such as carbon emissions and ecological footprints, which primarily capture demand-side pressures (Lin and Ullah, 2024; Ullah and Lin, 2025a). Recently, the load capacity factor (LC) has been introduced as a more comprehensive metric, incorporating both ecological supply and human demand. An LC value greater than one indicates ecological balance, whereas values below one signal ecological stress (Siche et al., 2010). As LC integrates both supply and demand dimensions, it offers a robust measure of sustainability, making it highly relevant for this study (Pata et al., 2023a).

Among the critical determinants of sustainability are economic and political uncertainties, which shape policy design, investment flows, and environmental outcomes (Dao et al., 2024; Sugar, 2024; Yuan et al., 2024). For instance, economic policy uncertainty (EPU) often deters investment in clean energy and green technologies, as firms hesitate to commit resources amid unstable policy conditions (Al-Thaqeb and Algharabali, 2019; Amin and Dogan, 2021; Jin et al., 2018). Likewise, political risk (PRI)—manifested through instability, shifting regulations, or policy volatility—can either obstruct or accelerate environmental initiatives (Aslan et al., 2024; Baker et al., 2016). In contrast, effective governance (GOV), characterized by institutional quality, accountability, and regulatory enforcement, provides the enabling conditions for sustainable development (Zhang S. et al., 2024). Although prior studies have investigated these factors individually, very limited research has considered their joint and interactive influence on sustainability outcomes (Andlib et al., 2024; Balsalobre-Lorente et al., 2024; Li W. et al., 2023).

The Canadian context offers a unique setting for analyzing these dynamics. First, Canada is disproportionately affected by climate change, facing rising sea levels, frequent wildfires, and ecosystem degradation—threats that endanger Indigenous communities, physical infrastructure, and biodiversity. Second, Canada's pledge to achieve net-zero emissions by 2050 underscores the central role of governance and policy stability in meeting climate commitments. Yet, uncertainties in economic policies, political shifts, and regulatory enforcement could undermine these objectives. Third, as a resource-dependent economy, Canada embodies the global trade-off between economic growth, resource reliance, and environmental regulation, making it a valuable case for broader policy discussions.

Despite increasing scholarly attention, significant gaps remain. First, most studies have relied on carbon emissions or ecological footprints, while the LC index as a sustainability indicator remains underexplored. Second, little is known about how EPU, PRI, and GOV collectively shape environmental sustainability, especially in resource-intensive economies such as Canada. Third, the potential moderating role of environmental innovation—as a mechanism to offset risks posed by uncertainty—has been largely overlooked. Addressing these gaps, this study applies quantile-on-quantile regression (QQR) to examine the heterogeneous effects of EPU, PRI, and GOV on sustainability (proxied by LC) under varying ecological conditions. Additionally, we assess whether environmental innovation mitigates the adverse effects of policy uncertainty and political risk, thereby strengthening sustainability pathways.

This study makes four key contributions. First, it broadens the literature on economic and political risks by applying LC, a more holistic sustainability indicator that captures ecological supply and demand. Second, it provides empirical evidence from Canada, offering insights transferable to other economies balancing resource dependence and sustainability goals. Third, by employing QQR and wavelet coherence models, the study ensures robustness while capturing nonlinear, asymmetric dynamics often missed in conventional models. Finally, the paper delivers policy-relevant contributions by highlighting the role of stable economic policies, strong governance, and environmental innovation in achieving sustainability. These findings directly support SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 16 (Peace, Justice, and Strong Institutions), thus aligning with international sustainability agendas.

2 Theoretical linkages and past literature

2.1 Theoretical mechanism

Achieving environmental sustainability requires an integrated understanding of how economic and political dynamics interact with governance structures. The influence of economic policy uncertainty (EPU), political risk (PRI), and governance (GOV) on sustainability (measured by the load capacity factor, LC) can be explained through several theoretical lenses.

Real Options Theory suggests that uncertainty increases the value of delaying investments in long-term projects (Chakraborty et al., 2025; Dixit and Pindyck, 1994). In contexts of high EPU, firms are likely to postpone or reduce investment in clean energy infrastructure, as unpredictable policies increase financial risk (Bloom, 2009; Wang et al., 2025). This dynamic undermines decarbonization pathways by creating hesitation in adopting green technologies.

Porter's Hypothesis and innovation-driven growth theory argue the opposite: under certain regulatory environments, policy uncertainty can stimulate proactive investment in eco-friendly technologies as firms hedge against future regulatory shifts (Yang et al., 2023). Hence, well-designed policies, even amid uncertainty, can catalyze green innovation and competitive advantage (Pata et al., 2023b; Porter and Van Der Linde, 1995; Yasin et al., 2024).

Institutional Theory emphasizes the importance of strong political institutions for environmental governance (North, 1990). Political instability weakens policy enforcement, enabling regulatory gaps, corruption, and unsustainable practices (Garfinkel and Skaperdas, 2000; Liu et al., 2023). However, under the conflict-resolution and political legitimacy hypotheses, unstable governments may adopt stringent environmental laws to build legitimacy or attract foreign investment, paradoxically enhancing sustainability under certain conditions.

Finally, the environmental governance framework underscores that robust governance reduces corruption, improves regulatory enforcement, and facilitates public–private partnerships (Ostrom, 1990; Ulussever et al., 2024; Wine, 2019). Conversely, weak governance leads to fragmented policies, deterring green investment and exacerbating ecological degradation (Barbier, 2010; Zhang and Wen, 2023).

This study integrates these perspectives into a unifying framework. We posit that EPU and PRI create risks that can either delay or, under certain conditions, accelerate green

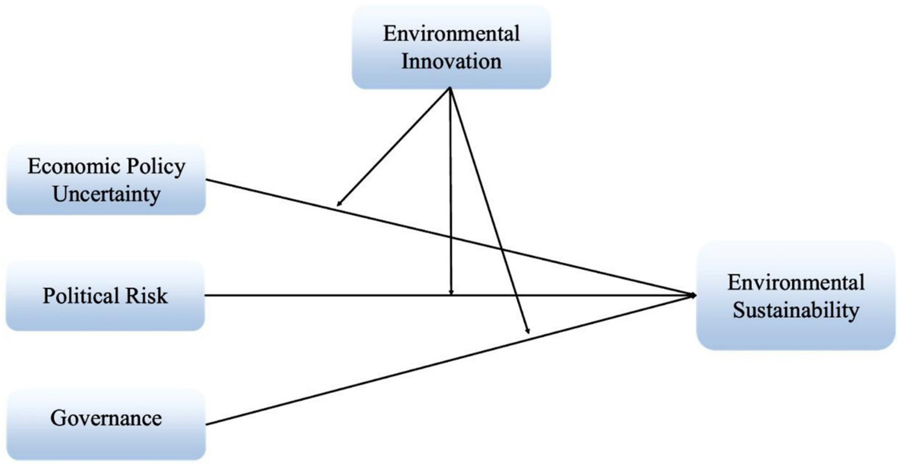

FIGURE 1
Conceptual framework diagram.

transitions, while governance provides the institutional backbone that determines the effectiveness of sustainability policies. Moreover, environmental innovation is expected to moderate these effects, reducing the adverse impacts of uncertainty and political instability. Figure 1 illustrates the conceptual framework of this study.

2.2 Literature review

The relationship between uncertainty, governance, and environmental sustainability has been widely debated, though findings remain mixed.

2.2.1 Economic policy uncertainty

Several studies report that EPU undermines green investment and ecological quality by discouraging firms from committing to clean technologies (Ullah and Lin, 2025b,c; Villanthenkodath and Pal, 2024). However, others find that uncertainty may push firms toward adaptive innovation and greener practices (Farid and Zafar, 2024; Jiao et al., 2022), consistent with the Porter Hypothesis. Recent works (Kartal et al., 2023; Xue et al., 2022), highlight that the effects of EPU are nonlinear and context-specific, depending on institutional capacity and market maturity.

2.2.2 Political risk

Many studies suggest that higher PRI undermines environmental sustainability by weakening regulatory enforcement and deterring investment (Ayhan et al., 2023; Khan et al., 2023; Ullah and Lin, 2025d). Yet, other research reports that governments under instability may pursue stricter environmental policies to gain legitimacy or attract foreign capital (Ashraf, 2023; Hassan et al., 2022). Recent scholarship emphasizes that the impact of PRI varies across political regimes, with democratic settings often moderating negative effects (Adebayo et al., 2022; Purcel, 2019; Van and Huang, 2020).

2.2.3 Governance

Governance quality has been consistently identified as a driver of sustainability. Strong institutions enable compliance, transparency, and accountability in environmental policy (Halkos and Tzeremes, 2013; Yi et al., 2023). Recent empirical works (Khan et al., 2022; Yadav et al., 2024; Zhang et al., 2021) confirm that governance positively influences renewable energy adoption, carbon reduction, and ecological balance, reinforcing its critical role in sustainability pathways.

The previously mentioned literature is summarized in Table 1.

2.3 Gaps in literature and theoretical advancement

Table 1 presents a range of studies examining the influence of EPU, PRI, or GOV on environmental outcomes. Building on these gaps, this study makes a unique conceptual contribution by integrating economic policy uncertainty (EPU), political risk (PRI), and governance (GOV) into a unified framework for understanding environmental sustainability, measured through the load capacity factor (LC). While prior research has examined these drivers individually, their combined effects on ecological capacity remain largely unexplored. Furthermore, by introducing environmental innovation (EI) as a moderating factor, we extend existing theories—such as real options theory, institutional theory, and the environmental governance framework—by demonstrating how innovation can mitigate the adverse effects of uncertainty and amplify the positive role of governance. This integrated perspective advances theoretical discourse by shifting from single-dimension analyses to a systemic model that captures the interplay of uncertainty, governance, and innovation. To the best of our knowledge, this represents the first attempt to test such a framework

TABLE 1 Literature review.

Authors	Region	Period	Methods	Findings
A: EPU- environment nexus				
Adedoyin and Zakari (2020)	U.K.	1985–2017	ARDL	Controversial effect
Wang et al. (2020)	USA	1960–2016	ARDL	Decreases ES
Liu and Zhang (2022)	China	2003–2017	Pooled regressions	Increases E.S.
Anser et al. (2021)	10 CO2 emitter	1990–2015	PMG-ARDL	Decreases ES
Adams et al. (2020)	10 resource rich	1996–2017	PMG-ARDL	Decreases ES
Syed et al. (2022)	BRICST	1990–2015	AMG and CCEMG	Controversial effect
Iqbal et al. (2023)	5 selected	2000–2001	ARDL	Decreases E.S.
Yu et al. (2021)	China	2008–2011	STIRPAT	Decreases ES
B: PRI-environment nexus				
Asif et al. (2023)	South Asian	1996–2019	ARDL	Decreases ES
Pata et al. (2023b)	South Asia	2002–2016	AMG	Increases ES
Simionescu et al. (2023)	11 selected	2007–2021	FMOLS and DOLS	Decreases ES
Yasin et al. (2019)	110 selected	1996–2016	Weighted panel EGLS	Increases E.S.
Kirikkaleli and Osmanli (2023)	Turkey	1990–2019	NARDL and DOLS	Increases ES
Wang et al. (2022)	Next-11	1990–2018	AMG and FMOLS	Increases ES
Su et al. (2021)	Brazil	1985–2018	FMOLS	Increases E.S.
Van and Huang (2020)	Vietnam	1990–2016	ARDL, G.C.	Decreases E.S.
C: GOV-environment nexus				
Zhang S. et al. (2024)	China	2002–2022	Dynamic ARDL	Increases ES
Yadav et al. (2024)	BRICS	2000–2021	CS-ARDL	Increases E.S.
Sun et al. (2023a)	BRICS	1996–2017	Nonparametric causality	Increases E.S.
Ali et al. (2022)	ECOWAS	1990–2016	AMG, PMG	Increases ES
Li R. et al. (2023)	158 selected	2002–2018	Panel threshold reg.	Decreases ES
Yasmeen et al. (2023)	BRI	1996–2018	MMQR	Increases ES
Sarwar and Alsaggaf (2021)	Saudia Arabia	1970–2018	Q regression	Increases ES

empirically in the Canadian context, thereby contributing both to theory and practice in environmental sustainability research.

3 Materials and methods

3.1 Data and variables

The present study incorporates annual data from 1990 to 2022 to investigate the impacts of economic policy uncertainty (EPU), political risk index (PRI), and governance (GOV) on environmental sustainability in Canada. The study used the load capacity factor as a proxy for environmental sustainability. The variable of load capacity factor is obtained through biocapacity/ecological footprints. The statistics for all these parameters is downloaded from the Global Footprint Network (GFN, 2023). The selection of explanatory variables is based on their critical role in shaping environmental policies and sustainability outcomes. Economic policy uncertainty (EPU) is a key determinant of investment and policy decisions that impact the adoption of clean technologies and sustainable practices. High levels of uncertainty can discourage long-term investments in environmental initiatives, making it an important factor to examine. The data for EPU is extracted from Economic Policy Uncertainty Index (EPU, 2023). Political risk (PRI) influences environmental sustainability by affecting regulatory stability, enforcement mechanisms, and investment confidence. Higher political risk can either delay or incentivize sustainability efforts, depending on governance effectiveness. The PRI data is sourced from Political Risk Services (PRS, 2023). Governance (GOV) plays a pivotal role in implementing and enforcing environmental regulations. Strong governance structures ensure effective policy execution, while weak governance can lead to regulatory inefficiencies and environmental degradation. To measure governance, this study constructs a composite governance index utilizing principal component analysis (PCA). The index integrates six dimensions of governance, providing a

TABLE 2 Sub-dimensions of governance index.

Major indexes	Definition of sub-indexes
Control of corruption	Elucidates the perspectives on the degree to which public authority is used for personal benefit, including both minor and major instances of corruption, as well as the appropriation of the state by privileged individuals and private entities.
Regulatory quality	Reflects the beliefs on the government's capacity to establish and execute effective policies and regulations that facilitate and encourage the growth of the private sector.
Govt. effectiveness	Pertains to the assessment of public services' quality, the civil service's quality and its level of independence from political influences, the effectiveness of policy development and execution, and the government's credibility in upholding these policies
Rule of law	Measures individuals' judgments about the level of trust and compliance with societal norms, specifically focusing on the effectiveness of contract enforcement, protection of property rights, law enforcement, and the judicial system, as well as the possibility of criminal activity and violence.
Political stability and absence of violence/terrorism	Political Stability and Absence of Violence/Terrorism assesses the perceived probability of political instability and/or violence driven by political motives, such as terrorism.
Voice and accountability	Reflects the perceived level of public participation in government selection, together with the presence of freedom of speech, freedom of association, and a free media in a nation.

TABLE 3 Variables and sources.

Variables	Symbol	Definition	Source
Load capacity factor	LC	The Load Capacity Factor compares biocapacity to ecological footprint, indicating whether a region consumes resources sustainably or unsustainably.	GFN, 2023
Economic policy uncertainty	EPU	A high level of index indicates a high level of economic policy uncertainty.	EPU, 2023
Political risk index	PRI	A high level of index indicates a high level of geopolitical risk	PRS, 2023
Government governance	Gov	Composite index of multiple indicators	Table 2
Environmental innovation	EI	The natural logarithmic value of total registered patents of environmental related technologies	OECD, 2023

comprehensive measure of institutional effectiveness in driving sustainability. Details of the governance index construction are presented in Tables A1–A3 and Figure A1. The single components of the index are given in Table 2. Further, Table 3 describes the specific information on the variables used in the research.

Before diving into the analysis, we ensure the time plots in Figure 2 have the right visual qualities for the raw data. The purpose is to look for signs of structural breaks, seasonality patterns, and drifts. The figure shows a general pattern of fluctuating values of LC, with a rise in the early 1990s, a decline in the mid-1990s, and a fluctuation in the early 2000s. Around 2000, there seems to be a slight rise in the LC related to technological breakthroughs or infrastructure improvements. Moreover, the EPU pattern demonstrates periods of stability and considerable fluctuation, with major rises in 2020 and falls in 2021 and 2022. Understanding these swings is critical for decision-making and successfully navigating the economic environment. Besides, the PRI graph shows a mostly stable trend with minor oscillations. According to the figure, the GOV experienced relatively stable negative values between 1990 and 1996, suggesting a period of consistent governance deficiencies. However, starting from 1996, there is a noticeable positive shift in the GOV, indicating an improvement in governance quality. It shows a significant upward trend in the GOV from the late 1990s to the early 2000s, reflecting positive governance reforms or initiatives undertaken during this period.

Furthermore, the data shows a generally increasing trend in governance scores from 2002 to 2017, indicating sustained efforts to enhance governance practices and institutions in Canada. Finally, from 1990 to the early 2000s, the EI displays some variability, indicating a mix of positive and negative trends. However, starting from the mid-2000s, there appears to be a general upward trend in the EI, pointing toward increased focus and advancements in environmental innovation in Canada.

3.2 Moderating relationship

Environmental innovation refers to creating and using novel technologies, methods, and remedies to reduce environmental harm, preserve resources, and advance sustainability. It involves developing and implementing inventive methods, goods, and services that help safeguard the environment, mitigate climate change, and conserve natural ecosystems (Skordoulis et al., 2020). In this study, environmental innovation is a moderating variable affecting the link between the independent variables (EPU, PRI, GOV) and the dependent variable (LC). It essentially helps to explain how the relationship between these variables is affected by the level of environmental innovation in Canada. The moderation analysis integrating environmental innovation will assist in creating a more thorough knowledge of how environmental issues interact with economic and governance-related variables to shape Canada's environmental sustainability. Numerous empirical investigations have used patents on environmentally related technologies to represent environmental innovation. Therefore, the current research utilized the log of patents related to environmental technologies as the dependent variable (Abbas et al., 2024). The data was obtained from OECD (2023).

3.3 Estimation techniques

This study investigates the linkages between environmental sustainability (LC), economic policy uncertainty (EPU), political

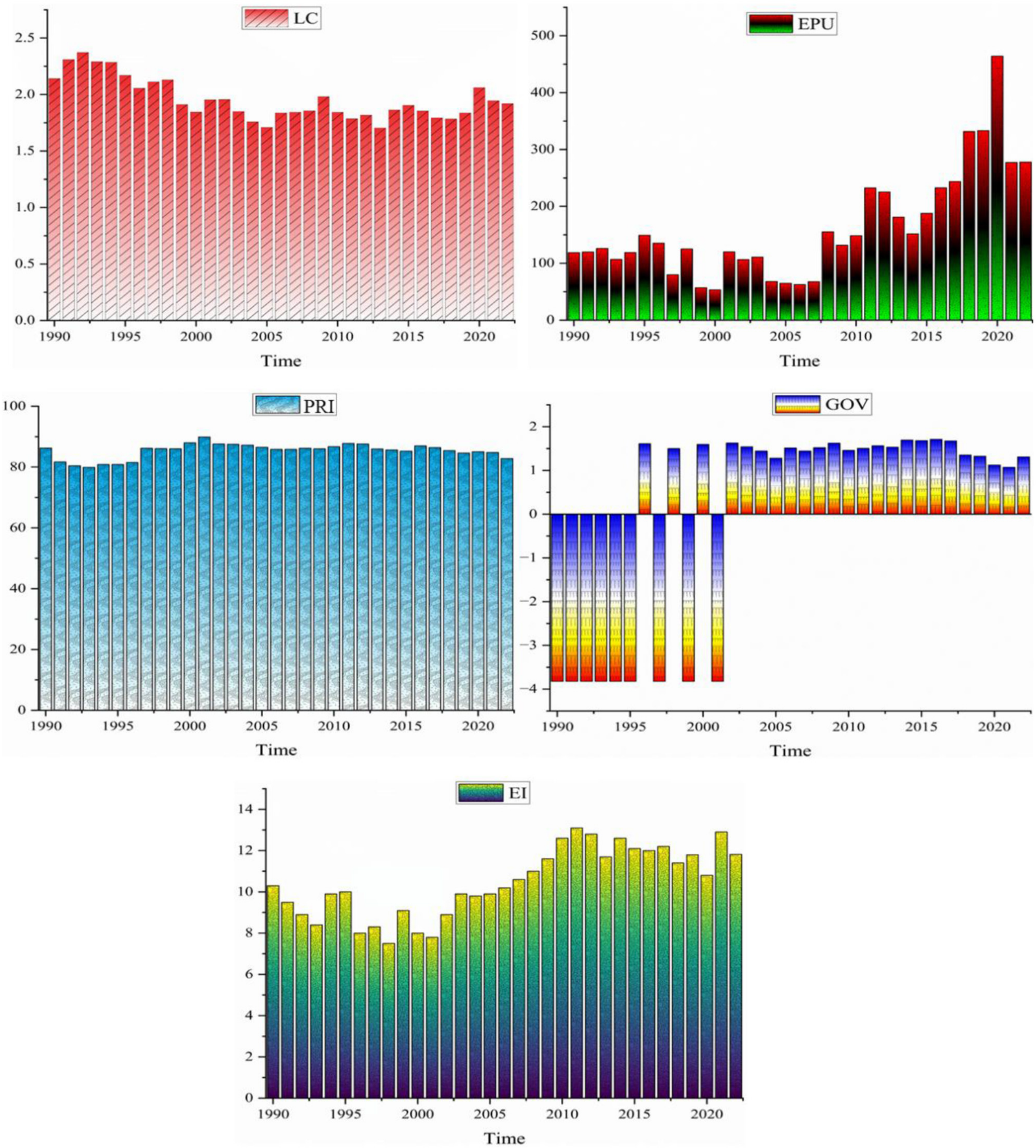

FIGURE 2
Annual values of LC, EPU, PRI, GOV, and EI of Canada from 1990 to 2022.

risk (PRI), and governance (GOV) in Canada by applying advanced quantile-based and time–frequency methods. Traditional econometric models such as ARDL, CS-ARDL, DOLS, and FMOLS are widely used in the environmental economics literature; however, they focus primarily on mean relationships and assume linearity and symmetry. These assumptions are restrictive in contexts where relationships may vary across different levels of environmental stress, governance quality, or uncertainty. For instance, EPU may exert a weak influence on sustainability under stable ecological conditions but a much stronger effect under high ecological pressure. Similarly, governance quality may matter more during periods of political instability. Such distributional heterogeneity cannot be adequately captured by mean-based estimators.

To address these limitations, this study employs a three-step strategy: (i) Xiao's (2009) quantile-based cointegration test to assess long-run relationships across quantiles; (ii) the Quantile-on-Quantile Regression (QQR) model of Sim and Zhou (2015) to capture cross-quantile linkages between explanatory and dependent variables; and (iii) the Wavelet Coherence Technique (WTC) to explore dynamic co-movements and lead–lag structures across multiple time horizons. Similar approaches have been used in recent environmental and energy economics research. For example, Ali et al. (2025) used QQR to analyze technology–environment linkages, Musibau et al. (2025) applied it to renewable energy and generation, while Yu et al. (2024) employed it to study CO2 emissions. Likewise, WTC has been used by Zhang W. et al. (2024) and Sun et al. (2023b) to assess energy–economic interactions. These studies highlight that quantile-based and wavelet methods are well-suited for uncovering nonlinear, asymmetric, and time-varying dynamics that are central to sustainability outcomes.

3.3.1 Quantile-on-quantile regression

The QQR method is a nonparametric econometric approach that combines quantile regression with nonparametric estimation. Unlike conventional OLS or ARDL models, which capture only average effects, QQR investigates how the θ-th quantile of the explanatory variable influences the τ-th quantile of the dependent variable. This makes QQR particularly suitable for environmental studies where the effects of uncertainty, political risk, and governance may differ across various ecological conditions. The research employed a fundamental nonparametric framework, as illustrated below:

$$Y_t = \beta^{\theta}\left(X_t\right) + v_t^{\theta} \tag{1}$$

In this context, θ represents the θth quantiles, capturing the distribution of the exogenous factors, X. At a given time t, Xt denotes the predictor variables, whereas Yt corresponds to the endogenous parameter. The quantile residual is indicated by v_t^{θ}. As there are inadequate facts to determine the relationship between the predicted parameter Yt and the regressor Xt, indicating that β^{θ} is uncertain. Consequently, the research employed one-step simple estimation model as recommended by Cleveland (1979). Taylor's notation β^{θ} focuses the θth quantile of X. The linear relationship can be represented as outlined below:

$$\beta^{\theta} \approx \beta^{\theta}\left(X^{\tau}\right) + \beta^{\theta'}(X^{\tau})(X_t - X^{\tau}) \tag{2}$$

Here β′θ shows a slope for βθ (Xt). The βθ(Xt) is commonly known as a partial effect. The terms β′θ(Xτ) and βθ(Xτ) denote the connection between the parameters τ and θ. The notation β′θ(Xτ) is expressed as β1(θ, τ), where βθ(Xτ) is signified by β0(θ, τ). As a result, the enlarged version of Equation 5 is:

$$\beta^{\theta} \approx \beta_{\theta}\left(\theta, \tau\right) + \beta_1\left(\theta, \tau\right)\left(X_t - X^{\tau}\right) \tag{3}$$

Following the methodology outlined in Sim and Zhou (2015), we integrate Equation 4 with Equation 2 to derive the foundational model:

$$Y_t = \frac{\beta_{\theta}\left(\theta, \tau\right) + \beta_1\left(\theta, \tau\right)\left(X_t - X^{\tau}\right)}{(*)} + v_t^{\theta} \tag{4}$$

The conditional quantile of the predictor variables is symbolized by (*). Equation 5 outlines the structural representation of the QQR analysis, illustrating the association among the θth quantile of X and the τth quantile of Yt. The coefficients β0 and β1 signify the linkage between regressor and regressand components, with this connection being indexed by θ and τ. The quantiles of the dependent and independent variables enable differentiation in the values of β0 and β1. This technique identifies the varying associations among research variables across lower and upper quantiles, yielding more precise and dependable findings than traditional methodologies. The choice of bandwidth is crucial for addressing diminution challenges in a distribution-free context, improving computational efficiency and accuracy. Bandwidth (h) measures the interdependence among the quantiles of exogenic and endogenic factors. Accordingly, this inquiry employs the kernel regression technique proposed by Marron (1991). The corresponding equation is presented below:

$$Min\delta_0\delta_1 \sum\nolimits_{t=1}^{n} \rho_{\varnothing}\left[EF_t - \delta_0 - \delta_1\left(X_t - X^{\tau}\right)\right] L\left[\frac{M_n(X_t - \tau)}{h}\right] \tag{5}$$

The Gaussian kernel, shown as L(.), is applied to approximate the weighting factors near to the regressand. This enhances precision through differential weighting of observations. Moreover, ρφ denotes the error function in QR.

Figure 3 presents a flowchart that effectively illustrates the methodological framework, facilitating a comprehensive understanding of this study.

4 Outcomes and interpretations

4.1 Descriptive statistics

Prior to doing the QQR examination, our aim is to uncover the quantitative characteristics of the series of logarithms. To begin, we review the summary statistics shown in Table 4. The average values suggest that all series maintain a positive mean over the observation period. The standard deviation results show that LC has less volatile behavior than EPU, which is the most volatile. Additionally, none of the variables follow a standard distribution based on the Jarque-Bera values. Linear econometric methods fail to account for non-parametric data when the indicators do not conform to a normal distribution. The non-normal distribution of the variables suggests that quantile approaches may provide excellent results. The study used quantile-based nonparametric techniques because, by taking into consideration nonlinearity and asymmetric interactions, quantile approaches may provide strong evidence of the interactions between non-normally distributed series.

In addition, we have examined the quantile plots, as shown in Figure 4, to investigate the normal distribution features of selected

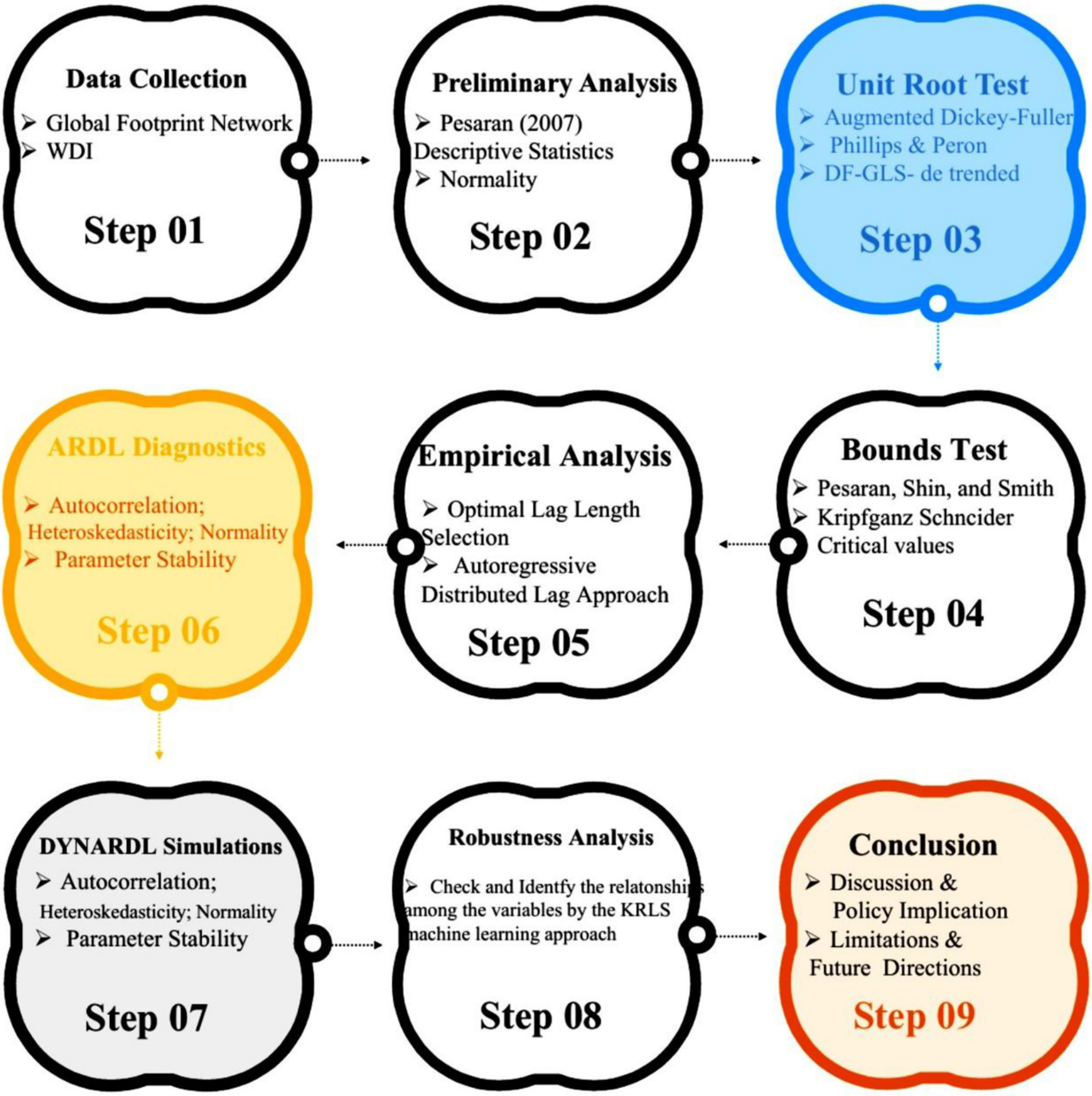

FIGURE 3
Roadmap of the research.

TABLE 4 Descriptive statistics.

Variables	Mean	Max.	Min.	Std. dev.	Kurt.	J.B
LC	1.9543	2.3717	1.7051	0.1816	2.6517	12.2232***
EPU	162.5823	464.2434	53.3663	94.4296	4.5064	39.9165***
PSI	85.3068	89.8750	79.9167	2.4552	2.9023	30.7994***
GOV	0.0397	1.7130	−3.8239	2.4070	2.0345	6.8775***
EI	10.4673	13.1000	7.5000	1.6734	1.8354	11.9581***

***Indicates a 1% level of significance.

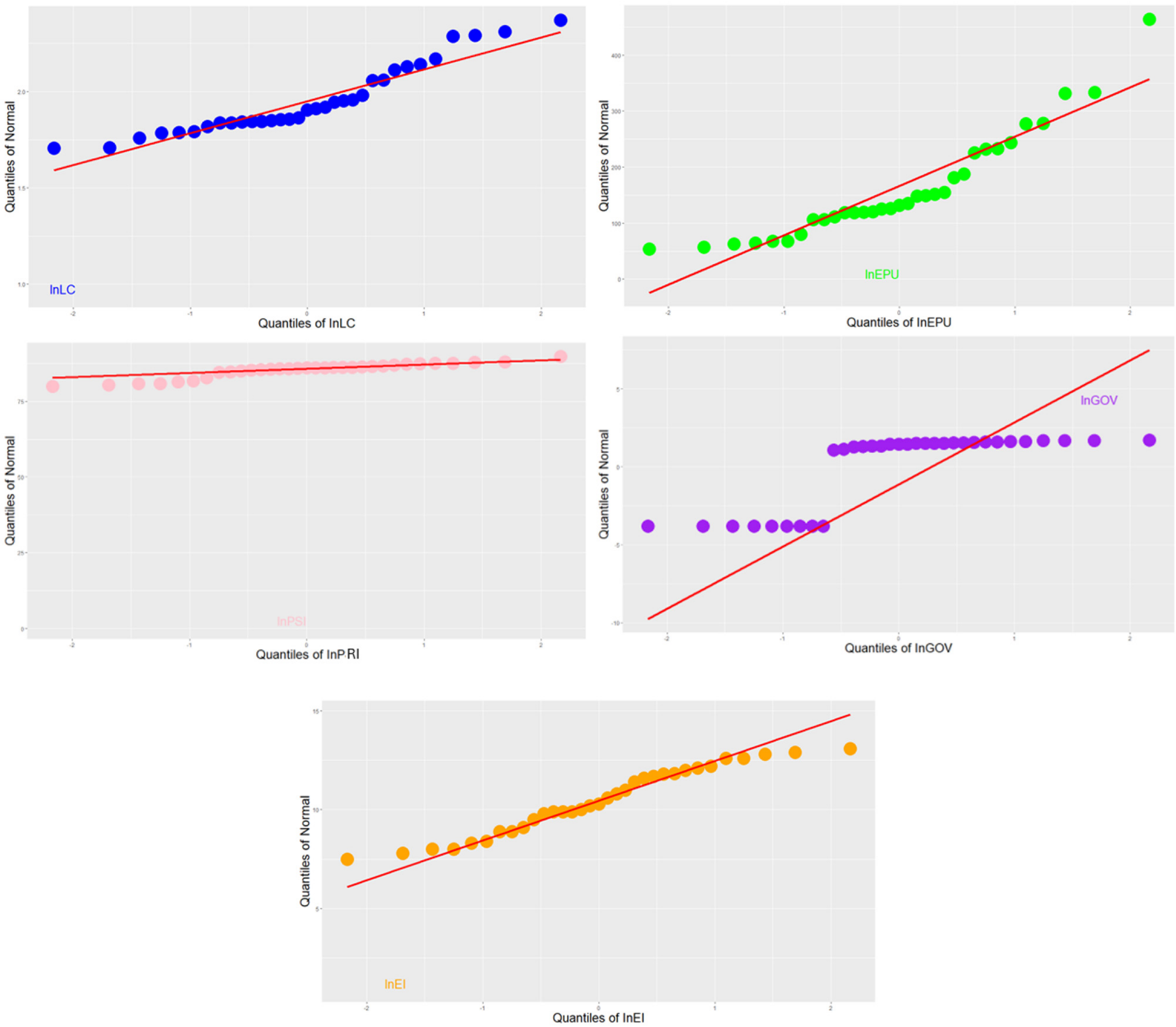

FIGURE 4
Q-Q plots.

variables thoroughly. The red lines in these Q-Q plots show a standard distribution, whereas the highlighted data points illustrate the real distribution of variables. The disparity between the red lines and the colored data points provides information about the departure from normality. The magnitude of this disparity indicates the level of asymmetry, as elucidated by Ozkan et al. (2024).

Additionally, Box plots are depicted in Figure 5, providing a succinct representation of the summary information. Moreover, Figure 6 illustrates the correlation between the factors.

4.2 Unit root test

In order to avoid biased results and make sure the empirical findings are accurate, the reliability of the model is checked by applying the Q stationarity test before the QQR method is used. Nineteen quantiles with values ranging from 0.05 to 0.95 are employed for this purpose. Finding quantile unit roots in data is done by comparing the t-statistic to critical values. The t-statistic and critical value resilience across various quantile ranges is shown in Table 5. Assuming the alternative hypothesis is accepted, the null hypothesis is maintained if the anticipated t-statistic value does not exceed the critical value. At the 5% significance level, this happens for every quantile, where $\alpha(\tau) = 1$. According to the quantile unit root test, unit roots exist at the quantile level for all variables.

4.3 Bound test

The research then moved on to examine the variables' long-term interdependence through a unique QC test (Xiao, 2009). The

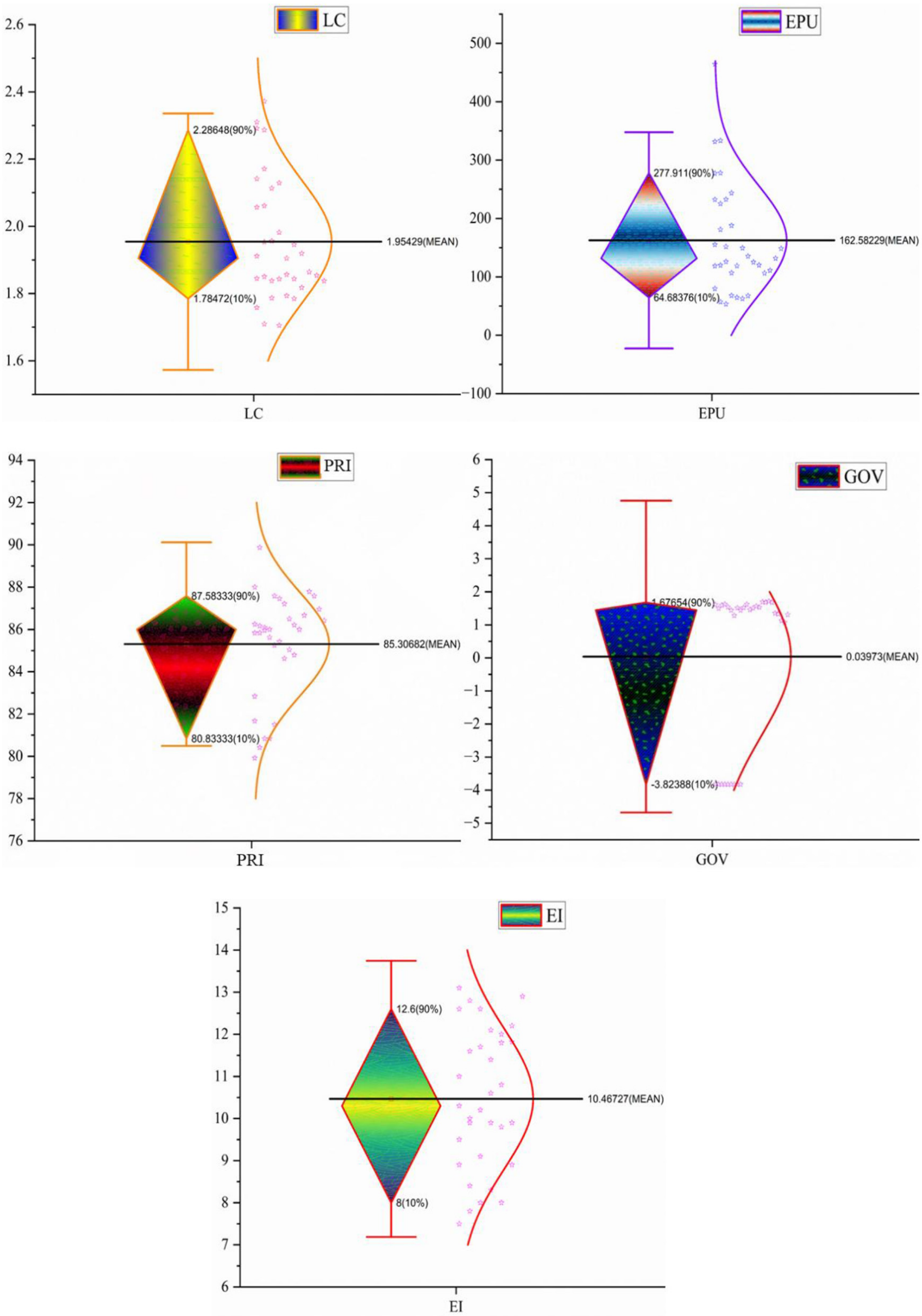

FIGURE 5
Boxplots of the study indicators.

coefficients represent the uniform norm and the critical values β and γ, while the significance levels of 1%, 5%, and 10% are denoted by CV1, CV2, and CV10, respectively. The test was reliably performed for over 19 quantiles, from 0.95 to 0.05. Table 6 indicates that, at a significance level of 1%, both the β and γ coefficients surpass all critical levels. As a result, the results show cointegration

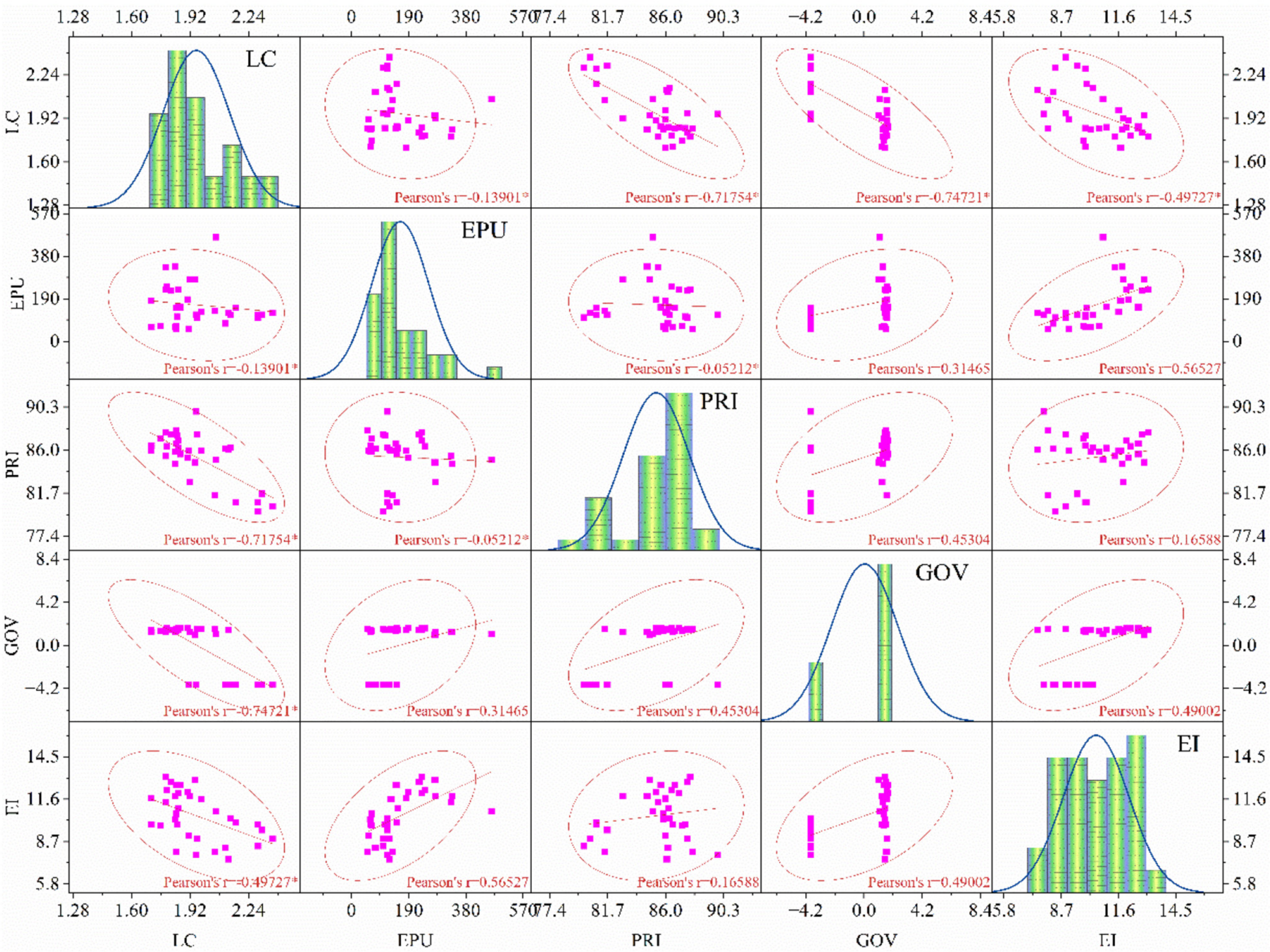

FIGURE 6
Correlation plot.

between a subset of the variables, exhibiting a steady, asymmetric, prolonged connection between these variables.

4.4 BDS test of nonlinearity

As the subsequent measure, Table 7 displays the results of the nonlinearity test. The results demonstrate that every variable has a multidimensional non-linear structure. Reflecting on these aspects, using a nonlinear approach for further empirical analysis may be the most suitable choice. Hence, the research utilizes the innovative QQR technique.

4.5 Quantile-on-quantile regression results

The core aim of this inquiry is to examine the interrelationships among EPU, PRI, GOV, and LC. Following the confirmation of cointegration among the variables, the study explores how these factors influence environmental sustainability in Canada using QQR, which allows for a detailed understanding of the relationships across the entire distribution of LC. Figures 7–9 present the estimated regression coefficient $\beta 1(\theta, \tau)$, representing the impact of the τ-th quantile of EPU, PRI, and GOV on the θ-th quantile of LC.

Figure 7 depicts the influence of EPU on LC in Canada, revealing notable heterogeneity across quantiles. At lower LC quantiles, where environmental sustainability is relatively weak, rising EPU negatively affects LC, reflecting increased investment uncertainty that discourages long-term commitments to renewable energy projects and green infrastructure. In such conditions, firms and policymakers may prioritize short-term stability, relying on conventional energy sources and thereby hindering sustainability progress. Conversely, at medium and higher quantiles, the effect of EPU becomes positive and increases in magnitude, suggesting that in more sustainable scenarios, uncertainty can stimulate adaptive policy responses and strategic investment in cleaner energy alternatives. Businesses anticipating long-term uncertainty hedge risks by diversifying into sustainable energy portfolios, while Canada's commitment to global environmental agreements and market-based green policies further supports sustainability efforts. These results are consistent with previous studies that have documented the nuanced positive effects of policy uncertainty

TABLE 5 Quantile unit root test.

τ	LC		EPU		PRI		GOV		EI	
	$\hat{a}$	t	$\hat{a}$	t	$\hat{a}$	t	$\hat{a}$	t	$\hat{a}$	t
0.05	6.432	0.003	4.06	0.61	−2.94	−0.051	−1.48	−0.03	−0.71	−0.03
0.1	6.605	0.002	4.53	0.59	−3.2	−0.052	−1.43	−0.027	−0.85	−0.036
0.15	6.337	−0.002	5.46	−0.4	−3.95	−0.051	−1.12	−0.02	−0.33	−0.014
0.2	6.013	0	4.89	0.02	−3.31	−0.046	−1.26	−0.024	−0.64	−0.022
0.25	4.924	0.002	4.21	0.37	−2.35	−0.032	−1.6	−0.029	−0.91	−0.033
0.3	5.208	0	5.07	−0.04	−2.97	−0.035	−1.97	−0.035	−0.83	−0.026
0.35	5.171	0.001	5.78	0.2	−3.31	−0.035	−2.15	−0.035	−0.79	−0.023
0.4	5.083	0.003	6.16	0.79	−3.59	−0.035	−2.28	−0.036	−0.68	−0.017
0.45	4.51	0.004	5.86	1.04	−2.98	−0.027	−3.1	−0.04	−1.34	−0.028
0.5	4.73	0.004	6	1.09	−3.16	−0.031	−3.23	−0.043	−0.95	−0.02
0.55	5.107	0.003	6.48	0.65	−3.94	−0.035	−2.78	−0.038	−0.89	−0.019
0.6	5.25	0.003	5.97	0.85	−3.59	−0.036	−2.71	−0.037	−0.98	−0.021
0.65	5.272	0.004	6.67	0.84	−3.76	−0.037	−2.89	−0.037	−1.03	−0.023
0.7	5.386	0.003	6.36	0.94	−3.8	−0.038	−3.09	−0.043	−1.08	−0.023
0.75	5.053	0.003	5.73	0.67	−3.04	−0.032	−3.04	−0.041	−1.48	−0.033
0.8	4.904	0.003	5.64	0.6	−2.92	−0.029	−2.54	−0.037	−2.01	−0.042
0.85	4.932	0.003	5.64	0.64	−2.88	−0.029	−2.68	−0.037	−2.09	−0.042
0.9	4.962	0.001	5.26	0.31	−2.55	−0.029	−2.13	−0.028	−2.13	−0.047
0.95	5.079	0	5.09	0.07	−2.54	−0.031	−1.65	−0.022	−1.7	−0.036

TABLE 6 Quantile cointegration.

Model	Coefficient	Suptτ|Vn(τ)|	CV1	CV5	CV10
LC-EPU	β	25.497	17.976	12.804	9.266
	α	30.921	22.647	13.927	11.885
LC-PRI	β	21.015	18.137	16.001	10.075
	α	32.25	25.316	21.613	18.639
LC-GOV	β	39.821	25.798	21.669	19.639
	α	56.971	43.813	38.001	27.562
LC-EI	β	20.39	14.305	11.071	7.899
	α	31.938	26.894	17.375	13.715

TABLE 7 BDS test results.

Variables	Dimensions					Decision
	2	3	4	5	6	
LC	0.0000	0.0000	0.0000	0.0000	0.0000	Non-linear
EPU	0.0000	0.0000	0.0000	0.0000	0.0000	Non-linear
PSI	0.0000	0.0000	0.0000	0.0000	0.0000	Non-linear
GOV	0.0000	0.0000	0.0000	0.0000	0.0000	Non-linear
EI	0.0000	0.0000	0.0000	0.0000	0.0000	Non-linear

Values show the probability values.

under certain economic and institutional conditions (Aslan et al., 2024; Pata et al., 2023b; Villanthenkodath and Pal, 2024).

Figure 8 illustrates the relationship between PRI and LC. At lower quantiles, higher political risk negatively affects sustainability due to heightened uncertainty, inconsistent policies, and reduced investor confidence, which can delay or reduce investment in green energy projects. Interestingly, at medium and higher LC quantiles, PRI exhibits a positive effect. While this may appear counterintuitive, it can be explained by Canada's strong institutional framework and adaptive mechanisms: moderate political risk can trigger proactive government and business responses, leading to resilient strategies that promote sustainability. The presence of environmental innovation further strengthens this effect, mitigating the potential negative impacts of political instability and allowing firms to implement adaptive technologies and practices. This observation aligns with evidence suggesting that robust institutions and innovation capacity can transform political risks into opportunities for sustainable investment (Kartal et al., 2024, 2022; Simionescu et al., 2023).

The effect of GOV on LC is shown in Figure 9. At lower quantiles, weak governance can impede environmental policies, resulting in inefficient resource allocation and regulatory shortcomings that negatively affect LC. As quantiles increase, the impact of governance becomes positive and more pronounced, indicating that economies with stronger institutional frameworks and governance mechanisms are better positioned to implement

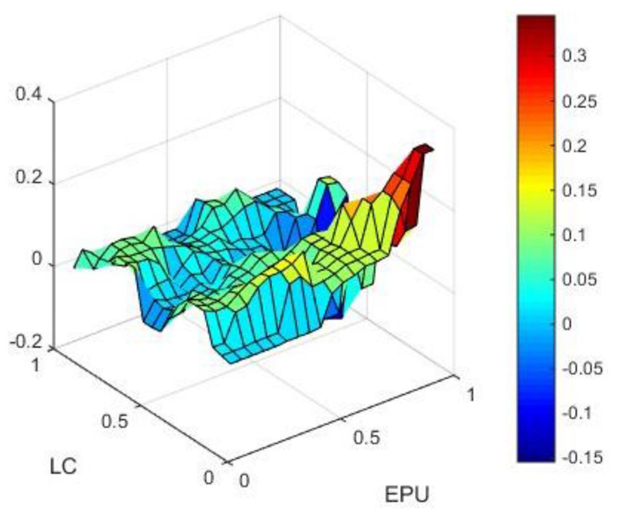

FIGURE 7
QQR estimates for the impact of EPU on LC.

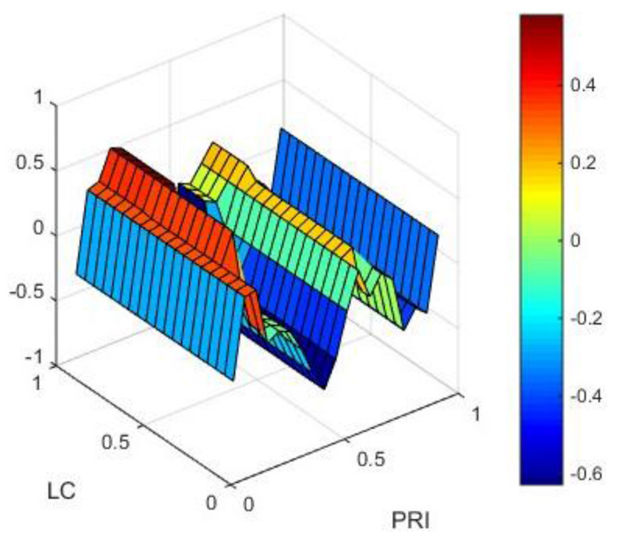

FIGURE 8
QQR estimates for the impact of PRI on LC.

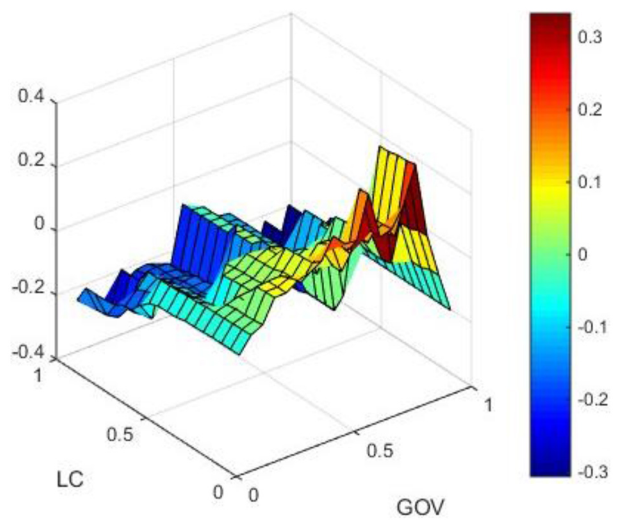

FIGURE 9
QQR estimates for the impact of GOV on LC.

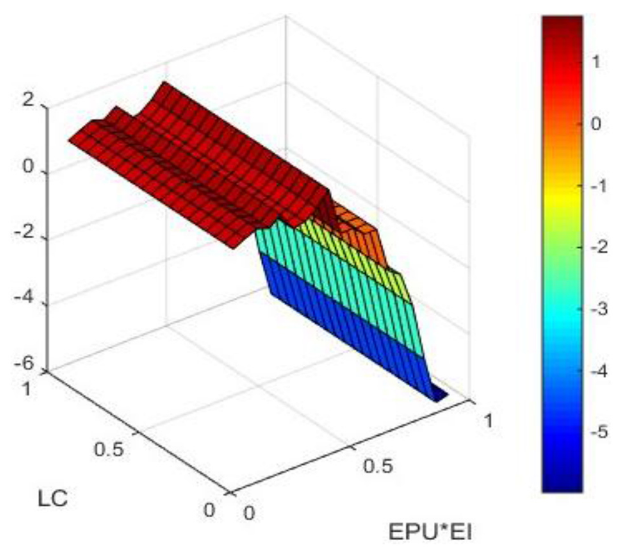

FIGURE 10
QQR estimates for the impact of EPU*EI on LC.

effective sustainability policies. The increasing magnitude of the coefficient at higher quantiles suggests that well-functioning governance enhances regulatory enforcement, encourages green investment, and supports sustainable infrastructure, ultimately fostering long-term improvements in environmental sustainability (Yadav et al., 2024; Yi et al., 2023; Zhang S. et al., 2024).

By examining the moderating role of environmental innovation, we further elucidated how varying levels of innovation intensity influence the relationships between EPU, PRI, GOV, and LC across the sustainability distribution. Figure 10 shows that the interaction term EPU × EI negatively affects LC at lower quantiles, suggesting that the benefits of innovation may be constrained under conditions of economic uncertainty, reduced investor confidence, and delayed policy implementation. However, at higher quantiles, this interaction becomes positive, highlighting that when innovation reaches a critical threshold or when economic conditions are stable, it can mitigate uncertainty and drive sustainable outcomes. Similarly, Figure 11 illustrates that PRI × EI positively influences LC across most quantiles, with the effect strengthening at higher levels. This indicates that strong environmental innovation can offset the adverse effects of political risk, enabling adaptive strategies that enhance resilience and sustainability. Figure 12 demonstrates that GOV × EI negatively affects LC at lower and medium quantiles but becomes strongly positive at higher quantiles, reflecting that the benefits of innovation are fully realized only when governance structures are robust and effectively implemented. These findings

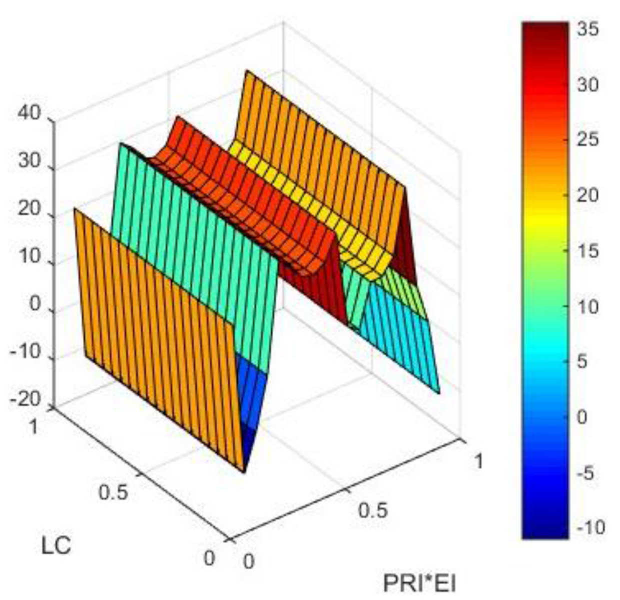

FIGURE 11
QQR estimates for the impact of PRI*EI on LC.

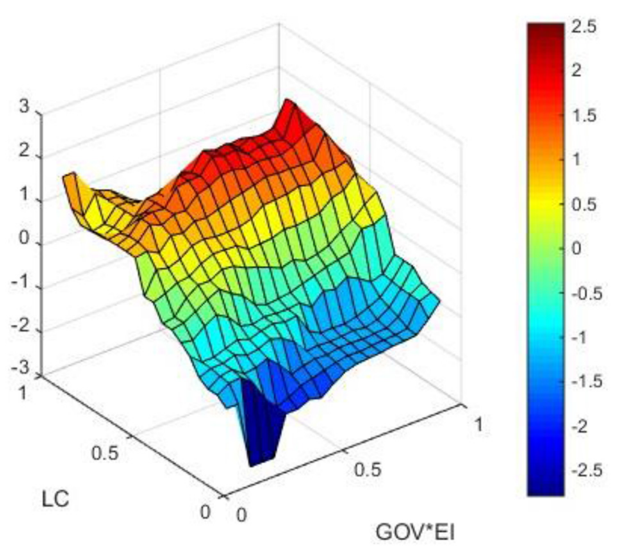

FIGURE 12
QQR estimates for the impact of GOV*EI on LC.

emphasize that environmental innovation amplifies the positive impacts of governance and policy while mitigating risks associated with economic and political uncertainty, thereby supporting more resilient and sustainable environmental outcomes.

Finally, the Wavelet Coherence (WTC) analysis (Figures 13A–C) confirms the dynamic linkages between LC and EPU, PRI, and GOV over time. Warmer colors indicate stronger interdependence, whereas cooler colors denote weaker association. The results show a strong positive correlation between EPU and LC over multiple periods (Figure 13A), a negative correlation between PRI and LC (Figure 13B), and a positive correlation between GOV and LC at medium and high frequencies (Figure 13C). These findings corroborate the QQR results and highlight the critical role of governance, institutional quality, and environmental innovation in shaping sustainable outcomes in Canada under varying conditions of policy and political uncertainty. More over, Figure 14 represents the graphical summary of the key results.

5 Conclusions and policy directions

5.1 Conclusion

This study employs the innovative Quantile-on-Quantile Regression (QQR) approach to investigate the nonlinear effects of Economic Policy Uncertainty (EPU), Political Risk Index (PRI), and Governance (GOV) on environmental sustainability, proxied by the Load Capacity Factor (LC), in Canada from 1990 to 2022. The findings reveal that the relationships among these institutional and policy variables and sustainability are highly heterogeneous across the distribution of LC, with environmental innovation (EI) playing a critical moderating role. Specifically, while EPU can have both positive and negative effects depending on the sustainability context, PRI generally constrains sustainability at lower quantiles but may foster adaptive responses at higher quantiles when supported by strong EI. Effective governance consistently enhances sustainability, particularly when coupled with innovation. These outcomes are corroborated by Wavelet Coherence (WTC) analysis, which confirms the temporal and frequency-dependent linkages among EPU, PRI, GOV, and LC. Collectively, these findings provide a nuanced understanding of how policy, institutional, and innovation mechanisms interact to shape environmental outcomes in Canada, offering both theoretical and practical contributions to sustainability research.

5.2 Implication

The empirical evidence underscores the importance of tailored and actionable policy interventions. First, to mitigate the destabilizing effects of political risk and maximize the adaptive potential of policy uncertainty, Canadian policymakers should implement transparent decision-making procedures, strengthen risk management frameworks, and promote policy predictability, particularly in sectors critical to clean energy investment. Second, fostering a robust ecosystem for environmental innovation is essential. This includes targeted financial incentives, tax breaks, and research grants for green technology development, as well as establishing knowledge-sharing platforms for best practices in sustainable business operations. Third, the synergistic relationship between governance and EI highlights the need for institutional reforms that enhance regulatory efficiency, ensure accountability, and integrate technological solutions into environmental monitoring and enforcement. By adopting these measures, Canada can leverage innovation and governance to transform potential policy or political risks into opportunities for long-term environmental sustainability.

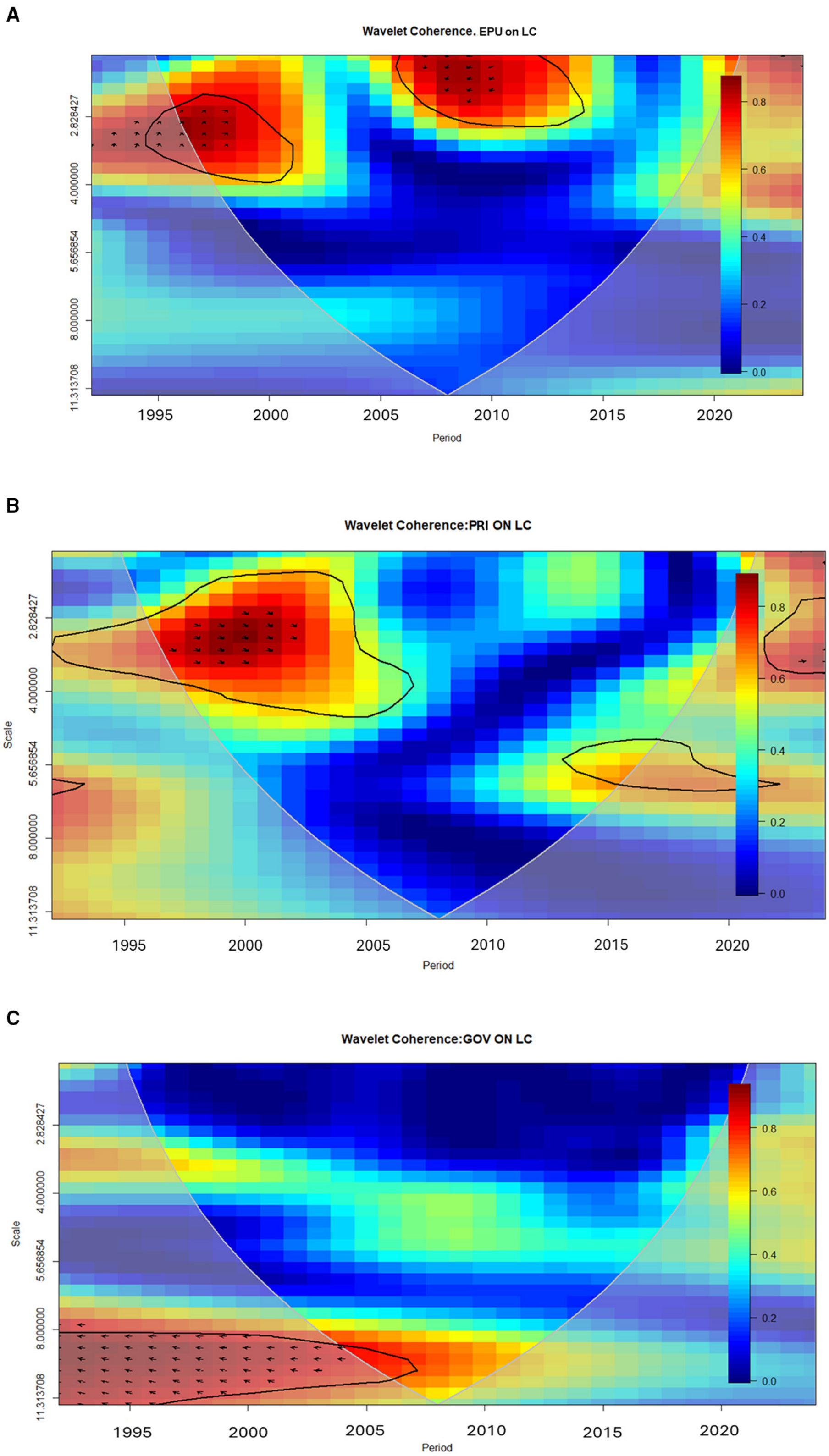

FIGURE 13
(A) Wavelet coherence impact of EPU on LC. **(B)** Wavelet coherence impact of PRI on LC. **(C)** Wavelet coherence impact of GOV on LC.

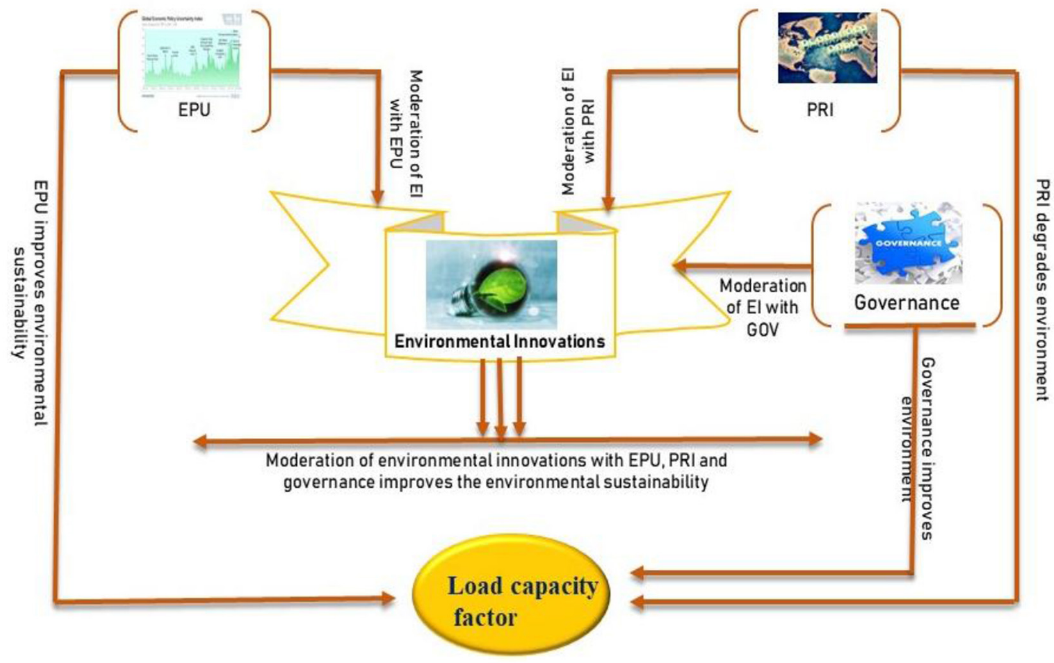

FIGURE 14
Graphical summary of EPU, PRI, GOV, EI, and LC relationships across quantiles in Canada.

5.3 Limitations and future research directions

While this study provides novel insights, certain limitations should be acknowledged. First, the analysis focuses exclusively on Canada, limiting the generalizability of the findings to other national contexts with different institutional or policy frameworks. Second, the study employs LC as a proxy for environmental sustainability, which, while comprehensive, may not capture all dimensions of environmental performance, such as biodiversity or ecosystem services. Future research could extend this work by incorporating multi-dimensional sustainability indicators, analyzing cross-country comparisons, and exploring the dynamic effects of other institutional or market variables, including climate finance and international policy commitments. Additionally, investigating the causal mechanisms through which environmental innovation interacts with governance and policy uncertainty could provide deeper theoretical understanding and inform more precise policy interventions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SU: Conceptualization, Data curation, Methodology, Software, Writing – original draft, Writing – review & editing. BL: Conceptualization, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

Table A1 Principal components analysis by Horn's parallel.

Components	Adjusted EV	Unadjusted EV	Bias estimated
Governance indicators			
1	5.357	5.926	0.569

Criterion: retain adjusted components > 1.

Table A2 Bartlett and KMO tests.

Decision criterion	Governance indicators
Bartlett test of sphericity	
Chi-squared	632.89
Probability value	0
Degrees of freedom	15
Sampling adequacy test (Kaiser–Meyer–Olkin)	
KMO value	0.838

Decision criterion for sampling adequacy of KMO > 0.5, Bartlett sphericity's $p < 0.05$.

Table A3 Principal components.

Variables	C-1	C-2	C-3	C-4	C-5	C-6
Governance indicators						
Political stability	0.405	0.868	0.181	0.182	−0.111	0.060
Rule of law	0.408	−0.033	−0.775	−0.014	0.180	0.446
Regulatory quality	0.410	−0.053	−0.286	−0.260	−0.233	−0.791
Control of corruption	0.409	−0.092	0.417	−0.610	0.515	0.116
Government effectiveness	0.409	−0.358	0.270	−0.020	−0.711	0.354
Voice and accountability	0.408	−0.324	0.195	0.726	0.361	−0.182

C-1 to C-6 are principal components of the factors.

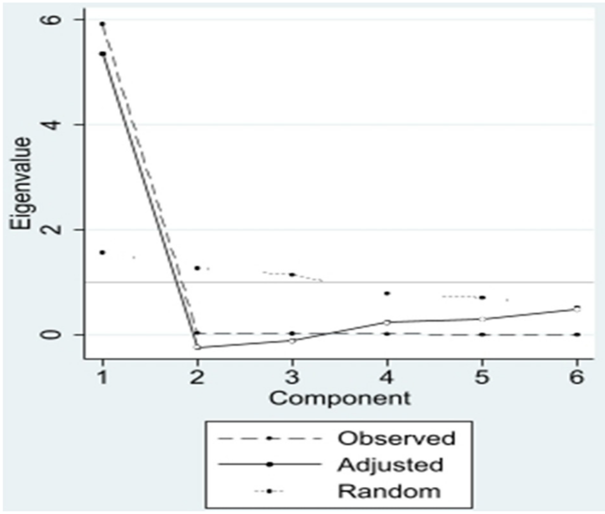

FIGURE A1
Scree plot of governance indicators.