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Advancing G20 Carbon Neutrality: Unpacking the Green Energy Supply-Ecological Degradation Nexus Under Green Innovations

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Abstract

This study investigates the determinants of environmental degradation in G20 countries, which account for a substantial share of global economic activity, energy consumption, and ecological pressure. Given their central role in both contributing to and potentially mitigating environmental challenges, examining sustainability drivers within this group is critically important. The study analyzes panel data for G20 economies over the period 2010-2024, employing the Quantile Generalized Method of Moments (Q-GMM) approach to capture heterogeneous effects across different levels of ecological footprint. The empirical results reveal that green growth, green trade, green energy supply, and green technology innovation all exert significant negative effects on ecological footprint, indicating their effectiveness in reducing environmental degradation. Among these, green trade and technological innovation demonstrate particularly strong impacts. Furthermore, the findings show that green technology innovation plays a crucial moderating role by strengthening the environmental benefits of green growth, trade, and energy transition. These results highlight the importance of integrating economic, technological, and environmental strategies. From a policy perspective, the study suggests that G20 countries should adopt a coordinated approach that simultaneously promotes green growth, expands green trade, accelerates renewable energy adoption, and strengthens innovation systems to achieve long-term environmental sustainability.

Keywords: Ecological degradation, Green energy supply, Green innovations, Green trade, Green growth.

1 | Introduction

This study investigates the determinants of environmental degradation in G20 countries, which account for a substantial share of global economic activity, energy consumption, and ecological pressure.

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Given their central role in both contributing to and potentially mitigating environmental challenges, examining sustainability drivers within this group is critically important. The study analyzes panel data for G20 economies over the period 2010-2024, employing the Quantile Generalized Method of Moments (Q-GMM) approach to capture heterogeneous effects across different levels of ecological footprint. The empirical results reveal that green growth, green trade, green energy supply, and green technology innovation all exert significant negative effects on ecological footprint, indicating their effectiveness in reducing environmental degradation. Among these, green trade and technological innovation demonstrate particularly strong impacts. Furthermore, the findings show that green technology innovation plays a crucial moderating role by strengthening the environmental benefits of green growth, trade, and energy transition. These results highlight the importance of integrating economic, technological, and environmental strategies. From a policy perspective, the study suggests that G20 countries should adopt a coordinated approach that simultaneously promotes green growth, expands green trade, accelerates renewable energy adoption, and strengthens innovation systems to achieve long-term environmental sustainability.

Environmental degradation has become one of the most critical challenges facing the global economy, particularly in large and highly industrialized economies [1]. The G20 countries play a central role in this context, as they account for a substantial share of global output, trade, and energy consumption. Their rapid industrialization, high resource demand, and dependence on fossil fuels significantly contribute to ecological pressure. At the same time, these economies possess strong financial systems, technological capacity, and institutional frameworks that enable them to lead global sustainability transitions. Previous studies emphasize that environmental outcomes in large economies are closely linked to economic structure, energy consumption patterns, and industrial activities [2], [3], [4]. Therefore, examining environmental degradation within the G20 framework provides valuable insights into global sustainability challenges and policy design.

Green Growth has emerged as a strategic approach to reconcile economic development with environmental sustainability. Unlike traditional growth models, which often increase environmental degradation, green growth promotes resource efficiency, cleaner production, and environmentally friendly technological advancement. The Environmental Kuznets Curve (EKC) hypothesis suggests that economic growth may initially increase environmental pressure but can eventually contribute to environmental improvement as economies adopt cleaner technologies and stronger environmental policies [5]. Moreover, empirical evidence indicates that sustainable growth strategies supported by renewable energy and structural transformation can reduce ecological footprint over time [2], [6]. However, the effectiveness of GG largely depends on the extent to which economies shift from resource-intensive to innovation-driven growth models, making its analysis particularly relevant for G20 countries.

Green Trade has gained increasing attention as an important channel through which environmental sustainability can be improved. International trade influences environmental outcomes through scale, composition, and technique effects. While trade expansion may increase environmental pressure through higher production levels, it can also facilitate the diffusion of cleaner technologies and environmentally efficient practices. Studies show that trade openness can support environmental sustainability when it promotes the exchange of green goods and technologies [7]. In addition, global integration enhances access to advanced production methods and renewable energy technologies, which can reduce ecological pressure [8]. Given that G20 countries dominate global trade flows, understanding the environmental implications of green trade is essential for evaluating its role in reducing the ecological footprint. Green Energy Supply, particularly through renewable energy sources, is widely recognized as a key driver of environmental sustainability. The transition from fossil fuels to renewable energy plays a crucial role in reducing greenhouse gas emissions and mitigating ecological degradation. Empirical evidence confirms that renewable energy consumption significantly lowers ecological footprint and improves environmental quality [9], [3]. Furthermore, investments in green energy technologies and infrastructure enhance long-term sustainability and energy efficiency [10]. For G20 countries, which are among the largest energy consumers globally, the shift toward renewable energy is essential for reducing environmental pressure and achieving sustainable development goals.

Green Technology Innovations are a fundamental component of sustainable development, as they enable economies to reduce environmental degradation while maintaining economic performance. Technological advancements improve energy efficiency, reduce emissions, and support cleaner production processes. Empirical studies show that green innovation significantly contributes to environmental sustainability by lowering ecological footprint and improving resource efficiency [11], [5]. Moreover, green technology innovations not only directly influence environmental outcomes but also enhance the effectiveness of other economic drivers such as growth, trade, and energy consumption. Therefore, investigating the role of this factor is crucial for understanding both its direct and moderating effects on environmental degradation in G20 countries.

The selection of G20 countries is justified by their dominant role in the global economy and environmental system. These economies account for a large share of global GDP, trade, and energy consumption, making them key contributors to environmental degradation. At the same time, they possess advanced technological capabilities and financial resources that enable them to implement sustainable development strategies. Previous studies emphasize that analyzing large and heterogeneous panels provides more comprehensive insights into environmental sustainability [2], [8], [10]. Furthermore, the diversity among G20 countries, ranging from developed to emerging economies, allows for capturing differences in economic structure, energy systems, and policy frameworks. Therefore, focusing on G20 countries enhances the relevance and generalizability of the study's findings. The Ecological Footprint is adopted as the primary indicator of environmental degradation due to its comprehensive nature. Unlike traditional indicators such as CO2 emissions, EF captures the overall demand placed on natural resources, including land, energy, and ecological capacity. This makes it a more holistic measure of environmental sustainability. Empirical research widely recognizes EF as a reliable indicator for assessing environmental pressure and sustainability performance [11], [3]. In addition, EF reflects the balance between ecological demand and environmental capacity, which is particularly relevant for cross-country comparisons. Therefore, using EF in this study allows for a more comprehensive evaluation of environmental degradation in G20 economies.

This study contributes to the existing literature in several important ways. First, it provides a comprehensive analysis of the combined effects of green growth, green trade, green energy supply, and green technology innovations on ecological footprint within the G20 context, which has received limited attention in prior research. Second, it integrates multiple dimensions of sustainability, economic, technological, and environmental, into a unified empirical framework, offering a more holistic understanding of environmental dynamics. Third, the study introduces the moderating role of green innovations in shaping the impact of green growth, green trade, and green energy supply on environmental degradation, thereby uncovering interaction mechanisms that are often overlooked in the literature. Fourth, by focusing on ecological footprint rather than conventional emission-based indicators, the study enhances the measurement of environmental sustainability. Overall, these contributions provide novel insights for policymakers seeking to design integrated strategies that align economic development with environmental sustainability.

This study aims to investigate the impact of green growth, green trade, green energy supply, and green technology innovations on environmental degradation, proxied by ecological footprint, in G20 countries. In addition to examining the direct effects of these variables, the study also explores the moderating role of green innovations in shaping the relationships between green growth, green trade, and green energy supply with ecological degradation. Accordingly, the main research questions are: how do green growth, green trade, and green energy supply individually affect ecological footprint in G20 countries? Does green technology innovation contribute directly to reducing environmental degradation? How does green innovation moderate the impact of green growth on ecological footprint? How does green innovation influence the relationship between green trade and ecological footprint? and what is the moderating role of green innovation in the nexus between green energy supply and ecological footprint? By addressing these questions, the study seeks to provide empirical evidence on the effectiveness of green economic and technological strategies in achieving environmental sustainability. The structure of the paper is organized as presented in *Fig. 1*.

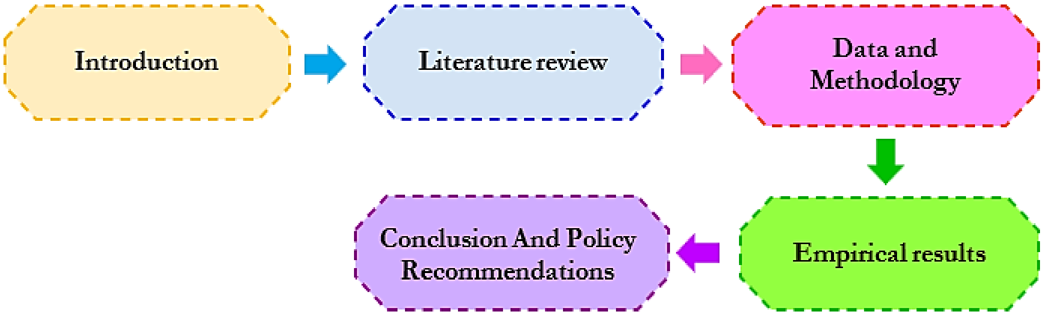

Fig. 1. Structure of the paper.

2 | Literature Review and Hypotheses Development

2.1 | Green Growth and Ecological Footprint

The relationship between economic growth and environmental degradation has long been debated in the literature. Traditional growth models suggest that economic expansion increases resource consumption and environmental pressure. However, the concept of green growth introduces a different perspective by emphasizing environmentally sustainable economic development. According to the EKC hypothesis, environmental degradation initially increases with economic growth but eventually declines as economies adopt cleaner technologies and stronger environmental policies [5]. Empirical evidence indicates that when growth is supported by renewable energy adoption and structural transformation, it can contribute to reducing the ecological footprint [2]. In this context, Lin and Ullah [12] and Saleem et al. [13] investigated that green growth could significantly reduce CO2 emissions for Pakistan and 12 Asian countries respectively. Similarly, a recent study conducted by Zahra and Fatima [13] found a negative relationship between green growth and ecological degradation for China. Nevertheless, in economies where growth is still driven by resource-intensive industries, the environmental impact remains negative. Given the mixed evidence, the relationship between green growth and ecological footprint remains an empirical question, particularly in G20 countries. Therefore, based on the above discussion, the following hypothesis is proposed: (H1) Green growth has a significant effect on ecological footprint in G20 countries.

2.2 | Green Trade and Ecological Footprint

International trade plays a complex role in shaping environmental outcomes. Trade expansion may increase ecological degradation through scale effects, as higher production leads to increased emissions. However, trade can also improve environmental quality through technology transfer and efficiency gains. Green trade, which focuses on environmentally friendly goods and technologies, is expected to reduce ecological pressure by facilitating cleaner production processes. Empirical studies suggest that trade openness can improve environmental sustainability when it promotes green technologies and efficient production systems [7]. In addition, globalization enhances access to renewable energy technologies and environmentally friendly innovations [8]. However, the effectiveness of green trade depends on whether trade is aligned with sustainability objectives. Therefore, its net effect on ecological footprint is uncertain and requires empirical investigation. Accordingly, the following hypothesis is formulated: (H2) Green trade significantly influences ecological footprint in G20 countries.

2.3 | Green Energy Supply and Ecological Footprint

Green energy supply, particularly renewable energy, plays a crucial role in reducing environmental degradation. The transition from fossil fuels to renewable energy reduces emissions and lowers ecological pressure. Empirical evidence consistently shows that renewable energy consumption improves environmental quality and reduces ecological footprint [9], [3]. Furthermore, investments in green energy technologies enhance energy efficiency and sustainability [10]. However, the environmental benefits of green energy supply depend on the scale of adoption and supporting infrastructure. In G20 countries, where energy demand is high, increasing renewable energy supply is essential for achieving sustainability goals. Based on this reasoning, the following hypothesis is developed: (H3) Green energy supply reduces ecological footprint in G20 countries.

2.4 | Green Technology Innovation and Ecological Footprint

Green technology innovation is widely recognized as a key driver of environmental sustainability. Technological advancements improve production efficiency, reduce emissions, and support renewable energy integration. Empirical studies show that green innovation significantly lowers ecological footprint and enhances environmental performance [11]. Additionally, environmental innovation contributes to cleaner production and sustainable economic activities [5]. Therefore, green technology innovation is expected to play a direct role in reducing environmental degradation. Thus, the following hypothesis is proposed: (H4) Green technology innovation negatively affects ecological footprint.

2.5 | Moderating Role of Green Technology Innovation

Beyond its direct impact, green technology innovation may also influence how other economic factors affect environmental degradation. Technological innovation enhances efficiency and enables cleaner production, which may reduce the environmental cost of economic growth. Similarly, green innovation can strengthen the environmental benefits of green trade and renewable energy by improving technological integration and resource efficiency. Prior studies highlight that innovation plays a complementary role in enhancing sustainability outcomes [10], [11]. Therefore, green technology innovation is expected to moderate the relationships between green growth, green trade, green energy supply, and ecological footprint. Accordingly, the following hypotheses are formulated: (H5): Green technology innovation moderates the relationship between green growth and ecological footprint, (H6): Green technology innovation moderates the relationship between green trade and ecological footprint, and (H7): Green technology innovation moderates the relationship between green energy supply and ecological footprint. Based on the empirical discussion, this study proposes a conceptual framework in which the study variables directly influence the ecological footprint. In addition, green technology innovation plays a moderating role by shaping how green growth, green trade, and green energy supply affect environmental degradation. *Fig. 2* presents the conceptual framework of the study, where green growth, green trade, green energy supply, and green technology innovation are hypothesized to exert direct effects on ecological footprint. In addition, the model incorporates the moderating role of green technology innovation, capturing how technological innovation may alter the magnitude and direction of the relationships between green growth, green trade, green energy supply, and environmental degradation.

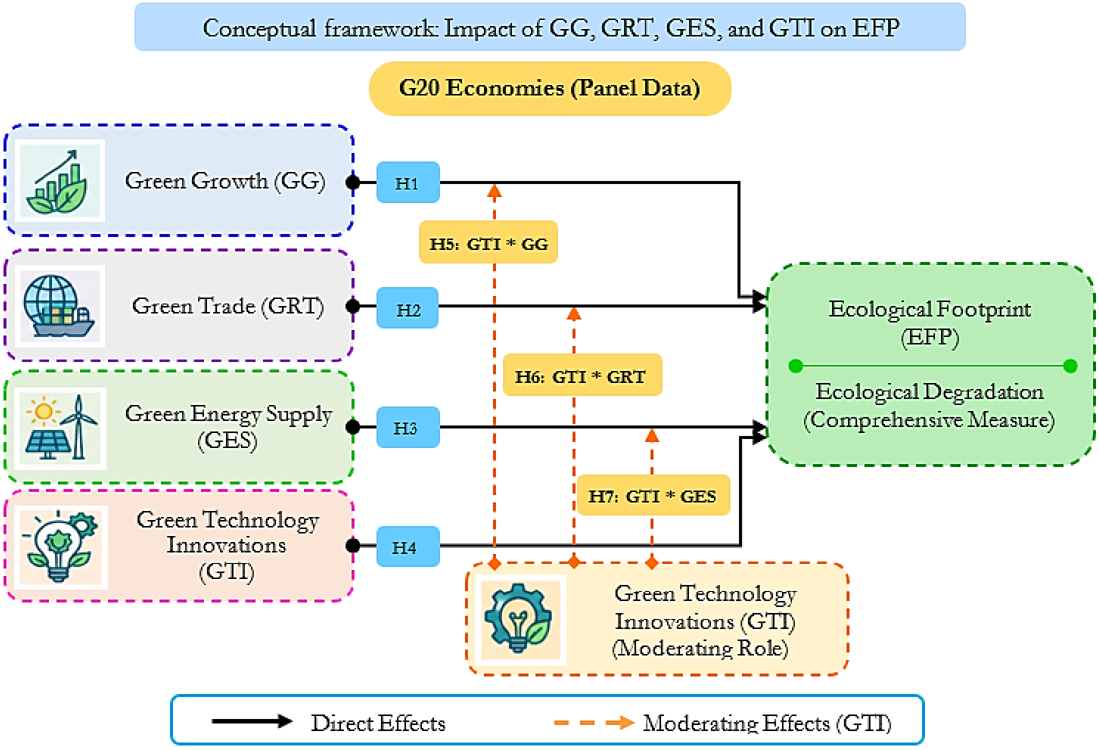

Fig. 2. Conceptual framework depicting the direct impacts of study variables on ecological footprint, along with the moderating role of green technology innovation.

3 | Data and Methodology

3.1 | Data

This study investigates the impact of green growth, green trade, green energy supply, and green technology innovation on environmental degradation, measured by the ecological footprint. The empirical analysis relies on panel data covering G20 countries over the period 2010-2024. The dataset is compiled from secondary sources obtained from internationally recognized and reliable databases, including the WDI database, OECD statistics, UNEP database, and GFN database. To enhance the consistency and statistical reliability of the analysis, all variables are transformed into their natural logarithmic form. This transformation serves multiple purposes: it stabilizes the variance, mitigates the influence of outliers, and improves the normality of the data distribution. Moreover, the logarithmic specification allows the estimated coefficients to be interpreted as elasticities, providing more meaningful economic insights. Overall, these adjustments contribute to improving the robustness, comparability, and interpretability of the empirical results. A complete analysis of the data used in the paper, including the sources, is presented in *Table 1*.

Table 1. Description and source of variables.

Description	Measurement	Source
Ecological Footprint (EFP)	Gha per capita	GFN
Green Growth (GG)	Adjusted net savings, including particulate emission damage	UNEP
Green Trade (GT)	Green trade openness index	OECD
Green Energy Supply (GES)	The share of renewable energy in total energy supplies	OECD
Green Technology Innovations (GTI)	Total Patent applications	WDI

3.2 | Methodology

To fulfill the objectives of this study, which aim to investigate the multidimensional effects of Green Growth (GG), Green Trade (GT), Green Energy Supply (GES), and Green Technology Innovation (GTI) on environmental degradation, as proxied by ecological footprint (EFP), a long-run panel data model is first formulated. This baseline specification enables the estimation of the direct influence of the explanatory variables on EFP while capturing the contemporaneous relationships among them. Accordingly, the long-run model is expressed as follows:

$$\mathrm{EFP}_{i,t} = \alpha_i + \beta_1 \mathrm{GG}_{i,t} + \beta_2 \mathrm{GRT}_{i,t} + \beta_3 \mathrm{GES}_{i,t} + \beta_4 \mathrm{GTI}_{i,t} + \varepsilon_{i,t} \quad (1)$$

where α_i denotes the country-specific intercept term, β_1 to $\beta_4$represent the long-run slope coefficients associated with each explanatory variable, and $\varepsilon_{i,t}$ is the stochastic disturbance term. This equation captures the direct effects of GG, GT, GES, and GTI on ecological footprint across G20 countries. While *Eq. (1)* focuses on direct relationships, the analysis is further extended to account for potential interaction effects, particularly the moderating role of GTI. The inclusion of interaction terms allows us to assess whether GTI alters the magnitude or direction of the relationships between the independent variables and environmental degradation. To incorporate this moderating mechanism, the following augmented specification is employed:

$$\mathrm{EFP}_{i,t} = \alpha_i + \beta_1 \mathrm{GG}_{i,t} + \beta_2 \mathrm{GRT}_{i,t} + \beta_3 \mathrm{GES}_{i,t} + \beta_4 \mathrm{GTI}_{i,t} + \beta_5 (\mathrm{GTI}_{i,t} * \mathrm{IVs}_{i,t}) + \varepsilon_{i,t} \quad (2)$$

where $IV_{i,t}$ represents the set of explanatory variables (GG, GT, and GES), and β_5 captures the interaction effects between GTI and each of these variables. This specification allows for a more comprehensive understanding of how technological innovation conditions the impact of economic, trade, and energy-related factors on ecological footprint. To ensure robustness and reliability of the empirical findings, a sequence of advanced econometric techniques is applied, which are elaborated in the subsequent sections.

Considering the structural properties of the panel dataset, such as cross-country heterogeneity, potential endogeneity, and dynamic interactions, the Generalized Method of Moments (GMM) framework is regarded as a suitable estimation approach for obtaining consistent and efficient results. Prior to implementing the selected estimation technique, it is important to briefly trace the methodological development of GMM. This estimator was initially introduced by Arellano and Bond [14] and later extended by Blundell and Bond [15] to address issues related to endogeneity and unobserved individual effects in dynamic panel settings. In its dynamic specification, the GMM model can be expressed as follows:

$$\Delta \ln \mathrm{EFP}_{i,t} = \alpha_i \Delta \ln \mathrm{EFP}_{i,t-1} + \beta_i \Delta \ln \mathrm{GG}_{i,t} + \gamma_i \Delta \mathrm{X}_{i,t} + \Delta v_i + \Delta \mu_t + \Delta \varepsilon_{i,t} \quad (3)$$

where EF_(i,t)denotes the ecological footprint, GG_(i,t)captures green growth, and X_(i,t) represents a vector of explanatory variables including GT, GES, and GTI. The inclusion of differenced individual and time effects allows the model to control for latent heterogeneity across countries and over time. Although GMM has been widely applied in empirical research, it is not without limitations. In particular, standard difference GMM estimators may suffer from weak instrument problems and reduced efficiency, especially in panels with large cross-sectional dimensions. To address these concerns, Blundell and Bond [16] proposed the system GMM estimator, which enhances estimation precision by combining moment conditions in both differenced and level equations. This hybrid approach improves efficiency and is especially advantageous when dealing with unbalanced panel datasets. Moreover, the adoption of one-step and two-step GMM estimators further strengthens the robustness of empirical findings. More recently, advances in econometric techniques have led to the integration of quantile regression within the GMM framework, enabling a richer analysis of heterogeneous effects. The quantile regression approach, originally developed by Koenker and Bassett [17], departs from mean-based estimation by focusing on different points of the conditional distribution of the dependent variable. Its general specification can be written as:

$$y_{i,t} = x_{i,t}\beta_\theta + \varepsilon_{\theta i,t}, \text{such that} Q_\theta(y_{i,t} \mid x_{i,t}) = x_{i,t}\beta_\theta. \quad (4)$$

where $\theta \in (0,1)$ indicates the quantile level. This formulation enables the estimation of varying effects of explanatory variables across lower, median, and upper segments of the ecological footprint distribution. The estimation of quantile regression parameters relies on minimizing an asymmetric loss function, defined as:

$$\min_{\beta} u \sum_{i=1}^{n} \rho_{\theta} \left(\varepsilon_{\theta i,t}\right), \tag{5}$$

where the loss function $\rho_{\theta}(u)$ assigns different weights to positive and negative residuals, as follows:

$$\rho_{\theta}(u) = \begin{cases} \theta \mid u \mid, & \text{if } u \geq 0, \\ (1-\theta) \mid u \mid, & \text{if } u < 0. \end{cases} \tag{6}$$

This asymmetric structure allows the model to capture distributional differences and nonlinear responses more effectively than conventional estimators. Building upon this framework, Machado and Santos Silva [18] proposed the Quantile GMM (Q-GMM) estimator, which integrates the strengths of moment-based estimation with quantile-specific analysis. The Q-GMM objective function can be expressed as:

$$\min \sum_{i=1}^{n} [\theta \mid y_i - x_i' \beta_{\theta} \mid \cdot I(u_i \geq 0) + (1-\theta) \mid y_i - x_i' \beta_{\theta} \mid \cdot I(u_i < 0)], \tag{7}$$

where $I(\cdot)$ denotes the indicator function. This formulation enables the estimation of heterogeneous effects across different quantiles while maintaining robustness against endogeneity and unobserved heterogeneity. Accordingly, this study employs the Quantile GMM approach in conjunction with panel quantile regression techniques to explore the distributional and heterogeneous impacts of green growth, green trade, green energy supply, and green technology innovation on ecological footprint across G20 countries. This combined framework ensures a more comprehensive and reliable assessment of the underlying relationships. Moreover, the estimation strategy that is utilized for empirical outcomes is depicted in *Fig. 3*.

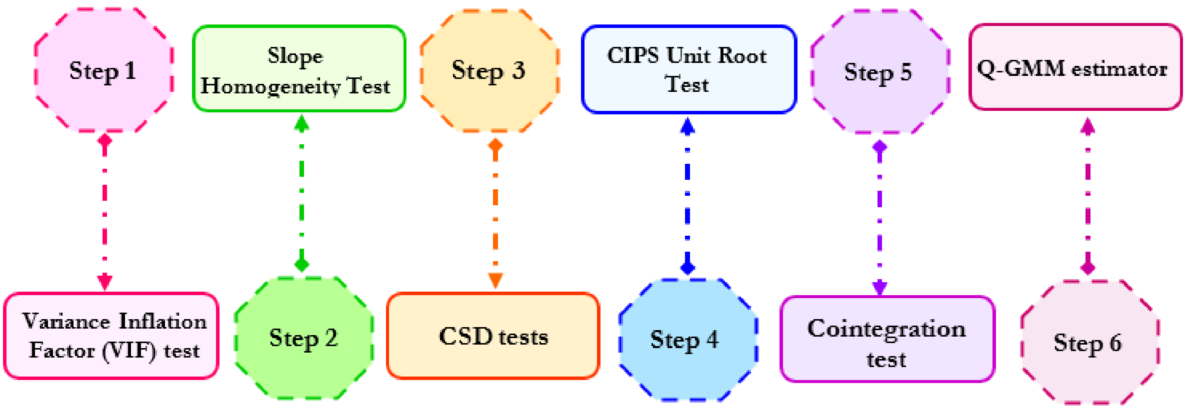

Fig. 3. Estimation Strategy.

4 | Empirical Results

4.1 | Descriptive Statistics and Pre-Estimation Analyses

The results of the Variance Inflation Factor (VIF) test reported in *Table 2* indicate that all explanatory variables exhibit VIF values well below the commonly accepted threshold of 5. Specifically, the mean VIF value is 2.03, suggesting a low degree of correlation among the regressors. This finding confirms that multicollinearity is not a serious concern in the model, and the estimated coefficients can be interpreted with confidence. From an econometric perspective, the absence of multicollinearity ensures the stability and reliability of parameter estimates, which is particularly important in multivariate panel models involving closely related variables such as green growth, green trade, and energy supply. Moreover, this result supports the appropriateness of using advanced estimation techniques such as the Quantile GMM (Q-GMM) estimator, as the independent variables contribute distinct information across different quantiles of the ecological footprint.

Table 2. VIF test.

Variable	VIF	1/VIF
EFP	3.26	0.277
GG	2.32	0.498
GRT	2.03	0.495
GES	1.85	0.644
GTI	1.03	0.99
Mean/VIF	2.03	

Table 3 presents the results of the slope homogeneity test. The null hypothesis of homogeneous slopes is strongly rejected at the 1% significance level, indicating that the estimated coefficients vary significantly across G20 countries. This finding reflects the structural heterogeneity among countries in terms of economic development, energy structure, technological capacity, and environmental policies.

Table 3. Slope homogeneity test.

Test	Statistics
$\Delta\sim$	15.958***
$\Delta\sim_{adj}$	18.998***

Note: *** indicates significance at the 1% level.

The results of the cross-sectional dependence tests reported in Table 4 indicate strong and statistically significant dependence among panel units. The rejection of the null hypothesis confirms the presence of cross-sectional correlation across G20 countries. This outcome is economically intuitive, as G20 economies are highly interconnected through trade, financial markets, and environmental spillovers. For instance, changes in energy policies or technological innovation in one country can influence environmental outcomes in others. From an econometric perspective, ignoring cross-sectional dependence may lead to biased and inconsistent estimates. Therefore, the presence of CSD further justifies the use of advanced panel estimation techniques that account for cross-country interdependencies, such as MMQR and other robust estimators.

Table 4. Cross-sectional dependent tests.

Test	Statistics
Pesaran CD test	6.880***
Pesaran scaled LM test	7.227***
Breusch-Pagan LM test	8122.05***

Note: *** indicates significance at the 1% level.

The CIPS unit root test results reported in Table 5 reveal that all variables are non-stationary at levels but become stationary after first differencing. This indicates that the variables are integrated of order one, I(1). This finding is consistent with macro-panel data characteristics, where economic and environmental variables typically exhibit trending behavior over time. The presence of unit roots implies that conventional regression models may lead to spurious results if long-run relationships are not properly addressed. Therefore, establishing cointegration among the variables becomes a necessary step to ensure meaningful long-run inference.

Table 5. CIPS unit root test.

Variable	Level	First Differences
lnEFP	-1.228	-4.228***
lnGG	-1.634	-3.807***
lnGRT	-1.720	-4.081***
lnGES	-2.490	-4.318***
lnGTI	-1.881	-3.113***

Note: *** indicates significance at the 1% level.

Table 6 reports the results of the Westerlund cointegration test, which confirm the existence of a long-run equilibrium relationship between ecological footprint and its determinants. The statistical significance of the test statistics indicate that the null hypothesis of no cointegration is rejected. This implies that Green Growth, Green Trade, Green Energy Supply, and Green Technology Innovation move together with the ecological footprint over the long term, despite short-run fluctuations. Economically, this result suggests that environmental degradation in G20 countries is structurally linked to economic, trade, energy, and technological factors. In other words, changes in these variables have persistent effects on the ecological footprint. From a methodological perspective, the confirmation of cointegration validates the use of long-run estimation techniques such as the Quantile GMM (Q-GMM) estimator, as it ensures that the estimated relationships are not spurious but reflect stable equilibrium dynamics.

Table 6. Westerlund's [19] cointegration test.

DH_g	Prob.	DH_p	Prob.
-1.719***	0.005	-1.422	0.056**

Note: *** and ** indicate significance at %1 and 5% levels.

Building upon the established evidence of long-run cointegration, the study subsequently employs long-run estimation techniques to rigorously examine the equilibrium relationships among the selected variables. The results from the Quantile GMM (Q-GMM) estimator are reported in *Tables 7-10*.

Table 7. Results of Q-GMM without moderating analysis.

Variables	Q10	Q25	Q50	Q75	Q90
lnGG	-0.6601**	-0.6589**	-0.6312**	-0.5814**	-0.6018**
lnGRT	-0.7182***	-0.7309***	-0.7781***	-0.8019***	-0.79.05***
lnGES	-0.3889***	-0.3915***	-0.4108***	-0.4082***	-0.3904***
lnGTI	-0.5841***	-0.5912***	-0.6018***	-0.5814***	-0.5931***
Cons	8.1254***	8.1579***	8.2102***	8.2418***	8.1098***

Table 8. Results of Q-GMM without moderating effects (GTI*GG).

Variables	Q10	Q25	Q50	Q75	Q90
lnGG	-0.6522**	-0.6358**	-0.6233**	-0.5614**	-0.6133**
lnGRT	-0.7018***	-0.7209***	-0.7617***	-0.8158***	-0.8019***
lnGES	-0.3641***	-0.3458***	-0.3847***	-0.3915***	-0.3818***
lnGTI	-0.5611***	-0.5722***	-0.5844***	-0.5611***	-0.5879***
lnGTI*lnGG	-0.0025**	-0.0048**	-0.0016**	-0.0014**	-8.0011**
Cons	9.5412***	9.12581***	9.8921***	9.8949***	9.5688***

Table 9. Results of Q-GMM without moderating effects (GTI*GT).

Variables	Q10	Q25	Q50	Q75	Q90
lnGG	-0.7008**	-0.6981**	-0.6509**	-0.6689**	-0.6307**
lnGRT	-0.6814***	-0.7023***	-0.7125***	-0.7627***	-0.7709***
lnGES	-0.3357***	-0.3187***	-0.3548***	-0.3742***	-0.3852***
lnGTI	-0.5817***	-0.5975***	-0.5819***	-0.5725***	-0.5689***
lnGTI*lnGT	-0.0037**	-0.0035**	-0.0028**	-0.0021**	-8.0024**
Cons	10.1189***	10.0894***	10.1039***	10.1087***	10.1208***

Table 10. Results of Q-GMM without Moderating Effects (GTI*GES).

Variables	Q10	Q25	Q50	Q75	Q90
lnGG	-0.7188**	-0.7058**	-0.6978**	-0.6819**	-0.6681**
lnGRT	-0.6971***	-0.6818***	-0.6749***	-0.7019***	-0.7159***
lnGES	-0.2659**	-0.2819**	-0.3057**	-0.3254**	-0.3609**
lnGTI	-0.5019***	-0.5187***	-0.5588***	-0.5421***	-0.5556***
lnGTI*lnGES	-0.0027**	-0.0025**	-0.0031**	-0.0033**	-8.0029**
Cons	9.8816***	9.7828***	9.6891***	9.7822***	9.8094***

The overall findings across *Tables 7–10* consistently indicate that GG exerts a negative and statistically significant effect on EFP across all quantiles and model specifications. This suggests that the expansion of environmentally adjusted growth strategies systematically contributes to reducing environmental degradation. The robustness of this relationship, even after incorporating interaction terms, highlights the structural importance of green growth in shaping environmental outcomes. From the perspective of G20 economies, this result is highly intuitive. These countries, particularly the advanced ones, have increasingly shifted toward innovation-driven and low-carbon growth models, supported by regulatory frameworks such as carbon pricing, environmental taxation, and sustainability-oriented investments. Even in emerging G20 economies, growing integration into global markets and international environmental commitments has encouraged gradual alignment with green growth pathways. In terms of the literature, these findings are broadly consistent with [2], [6], who document the environmental benefits of sustainable growth strategies. However, they diverge from earlier strands of the literature that emphasize the pollution-increasing effects of economic growth in the absence of structural transformation.

The empirical results reveal that GT has a strong, negative, and highly stable impact on EFP, with coefficients that are consistently larger in magnitude compared to other explanatory variables. This indicates that trade in environmentally friendly goods and technologies plays a particularly powerful role in mitigating environmental pressure. Within the G20 context, this outcome aligns closely with economic realities. These countries dominate global trade flows and serve as key hubs for technology diffusion, global value chains, and environmental standard-setting. Advanced economies facilitate the export of clean technologies, while emerging economies benefit from their import and adoption, collectively improving environmental efficiency. Moreover, trade-driven competition encourages firms to adopt cleaner production processes. These findings are in line with Wang et al. [8] and Alola et al. [7], which emphasize the environmental gains from green-oriented trade openness. At the same time, they contrast with studies that highlight the scale effect of trade as a driver of environmental degradation, suggesting that the composition and technique effects dominate in the G20 setting.

The results consistently show that GES has a negative and statistically significant effect on ecological degradation, confirming that a higher share of renewable energy contributes to environmental improvement. However, the magnitude of this effect is somewhat smaller compared to the green trade. This implies that while renewable energy plays a crucial role, its environmental impact may be moderated by structural and transitional factors. In G20 economies, this finding reflects the reality of high energy demand, entrenched fossil fuel infrastructure, and varying stages of energy transition across countries. Advanced economies have made substantial progress in renewable integration, whereas emerging economies still face technological and financial constraints. As a result, the full environmental benefits of green energy are realized gradually rather than immediately. These findings are consistent with Sharma et al. [9] and Li et al. [3], which document the environmental advantages of renewable energy adoption, although the relatively moderate effect size also resonates with studies suggesting that the energy transition is subject to structural limitations.

The estimates across all models demonstrate that GTI has a robust and significantly negative impact on environmental degradation, indicating that technological advancements play a direct and critical role in reducing environmental degradation. This effect remains stable across all quantiles, underscoring its broad-based influence. In the context of G20 economies, this outcome is strongly supported by their high levels of R&D investment, advanced innovation systems, and strong institutional capacity. Green innovations enhance energy efficiency, enable cleaner production, and facilitate the integration of renewable energy systems. Furthermore, innovation-driven improvements in resource utilization contribute to lowering the ecological burden of economic activity. These findings are consistent with Koseoglu et al. [11] and Khan et al. [5], which highlight the environmental benefits of green innovation. However, they differ from studies that argue innovation effects are delayed or uncertain, suggesting instead that in technologically advanced economies, these benefits are already materializing.

The interaction term between GTI and GG is negative and statistically significant, indicating that GTI amplifies the environmental benefits of GG. In other words, the effectiveness of GG in reducing environmental degradation is significantly stronger in the presence of higher levels of technological innovation. This finding is particularly relevant for G20 economies, where innovation capacity enhances the transition toward cleaner production and more efficient resource use. It suggests that growth strategies become truly "Green" only when supported by technological progress. This result aligns with Ahmed et al. [10], which emphasizes the complementary role of innovation, while challenging perspectives that treat green growth as independently sufficient for environmental sustainability.

The results further show that the interaction between GTI and GT is negative and significant, implying that technological innovation strengthens the environmental impact of GT. This suggests that trade becomes more environmentally beneficial when it is accompanied by innovation-driven improvements in production and technology transfer. In G20 economies, this reflects the role of innovation-intensive trade structures and advanced global value chains, where technology and trade are deeply interconnected. The findings are consistent with Wang et al. [8], which underscores the importance of technology in shaping the environmental effects of globalization, while contradicting views that consider trade inherently detrimental to environmental quality.

Finally, the interaction between GTI and GES is also negative and statistically significant, indicating that innovation enhances the effectiveness of renewable energy in reducing environmental degradation. This implies that the environmental benefits of green energy are not solely dependent on its adoption, but also on the technological sophistication with which it is implemented. In the G20 context, this highlights the importance of smart grids, energy storage technologies, and efficiency-enhancing innovations, which allow renewable energy systems to operate more effectively. This result is in line with Ahmed et al. [10] and Koseoglu et al. [11], which emphasize the synergistic relationship between innovation and energy transition, while extending beyond studies that examine renewable energy in isolation. A summary of the findings from the estimations is also depicted in *Fig. 4*.

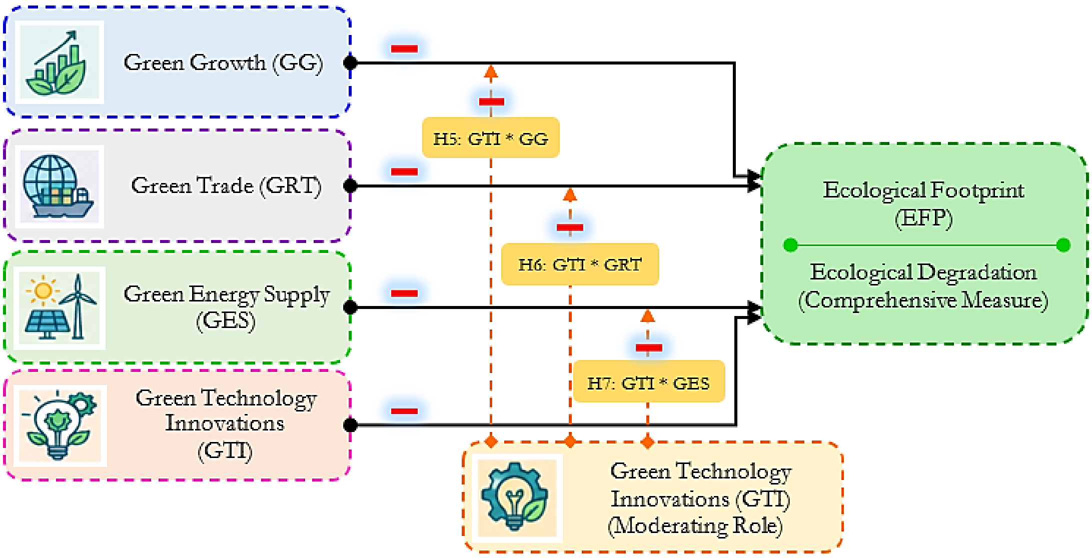

Fig. 4. Graphical presentation of empirical findings.

5 | Conclusion and Policy Recommendations

5 | Conclusion

This study addresses one of the most pressing challenges of the modern global economy, environmental degradation, by examining the role of green economic and technological factors in shaping ecological sustainability. Given the dominant contribution of G20 countries to global output, energy consumption, and environmental pressure, understanding the drivers of ecological footprint within this group is both timely and essential. The novelty of this study lies in its integrated framework, which simultaneously evaluates the effects of green growth, green trade, green energy supply, and green technology innovation, while also incorporating the moderating role of innovation. By moving beyond traditional single-factor analyses and adopting a multidimensional perspective, this research contributes to the growing body of literature on sustainable development and offers deeper insights into the mechanisms through which economic and technological transitions influence environmental outcomes.

Empirically, the study utilizes panel data for G20 countries over the period 2010-2024 and applies advanced econometric techniques, including Quantile Generalized Method of Moments (Q-GMM), to capture heterogeneous effects across the distribution of ecological footprint. The findings reveal that green growth, green trade, green energy supply, and green technology innovation all significantly reduce environmental degradation. Furthermore, green technology innovation strengthens the environmental benefits of the other variables, highlighting its critical role as a complementary factor. These results underscore the importance of adopting integrated and innovation-driven strategies to achieve long-term environmental sustainability in both developed and emerging G20 economies.

5.2 | Policy Recommendations

The empirical findings of this study provide several practical and policy-relevant insights for G20 economies seeking to reduce ecological degradation. First, policymakers should prioritize the transition toward green growth by promoting environmentally sustainable production and consumption patterns, supported by regulatory instruments such as carbon pricing, green taxation, and sustainability-linked incentives. Second, expanding green trade should be a central policy objective, particularly through reducing trade barriers for environmentally friendly goods and fostering international cooperation in clean technology exchange. Third, governments must accelerate investments in renewable energy infrastructure to increase the share of green energy in national energy mixes, while simultaneously addressing structural constraints such as grid integration and energy storage. Most importantly, the results highlight the pivotal role of green technology innovation; therefore, strengthening research and development (R&D), supporting innovation ecosystems, and encouraging public–private partnerships are essential for enhancing technological capacity. Additionally, integrating innovation policies with trade and energy strategies can generate synergistic effects, amplifying environmental benefits. Overall, a coordinated policy framework that simultaneously promotes green growth, trade, energy transition, and innovation is crucial for achieving sustainable development goals and ensuring long-term environmental resilience in G20 economies.

Authors' Contributions

K. K.: Writing-original draft, Methodology, Data Curation, Conceptualization, Software, and Visualization, Writing-Review & Editing, and Validation. R. M.: Writing-Review & Editing, Formal Analysis, and Investigation. M. K.: Validation, Writing-Review & Editing, and Formal Analysis. The authors have read and agreed to the published version of the manuscript.

Data Availability

The data is available on request from the corresponding author.

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Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The authors have given consent for the publication of this manuscript.

Ethics Approval and Consent to Participate

The authors confirm that this research did not involve human participants or animal subjects.

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